Beach nourishment and the ecosystem response

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Abstract:

Beach nourishment is the process of adding new sand to restore beach elevation and width lost to erosion. The process has proven to be viable in restoring recreational value and in extending protection to critical infrastructure and investment, both public and private, in the coastal zone. Uncertainty, however, remains as to whether it represents a viable solution from an ecological perspective. In the past five decades much research has been directed at reducing some of this uncertainty, but much remains to be learned. Ecosystem recovery following nourishment hinges on the engineer's ability to find a source of sand that matches as closely as possible the characteristics of the original beach sediment. Other factors, such as organic content, time of year, and quantity of sand placed all play important roles, but it is the match in terms of the mean sand particle diameter and its associated variance that determines success—where success is defined in terms of ecosystem vitality following the nourishment event. Considering these assertions, nevertheless, much more research remains to be done to better identify how species respond to and recover from stressors tied to the nourishment process.

Keywords: sandy beach, coastal erosion, beach nourishment, beach ecosystems and ecology

Introduction:

Occupying more than half of all non-polar coastlines, sandy beaches constitute one of Earth's most distinctive geographic zones (Woolridge et al. 2016; Luijendijk et al. 2018). This distinction, however, has historically come not from a primary recognition of their place as a critical ecotone between the terrestrial and oceanic realms, but instead for their universal appeal as a recreational destination and their associated contribution to an increasingly tourism-dependent global economy (Klein et al. 2004; Houston 2008; Houston 2020). Sandy beaches account for about 85% of tourism revenue in the United States annually (Houston 2020; World Travel and Tourism Council 2020). According to Klein et al. (2004), the primary determinant in the perceived recreational value of a sandy beach is its width--the wider the beach, the greater its perceived value, and the more valuable the properties juxtaposed behind it. But there is a problem that has long beset the world's beaches: erosion; most of the world's sandy beaches are narrowing through time because of loss due to erosion (Bird 1985; U.S. Army Engineers 1994; Moore et al. 1999; Morton and McKenna 1999; Galgano 2004; Zhang et al. 2004; Phillips and Jones 2006; Woolridge 2015 ). Furthermore, for most of these eroding beaches the problem is chronic (Galgano 2004). Several solutions have been tried to counter beach loss (McLachlan and Defeo 2018). The most common and highly regarded solution in terms of efficacy and collateral impacts is beach replenishment or nourishment (Bitan et al. 2020; Houston 2020; Woolridge et al. 2016; Nordstrom et al. 2011; McLachlan and Defeo 2018).

Beach nourishment is the process of placing a veneer of new sand on a beach to counter or offset elevation and width losses due to erosion. (Dean 2003; Slott et al. 2008). Its application is commonly justified to enhance, preserve, or restore recreational value or to protect nearby public and private infrastructure from storm flooding and wave attack (McLachlan and Defeo 2018). Less frequently, it is called upon to safeguard or reestablish an indigenous ecosystem (Jackson et al. 2007; Woolridge et al. 2016; McLachlan and Defeo 2018). The approach, first introduced in the United States about a century ago (Farley 1923; Valverde et al. 1999), is today the most common, and by many accounts thought to be the most ecologically sound, option to combat ocean beachfront losses (Greene 2002; Speybroeck et al. 2006; Nordstrom et al. 2011; Houston 2008; Whitehead et al. 2008; Bocamazo et al. 2011; Landry and Hindsley 2011; Bitan et al. 2020; Houston 2020). In some instances, such as in the State of North Carolina, where regulations prohibit structural countermeasures (e.g., seawalls, bulkheads, sandbags), it is possibly the only option that remains for communities in response to chronic erosion (NC Coastal Resources Commission 2014). In others, there is ample evidence that hard-structure approaches perform poorly, often bringing with them more problems than they resolve, leaving nourishment as the only viable erosion response (Pilkey and Wright 1989; French 2002; Airoldi et al. 2005).

