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 storm protection to critical public and private infrastructure and investment in the coastal zone.

There, however, remains much debate regarding nourishment’s potential ecological ramifications both in short and long-term. Over the past five decades much research has been directed at defining the impact, but much remains to be learned. Ecosystem recovery following nourishment hinges on the replacement material matching the grain-size distribution of the original beach sediment. Other factors, such as organic content, time of year, and quantity of sand placed are also important, but it is the match in terms of the 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 beach ecological populations respond to and recover from stressors tied to the nourishment process.

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

**1. 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 a 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; many of the world's sandy beaches are under threat from shoreline recession and 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 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), nourishment is often the preferred option for communities to mitigate chronic erosion (NC Coastal Resources Commission 2014). Many studies show that hard-structures often induce unintended problems, often leaving nourishment as the most preferred erosion response (Pilkey and Wright 1989; French 2002; Airoldi et al. 2005).

The repercussions associated with beach nourishment are often viewed as transient pulse-like phenomena on the affected beach (Bender, 1984), with beach ecosystem recovery coming quickly, sometimes in as little as a few months. But numerous studies show that during the first days following nourishment a nearly-complete die-off of most if not all indigenous macrofauna populations is commonplace (Rakocinski et al. 1996; Bilodeau and Bourgeois 2004; Peterson et al. 2006; Jones et al. 2008; Leewis et al. 2012; Viola et al. 2014; Woolridge et al. 2016) and suggest further that neither a quick nor complete recovery can be assured (Peterson et al. 2006; Jones et al. 2008; Leewis et al. 2012; Viola et al. 2014; Woolridge et al. 2016). Results of individual studies vary widely on the specific environmental (e.g., ecosystem) consequences, and much remains unknown. This is true both in terms of the magnitude and duration of the impacts experienced as well as the persistent changes that follow, for 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 brings together what is presently known about beach nourishment and the ecosystem response, and more importantly, aims to highlight 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 knowledge review of the multi-scale spatial and temporal ecological impacts to sandy beaches associated with nourishment. We additionally identify some of the current gaps in our knowledge, and finally offer several suggestions on how the engineering and scientific communities might proceed with future research.

**2. The beach and nearshore ecosystem, a brief overview**:

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 macrofauna 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 diversity of species, by a variety 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 are home to most of these species, a group that includes a collective of micro and macro-organisms such as crabs, mollusks, worms, amphipods, isopods, 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). Macroinvertebrate populations, 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 (FIGURE XXXXX???) 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). Shorebirds 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 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 hatchlings, for various predator species (Madden et al. 2008). Interestingly, while turtles are impermanent visitors to the beach, they may play an important role in modifying 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, has been suggested as contributing 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 (Figure 1) (Brown and McLachlan 1990; Peterson and Manning 2001). While many species have been documented, common fish include anchovies (family *Engraulidae*), sardines (familyCl *Clupeidae*), silversides (*Menidia menidia*), and larger finfish such as spot (*Leiostomus xanthurus*), pompano (family *Carangidae*) bluefish (*Pomatomus saltatrix*), red drum (*Sciaenops ocellatus*), and flat fish (families *Pleuronectidae*, *Paralichthyidae*, and *Bothidae*). Investigators report that during warmer months 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; Able et al. 2012). 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).

**3. Impacts associated with the nourishment construction phase:**

The nourishment construction phase is here defined as the time period during which new beach fill material is being actively placed and redistributed on the project beach. It is during this stage, a period that can span from a few days to several weeks, that the most rapid and extensive morphological and biological changes associated with beach nourishment take place. The beach surface topography is completely transformed through the addition of a meter or more of new fill sediments (Speybroeck et al. 2006; Leewis et al. 2012) and the resultant biological disturbances contribute to high rates of indigenous organism mortality (Viola et al. 2014). The following sections will explore in more detail these impacts.