Changes to the sandy beach ecology attributed to nourishment, though often initially severe---disruption or near-total die-off of most indigenous macrofauna in residence at the time are commonplace--are nevertheless thought to represent transient phenomena, with the restored beach recovering quickly following the introduction of new sands (Rakocinski et al. 1996; Bilodeau and Bourgeois 2004; Peterson et al. 2006; Jones et al. 2008; Woolridge et al. 2016). Results of individual studies, however, vary on the specific environmental (ecosystem-focused) consequences, and much remains unknown. This is true both in terms of the magnitude and duration of the impacts experienced, and the persistent changes that follow, on the reconstructed beach (Hayden and Dolan 1974; Gorzelany and Nelson 1987; Menn et al. 2003; Jones et al. 2008; Leewis et al. 2012; Schlacher et al. 2012; Manning et al. 2014; Peterson et al. 2014). This paper is an attempt to bring together what is presently known about beach nourishment and the ecosystem response, and more importantly, to consider what we still do not know. Although similar reviews exploring ecological impacts and recovery exist in the primary literature (Nelson 1989; Hackney et al. 1996; Hanson et al. 2002; Hamm et al. 2002; Greene 2002; Peterson and Bishop 2005; Peterson and Bishop 2005; Speybroeck et al. 2006; Wilber et al. 2009; Roscov et al. 2016), our objective is to build on these prior compilations and present an updated state of the knowledge review of the multi-scale spatial and temporal ecological impacts to the sandy beach associated with nourishment. We will additionally identify some of the current gaps in our knowledge, and finally offer select suggestions on how the engineering and scientific communities might proceed with future research in regard.

The Beach and Nearshore Ecosystem:

Hidden within the sands along and across most beaches are a broad, dense, and diverse array of biological communities (Figure 1; Cooke et al. 2012). While macro-fauna such as sea turtles and shorebirds transiently occupy the supratidal beach, and sometimes in large numbers for the latter group (Defeo et al. 2009), the beach ecosystem is dominated in both number and variety of species, by a mix of invertebrates that inhabit the uppermost meter of sand from nearshore to dune (Brown and McLachlan 1990). The inter-tidal surf and shallow subtidal zones of the sandy beach is home to most of these species, a group that includes a collective of invertebrates such as crabs, mollusks, worms, amphipods, isopods, protozoans, bacteria, insects, zooplankton, phytoplankton, and crustaceans (Knott et al. 1983; Charvat et al. 1990; Van Dolah et al. 1994; Wood and Bjorndal 2000; Fenster et al. 2006; Stull et al. 2016; McLachlan and Defeo 2018). Populations in this invertebrate group, particularly in the nearshore, surf and swash zones, can reach densities approaching 100,000 individuals per cubic meter of beach (Schlacher et al. 2007; Defeo et al. 2009). These animals form the base of a trophic hierarchy that includes larger macro-species such as fish and crabs living in the nearshore, and for birds and other animals that forage in the inter and supra-tidal zones (McLachlan and Jarmillo 1995; Hawkes et al. 2009; Cooke et al. 2012). Example species along the supra-tidal beach include the sand hoppers (*Talitrus* *saltator*), as well as animals from the *Ocypodidae* family, a large group that includes the common “ghost” and “fiddler” crabs whose dens can sometimes be seen in abundance on the beach surface from the swash zone to the dunes (Greene 2002; Fanini et al. 2007).

Numerous shorebirds use the beach and the adjacent nearshore waters for seasonal nesting, rearing, and year-round resting and feeding (Peterson et al. 2001; Vanden Eede et al. 2014). Shore birds rely on a host of invertebrates and other benthic in-fauna that inhabit the subaerial and intertidal zones as a food source (Greene 2002; Grippo et al. 2007). The direct trophic link between shore birds as predator and the beach macro-faunal communities as prey has been cited as a potential barometer of the macro-faunal abundance and diversity, and by association overall ecosystem health, across the intertidal beach (Bowman and Dolan 1985; Vanden Eede et al. 2014; Rosov et al. 2016).

In warmer latitudes, sea turtle nests are commonly found along sandy beaches. Sea turtles are animals entirely adapted to life in a marine environment, with a single exception: the female turtle must come ashore to lay her eggs (Madden et al. 2008). Typically, eggs are deposited in deeply dug nests on the dry beach berm above the local high-tide line (Grain et al. 1995; Davis et al. 1999; Brock et al. 2009), though if space is limited the female may lay her eggs in shallow nests closer to the swash (Madden et al. 2008). Sea turtles are not consumers of the plants and animals found at and around their nesting sites, but they are often prey, both the eggs and new hatchlings, for various predator species (Madden et al. 2008). Interestingly, while turtles are impermanent visitors to the beach, they may play an inordinate role in shaping ("engineering") the ecosystems where they nest (Hall and Parmenter 2006). The overturning of nest debris by predator invasion, or as hatchlings dig their way out of the nest, it has been suggested, contributes beneficial sediment mixing, oxygenation, and nutrient loads to the surrounding sands (Hall and Parmenter 2006; Madden et al. 2008). In areas where the number of nests is high, this contribution can be significant (Hall and Parmenter 2006; Madden et al. 2008).

Some species of marine fish rely on the nearshore and surf zone both as a source of habitat and for food (Brown and McLachlan 1990; Peterson and Manning 2001). Investigators further report that during the local warmer months of the year species abundance and diversity can be quite high, especially in the surf zone, providing a potentially rich and varied feeding ground for a broad range of opportunistic species (Modde and Ross 1981). Additionally, these regions may also represent shore-parallel migration routes for some species, particularly smaller varieties, or juveniles, moving locally or over longer distances between seasonal spawning and feeding grounds (Hackney et al. 1996).

Potential impacts to the ecology on the nourished beach:

The greatest alteration and impact to both the beach’s morphology and ecology comes when a thick carpet of new sand associated with a nourishment project is deposited on the beach surface. While studies have shown that under certain circumstances many species can survive this new overburden, either by sheltering in place or by burrowing laterally or upward (Hayden and Dolan 1974; Essink 1999; Menn et al. 2003), most nourishment projects result in complete, or near-complete mortality for most species in the impacted area (Leewis et al. 2012). Beach nourishment typically involves the placement of 1-4 meters of sand on the beach surface (Leewis et al. 2012). For the rates and volumes of sand applied, few organisms will have sufficient time to move themselves out of harm’s way under most circumstances (Greene 2002; Speybroeck et al. 2006). The newly introduced sediment can also harbor organic and inorganic toxins, and non-native plant specimens and animal species that could affect the indigenous organisms survivability during nourishment, and further alter the resultant composition and health of the restored ecosystem (Greene 2002).

Project timing is also a factor. Sand placement during periods when species abundance and activity is high, or during breeding seasons, places additional stressors on benthic communities, which can culminate in high mortality rates (Nicoletti et al. 2006). Larger species such as birds and turtles can also be affected during this period as feeding and nesting sites, along with both bird and turtle nests themselves, can be disturbed or destroyed if sand application is not carefully timed (Grain et al. 1995; Grippo et al. 2007). This can slow recovery and increase the likelihood that the new occupying species will differ in type and diversity once recovery is realized (Van Dolah et al. 1994; Greene 2002). Even with careful selection of the timing and duration of a nourishment project, it is assumed that most if not all indigenous species resident in the shallow beach and nearshore—though exceptions are noted—will be killed off rapidly and in sufficient numbers toward extinction (van Egmond et al. 2018).