**3.1 Direct impacts to the beach ecology during the nourishment construction phase:**

Beach nourishment typically involves the placement of 1-4 meters of sediment (mostly sand) on the beach surface (Leewis et al. 2012). While studies have shown that in some cases 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), for the rates that fill is typically added to the beach during construction, few organisms will have sufficient time to move themselves out of danger in most circumstances (Greene 2002; Speybroeck et al. 2006). As a result, nearly all nourishment projects bring about complete, or near-complete mortality for species in the impacted area (Leewis et al. 2012). The newly introduced sediment can also harbor toxins such as hydrogen sulfide (Gorzelany and Nelson, 1987; Adriaanse and Coosen, 1991), and non-native plant specimens and animal species that could affect the indigenous organisms survivability during nourishment, and 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 is at or near the seasonal high, or during the breeding season, places increased numbers of living organisms at risk and/or can limit the number of offspring produced (Nicoletti et al. 2006). Larger species such as birds and turtles can also be affected during this period as potential feeding and nesting sites, along with the existing 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 species resident in the shallow beach and nearshore—though exceptions are noted—will be killed off rapidly and in large numbers (van Egmond et al. 2018).

Following sand placement, heavy earth-moving equipment are used to distribute the new materials 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 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 begin reworking the beach surface toward a new equilibrium profile 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, the local winds and waves, and by the physical properties of the emplaced sediment (Basterretxea et al. 2007). This material not only dictates the character of the new beach surface, but also that of the shallow subsurface, where compaction, mineral composition, and particle size each influence the reestablished ecosystem (Grain 1995; Peterson et al. 2000).

**3.2 Impacts to the beach ecology associated with the introduction of excess fine-grained sediment during the nourishment construction phase**:

Excess fine-grained (i.e., silt and clay sized particles) present in nourishment sands can increase suspended particle concentrations within the interstitial spaces between sand grains across the beach (Naqvi and Pullen 1982), and in the surf zone and nearshore waters (Wilber 2003; Wilber et al. 2006). The interstices or pore spaces between sediment grains are important conduits for the transport and exchange of groundwater, nutrients, dissolved gasses, and heat energy across the beach’s shallow subsurface (Lindquist and Manning 2001; Speybroeck et al. 2006; Jackson et al. 2007). Alteration of these pathways 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 these constituents 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 nutrients into pore waters 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 the chemical composition and concentrations and material transport within the inter-grain pore waters that play an important role in defining the species make-up in the habitats that emerge along the nourished beach (Goldberg 1988).

Suspended sediment concentrations in the surf and subtidal zones are also typically elevated during and immediately following a nourishment event (Wilber, 2006). Turbidity during this time can reach levels similar to those observed during strong storms (Wilber et al. 2006). Over the longer term, in the presence of excess fine sediments, turbidity levels can remain elevated in the surf zone and nearshore water columns, potentially decreasing available dissolved oxygen (Goldberg 1988), blanket grass beds and reefs with excess sediment (Jordan et al. 2010), and reduce overall incident sunlight penetration and photosynthesis (Essink 1999). This loss of sunlight at depth can threaten the health of submerged flora (e.g., submerged aquatic vegetation or SAV) and coral resident in and around the construction area (Goldberg 1988; Guidetti and Fabiano 2000; Ruiz and Romero 2003; Gambi et al. 2005; Erftemeijer et al. 2012). 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). Some research has hinted that the increases in short-term water-column turbidity levels tied to nourishment can even be advantageous to some species (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 nutrients can stimulate plankton growth (a primary food source for several invertebrates) in surf zone and nearshore waters (van de Koppel et al. 2001). Research also suggests that SAV might benefit from the sunlight attenuation tied to beach nourishment (Ballesta et al. 2000). For instance, Micheli et al. (2012) observed that a meadow of the Mediterranean species *Posidonia oceanica* located adjacent to a recently nourished beach in the Italian Cinque Terre village of Monterosso al Mare 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.

**3.3 Changes to beach morphology during the nourishment construction phase:**

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 is reworked by wave and wind-induced erosion and redeposition (Nelson et al. 1987; Dean 2001). Scarps have been observed to hinder or obstruct movement of beach macro and microfauna 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 (Peterson et al., 2014). 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.

**4. Post-Nourishment Recovery**:

Recovery—the restoration of the beach ecosystem in the weeks to years following the nourishment construction phase—hinges on several environmental factors. Important among these are the material properties (e.g., grain-size, mineral composition, percent organics present) of the fill material used, littoral-zone sediment transport, the amount of material placed and its physical placement and distribution across the beach surface, and finally, the time of year in which the project was undertaken. These factors contribute to the pace of recovery and the composition, abundance, and diversity species that repopulate the beach.