Following sand placement, heavy earth-moving equipment are used to distribute the new materials uniformly across the project beach as per design specifications. The use of this equipment and the compressive ground-pressures they impart during construction can result in localized excess sand compaction in those areas where bulldozing was undertaken. Though excess material compaction does not always occur during nourishment (Rimkus 1992), where it does the resulting new sand layer can be 3 to 4 times denser than that of the sediment making up the original beach (Ryder 1991; Rice 2001). This compaction contributes to initial mortality through sediment dewatering and the associated loss of dissolved oxygen, and by making mechanical digging through the denser materials more difficult (Ryder 1991; Greene 2002; Speybroeck et al. 2006). Further, excess compaction over the longer-term can slow ecosystem reestablishment, and alter species composition and abundance along the nourished beach (Greene 2002).

After initial sculpting of the newly placed sands, the natural wind and wave regime takes over to finish reworking the subaerial and nearshore subaqueous surfaces toward a new equilibrium topography in the weeks and months that follow. (Dean 2003; Basterretxea et al. 2007). The sketches seen in Figures 2 and 3 provide a simplified graphic depiction of this reworking process. How quickly this morphological re-engineering is realized, and the nature of the resulting topographic geometry, is driven in part by the antecedent geology underlying the new beach and the local winds and waves, but more importantly by the physical properties of the emplaced sand (Basterretxea et al. 2007). This new sand not only dictates the character of the new beach surface, but also that of the shallow subsurface, where sand compaction, particle size, and composition can each influence the reestablished ecosystem (Grain 1995; Peterson et al. 2000).

Impacts associated with the introduction of excess fine-grained sediment:

Excess fine-grained (i.e., silt and clay sized particles) present in nourishment sands can temporarily or sometimes permanently increase suspended particle densities within the interstitial spaces of sands across the beach (Naqvi and Pullen 1982), in the surf zone and nearshore waters (Wilber 2003; Wilber et al. 2006). The interstitial spaces between sand grains are important highways for the transport and exchange of groundwater, nutrients, dissolved gasses, and heat energy across the shallow subsurface (Lindquist and Manning 2001; Speybroeck et al. 2006; Jackson et al. 2007). Alteration of these pathways either temporarily or permanently will affect this material transport, and in turn, the resultant habitats, and species that recolonize the beach (Lindquist and Manning 2001). Some research suggests that short-term elevations in interstitial concentrations do no lasting damage, and in some cases might even be beneficial to the recovering beach. van de Koppel et al. (2001), for instance, proposed that an excess of fine sediment in nourishment sands can introduce interstitial nutrients that encourage phytoplankton growth, a primary food source for many beach recolonizing invertebrates. Other investigations, however, find that the long-term presence of excess silt and clay introduced via nourishment can have prolonged deleterious effects on inter-grain interstitial chemistry and material transport that are manifest in the cross-section of colonial species and the character of the habitats that the new species occupy (Goldberg 1988).

Suspended solid concentrations in the surf and subtidal zones are also typically elevated during and immediately following an nourishment event (Wilber, 2006). Turbidity during this time can reach levels like those seen during strong storms (Wilber et al. 2006). Over the longer term, in the presence of excess fine sediments, turbidity levels can persist in the surf zone and nearshore water columns, potentially decreasing available dissolved oxygen (Goldberg 1988) and permanently reducing overall incident sunlight penetration and photosynthesis (Essink 1999). This reduction or loss of sunlight at depth can threaten seagrass populations resident in and around the construction area (Goldberg 1988; Guidetti and Fabiano 2000; Ruiz and Romero 2003; Gambi et al. 2005). Most turbidity effects associated with nourishment, however, are short-lived (Wilber 2003). Water clarity usually returns to pre-nourishment levels within two years, often much sooner (Wilber et al. 2006). Moreover, some research has hinted that the increases in short-term water-column turbidity levels tied to nourishment can be advantageous to some species of indigenous flora and fauna (Gorzelany and Nelson 1987; Van Dolah et al. 1994; Rakocinski et al. 1996; van de Koppel et al. 2001). For example, temporarily reduced water clarity associated with increases in turbidity provide fish some additional level of protection from predation (Beyst et al. 2002). The temporary increases in interstitial nutrient loadings and their propensity to stimulate plankton growth as already reported by van de Koppel et al. (2001), have also been observed in surf zone and nearshore waters (van de Koppel et al. 2001). Research also suggests that sea grass might even benefit from the sunlight attenuation tied to beach nourishment (Ballesta et al. 2000). For instance, Micheli et al. (2012) found that the sea grass species *Posidonia oceanica*, a prolific, wide-ranging variety found in abundance in littoral coastal regions of the Mediterranean Sea (Nicoletti et al. 2006), growing in meadows nearest to a nourishment-impacted beach evolved greater genetic variability and resiliency over time relative to their more distant counterparts. The authors postulated that increased water column turbidity coming from excess fine sediment suspension and the associated stresses compelled the evolution. They cautioned, however, that the grasses were positioned adjacent to and not directly within the project impact zone and so experienced only moderate increases in water turbidity.

Impacts associated with nourishment-induced changes in beach morphology:

Changes in beach morphology are also seen with the placement of nourishment sands on the beach (Roberts and Wang 2012). Excessive beach slopes and scarping (Figures 4a and b) are commonplace following nourishment, as the restored beach evolves toward an equilibrium morphology (Nelson et al. 1987; Dean 2001). During this initial period, these features have been observed to hinder or obstruct movement of beach macro and micro fauna between the berm and swash zones (Nelson et al. 1987; Grain et al. 1995). The steeply sloped topography following nourishment, however, is usually only a temporary phenomenon, though the restored beach can and often does exhibit a post-nourishment morphology that differs from the original by virtue of design (Kaufmann and Pilkey 1983). Such differences can be sufficient to create a different intra-faunal community from pre-nourishment (McLachlan 1983; Grain et al. 1995). Greene (2002) asserts that these alterations to beach morphology could play a more significant role in determining the ecosystem outcome than those associated with burial during the construction phase.

Potential longer-term factors:

Studies suggest that both the pace of recovery and the post-reconstruction ecosystem that emerges following nourishment will be determined in large measure by the material characteristics of the new beach sands (McLachlan 1983; Degraer et al. 2003; Rodil and Lastra 2004; McLachlan and Dorvlo 2005; Peterson et al. 2014; Vanden Eede et al. 2014; Voila et al. 2014). Characteristics include mineralogical makeup, particle size and shape distributions, and color. The sediment particles themselves can consist of sands from a variety of terrestrial or marine sources, along with durable shells, shell fragments, and finer-ground shell-derived hash, all varying in size, shape, composition, and quantity. Perishable organic content may also be interspersed with the sediments. These material qualities and relative quantities play a crucial role in determining indigenous species composition, diversity, variability, and abundance in the beach ecosystem (Greene 2002).

A study by Benedet et al. (2004) asserts that even minor differences in grain size between the fill materials versus those existing on the original beach surface can yield large changes in both the resulting beach morphology and habitat. Peterson and Manning's (2001) work along two North Carolina ocean beaches and in experimental wave tanks emphasized this grain-size-habitat relationship, suggesting strong correlation between grain size and survival/recovery of fauna on the nourished beach. Over a two-year period, the beaches that received sands smaller in average size than what was present on the pre-nourished beach exhibited poor recovery for species of amphipods (specifically: *Parahaustorius longimerus* and *Amphiporeia virginiana*), and mole crabs (*Emerita talpoida*). Only a variety of polychaete worm (*Scolelepus squamata*), a cosmopolitan species that can tolerate a broad range of environmental conditions (van Tomme et al. 2013), appeared to recover and emerge quickly following nourishment. In contrast, Woolridge et al. (2016) found that nourishment had a longer-term detrimental impact on the polychaetes, with population numbers 15 months after sand placement, and across eight Southern California beach sites, all remaining below pre-nourishment levels. Woolridge et al. (2016) also observed quick (within one-year) recovery for *talitrid* amphipods and the clam *Donax gouldii*. Mole crab (*Emertia analogia*) recovery was highly variable, though their return to pre-nourishment population levels was delayed relative to other dominant species on all eight study beaches.

Numerous other studies exist in the primary literature detailing the importance of sand particle size in the recovery of a nourished beach. Steinitz et al. (1998) and later Rumbold et al. (2001) studied how changes in grain size in nourishment sands affected longer-term (e.g., the Steinitz et al. (1998) study spanned 7 years) nesting rates, egg viability, and hatchling success of sea turtles along Florida’s Jupiter Island coast. Ryder (1991), Grain et al. (1995), and Davis et al. (1999) conducted similar grain-size-based studies on sea turtles along other Florida beaches. Ross and Lancaster (1996) investigated impacts to surf zone and nearshore fish nursery habitats and the subsequent movement of juvenile fishes in relation to nourishment sediments along estuarine reserve beaches near Wilmington, North Carolina. Rakocinski et al. (1996) explored impacts on macrobenthic fauna in the near shore resulting from nearby large-scale beach restoration project at Perdido Key, Florida. Peterson et al. (2000) studied how changes in lower tropic level invertebrate populations, such as the mole crab *Emerita talpoida*, were reflected in higher tropic-level animals, such as the common ghost crab *Ocypode quadrata*, on recently nourished beaches along North Carolina’s Bogue Banks. Jackson et al. (2007) similarly looked at impacts associated with the health and survivability of horseshoe crabs on estuarine beaches in Delaware Bay. Finally, Peterson et al. (2014) followed the recovery and population cross-section for select invertebrate fauna along North Carolina’s Bogue Banks over a longer three-to-four-year period following nourishment. Results from these studies all point to the proper matching of fill sands to the beach as the critical factor dictating the timing and character of recovery. The closer the match in characteristics between the existing and replacement sand, the more rapid the potential pace of recovery (Nordstrom 2005; Wilber et al. 2009; Peterson et al. 2014). The greater the mismatch between the two, the more prolonged the time required for the beach ecosystem to recover or reach a new stasis (Voila et al. 2014), though precisely how prolonged for a given difference is unclear (Schlacher et al. 2012).

Changes in inorganic and organic content, such as shells, shell fragments, and more perishable organic detritus, can play a role in post-nourishment outcomes (van der Wal 1998; Peterson et al. 2000; Peterson et al. 2014). Some investigators have found that high shell content in replacement sands will affect compaction and permeability of the new beach (McLachlan 1996; Rakocinski et al. 1996; Lindquist and Manning 2001; Peterson et al. 2000; Peterson and Manning 2001). Excess shell material on the beach’s surface can create an armor-like veneer that may inhibit invertebrate burrowing (Peterson et al. 2000) and interfere with the ability of shore birds and sea turtles to establish viable nesting sites (Peterson et al. 2014). Other studies, however, indicated that changes in the surface veneer had little effect on animal behavior and in some cases even enhanced, nesting viability for shore birds (Melvin et al. 1991) and turtles (Davis et al. 1999) on dry sections of the nourished beach. Davis et al. (1999), in their study, stated emphatically that turtles along the Gulf Coast of Florida “...paid no attention to compaction” or other surface phenomena.

Shells, shell fragments, or hash present in significant quantities can also alter the resultant beach surface topography. The larger shelly material skews the effective mean grain size toward lower phi sizes (larger effective diameters), which collaterally changes the total sediment transportability on the beach by both winds and breaking waves (Nelson et al. 1987; Peterson et al, 2001; Greene 2002; Speybroeck et al. 2006). The (re)development of dunes, and the subsequent (re)establishment of vascular plant growth also depend on this transportability of the new fill sands (McLachlan 1991; Peterson et al. 2014). Regular sand transport is also thought to be important in controlling fungal growth on the dune. Left unchecked the fungal growth can harm the root systems of certain beach and dune grasses (van der Putten and Peters 1997) that populate the upper beach and dune systems.

Nourishment Design Considerations:

To this point, we have assumed and described the implications of a nourishment event that places a blanketing veneer of new sand across an entire alongshore section of beach, from nearshore to dune—this is not always the case. Capobianco et al. (2002), for instance, presents four differing designs that can be employed to address specific problems on a beach. These four include: dune only augmentation or re-construction; 2.) subaerial elevation adjustment; 3.) subaerial profile reshaping; and 4.) nearshore-only fill. The extent of coverage and degree of impact will differ for each option. For options 2 and 3, alternatives where blanket coverage is possible, the entire beach may receive replacement sand, or it may only be applied as augmentation in locations where needed. Differences here will certainly have a bearing on the nature of impact and subsequent recovery, as well as to the character of the biotic community that emerges (Capobianco et al. 2002). Limiting nourishment coverage will reduce the degree of ecosystem impact.

Stive et al. (2013) introduced another variant on nourishment designed to reduce long-term costs and increase the interval between consecutive projects: the mega-nourishment. Mega-nourishment employs exceptionally large volumes of sand placed at a strategic location along the beach. This large volume of sand provides a sediment resource that leverages littoral currents to redistribute replacement materials up and down the beach more naturally. Coverage can span 10 to 20 km of shoreline or more with a 20-year anticipated project lifespan (Stive et al. 2013). The approach is further thought to reduce the overall ecosystem disturbance associated with sand placement by reducing the number and frequency of disruptive nourishment events and provide for additional novel habitats within and adjacent to the mega-nourishment site (van Egmond et al. 2018).

Along with application scale, the timing of a single nourishment event, and the repetition frequency for beaches receiving regular maintenance (e.g., Miami Beach, Wrightsville Beach, Virginia Beach), are also important considerations. Unfortunately, at the present time there is little publicly available or peer-reviewed published research that explores impacts to a beach ecosystem subjected to repeated application of nourishment sands. Armstrong and Lazarus (2019) and Houston (2020) do provide arguments for the efficacy of repeated nourishment in opposition to erosion from local effects and long-term sea level rise, with conclusions in both reports suggesting that regular renourishment can offset and even reverse erosion trends along a beach. These findings, however, are focused more on the beach as a recreational and economic instrument, not the short term or lasting impacts that such practices might impose on the health and survivability of the indigenous beach ecosystems.

Discussion:

For the engineer, a successful beach nourishment project is gauged on how well it satisfies its principal design objectives. Those objectives can include the restoration of the recreational aspects of the beach, reestablishment of a suitable protective interface for existing built infrastructure, protection and preservation of an ecosystem, or simply a move to find an economical home for dredge spoil pulled from a nearby navigation channel. Klein et al. (2004) and Whitehead et al. (2008) both demonstrated that a high positive correlation exists between beach width and perceived recreational value. The assertion that nourishment can maintain or enhance the value of public and privately held properties in coastal communities has also been advanced in studies by Gopalakrishnan et al. (2011) and Landry and Hindsley (2011), and for historic property preservation by Bitan et al. (2020). Opportunistic use of dredged sediment materials is also considered to be a potentially viable option for sourcing beach nourishment sands in some locations (Jackson et al. 2005). Houston (2016) found evidence for the long-term effectiveness of nourishment so compelling as to recommend that state and national government programs should include its regular application in their strategic plans. Economic and protection arguments notwithstanding, it is with the complex ecological realm surrounding beach nourishment that most of the controversy, uncertainty, and debate on the merits and faults dwell (Greene 2002; Speybroeck et al. 2006; Peterson et al. 2014; Rosov et al. 2016). The numerous studies carried out over the past 40 years, some of which are mentioned and described herein, have attempted to expand our understanding of how the application of a thick layer of sand to the surface of an eroding beach might impact the resident beach ecology. Their findings, though far from complete, have yielded the following general conclusions:

1.) Biology of the beach and its morphology are tightly coupled. Morphological changes, even if small and limited in scope, can have profound effects on the resident ecology, in terms of abundance and diversity.

2.) Grain size is the most crucial factor deciding the nourished beach’s resultant morphology and ecology. Even minor differences in median grain size between the new nourishment sands and the original will alter the character of the restored ecosystem in terms of species types, abundance, and diversity, as well as the pace of recovery. If beach geometry and habitat restoration mirroring the pre-nourishment structure is the objective, selected replacement sands should match the size and distribution of the pre-nourished beach.

3.) Composition of the sand placed on a beach during nourishment also regulates its resulting ecosystem. Quantities of fine sediments (i.e., slits and clays) or shelly material modulate compaction, grain interstitial character, and surface competence and permeability, attributes that influence invertebrate and vertebrate community composition and behavior. Studies, however, conflict on whether these impacts are to be interpreted as positive or negative.

4.) Quantity of sand placed on the beach is important. Much research to date has demonstrated that burial to typical nourishment depths (1 to 4 meters) results in almost complete destruction of the impacted habitat and the die-off of resident invertebrate populations. Research, however, is also mixed on the extent of long-term to permanent consequences owed to this burial on the repaired beach’s ecosystem.

5.) The time of year that the nourishment occurs, and spatial extent are also important considerations. Placement of sands during the local warm season, when species recruitment and reproduction rates are high, have been shown to result in more species die-off and slower recovery rates versus application during months when most species are dormant. Further, limiting application to smaller sections of beach can concomitantly limit the impacts to the local ecosystem.

Conclusion:

Beach nourishment has become the “go-to” solution to the coastal loss/preservation problem associated with beach erosion (Finkl and Walker 2004). Many studies find nourishment to be an effective means (e.g., Houston 2016; Armstrong and Lazarus 2019; Houston 2020) of ensuring at least short-term survival of the physical beach. There is much less consensus on the ecological implications (Finkl and Walker 2004; Peterson and Bishop 2005; Dugan 2010; Leewis et al. 2012; Schlacher et al. 2012; Peterson et al. 2014). Most ecosystem studies to date have focused on the ecological impacts only through the first few weeks and up to 2 years (Peterson and Manning 2001; Greene 2002; Speybroeck et al. 2006), so little is known of the longer-term effects. An additional limitation with most existing studies is the exclusive focus on a single nourishment event. Less is known about impacts associated with repetitive application, or how the frequency of these events might manifest in the beach ecosystem over time (Peterson and Manning 2001; Basterretxea et al. 2007). Future research must consider the longer term and the effects associated with repetitive nourishment events. Further, there remains more to learn about the animals themselves that inhabit the beaches: their variable behaviors and interactions with their neighbors and their environments are not well understood. Future work should thus be directed at providing a better understanding of the lifecycles and behaviors of the many species indigenous to beach habitats. The high degree of variation shown by many species, particularly those residents in the inter-tidal zone, present a current conundrum in terms of population distributions and dynamics. Ecosystem recovery is another factor that is difficult to quantify. We know little about the species involved and how they response to stressors. Better understanding would allow us to define recovery, predict what recovery might look like, and enable our ability to detect it within the beach system if or once it occurs.

Beach nourishment appears to be here to stay as a solution to beach erosion. Knowledge gaps, as addressed above, will become critical to inform future planning and engineering designed to maintain the beach’s economic and ecological integrity (Haddad and Pilkey 1998 ; Hoagland et al. 2012). Whether our goal is to protect human interest and investment, to provide a safe enjoyable place to spend a day or a vacation, or to preserve an important ecological niche, an understanding of what happens when we choose to augment our beaches with new sand is vital.

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