**4.1 Sediment grain-size controls on post-nourishment recovery:**

Research suggests that following nourishment both the pace of recovery and the eventual post-reconstruction ecosystem that emerges will be determined in large measure by the characteristics of the new beach sediment (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). Important sediment characteristics include mineralogical makeup, particle size and shape distributions, and color. The sediment particles themselves can consist of muds, sands, and gravels, 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. Degradable organic content may also be interspersed with the sediments. These material qualities and relative quantities play a crucial role in determining species composition, diversity, variability, and abundance in the beach ecosystem (Greene 2002).

A study by Benedet et al. (2004) asserted that differences in grain size between nourishment fill materials versus those from the original beach can yield large changes in the resulting modal beach morphology. Modality here refers to the geometry or shape that the beach profile will assume under what might be considered typical wind and wave conditions for a given locale (Wright and Short, 1984). Peterson and Manning's (2001) work along two North Carolina ocean beaches and in experimental wave tanks had earlier recognized this sediment size-profile relationship while also observing a correlation between changes in sediment size and the survival/recovery of fauna on the nourished beach. Over a two-year period in the Peterson and Manning study 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 remerge quickly following nourishment. In contrast, Woolridge et al. (2016) found that *Scolelepus squamata* remained below pre-nourishment population levels after 15 months at all eight Southern California beach sites included in their study. A later study by Peterson et al. (2006), again focusing on a recently nourished beach in North Carolina, observed a rapid recovery for *Emerita talpoida*, while sp. *Donax* was much slower to rally. In this case the fill materials were coarser in average size than that found on the existing beach, and contained an abundance of gravel-sized shell hash. *Emerita* are thought to prefer a relatively coarser sediment mixture (Bowman and Dolan, 1985). *Donax* on the other hand, seem to favor a substrate that is finer grained (McLachlan, 1996), with less shell matter—a material that interferes with the animal’s ability to burrow into the beach surface (Manning, 2003). The coarser (approximately 1 phi size larger) fill material used for the nourishment project could explain the contrast seen in the recovery rates for these two species (Peterson et al. 2006).

Numerous other research is presented 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) looked at 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, each showing evidence for reduced nesting success resulting from sediment-size changes which altered compact-ability and nest chamber integrity. 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 nearshore resulting from nearby large-scale beach restoration project at Perdido Key, Florida. The authors concluded that the increased silt and clay content in the replacement materials used to reconstruct the beach were responsible for the slowed recovery for many species that persisted for more than two years after the restoration work was completed. 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 after nourishment. Results from these studies all point to the fill sand as a critical factor dictating the timing and character of recovery. The closer the match in sediment grain-size and sorting (sorting is analogous to the sediment size distribution’s standard deviation) 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, the more time will be required for the beach ecosystem to recover or reach a new stasis (Voila et al. 2014), though precisely how long for a given difference is unclear (Schlacher et al. 2012).

**4.2 Shell and organic material** **controls on post-nourishment recovery:**

Changes in inorganic and organic content, such as shells, shell fragments, and more degradable 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 affects 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; Peterson et al. 2014) 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) 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 (van der Putten and Peters 1997). Left unchecked the fungal growth can harm the root systems of certain beach and dune grasses that populate the upper beach and dune systems (van der Putten and Peters 1997).

**4.3 Littoral sediment transport** **controls on post-nourishment recovery:**

While grain-size is thought by many investigators and engineers to be the most influential control on ecosystem response, there are other factors that also contribute to recovery, and in particular the pace of recovery, following a nourishment event. One of these is the average rate or trend in alongshore (littoral) sediment transport (Peterson et al. 2006). Alongshore sediment transport has received much less attention as a post-nourishment beach ecosystem driver, but Peterson et al. (2006) points to some interesting patterns in the results from other peer-reviewed research. Foremost among these is that outcomes from other investigations appear to cluster into two groups: those that saw a quick recovery and little or no lasting impacts tied to nourishment (Hayden and Dolan, 1974; Naqvi and Pullen, 1982; Gorzelany and Nelson, 1987; Burlas et al., 2001) versus those where post-nourishment recovery was delayed or, for the duration of the study, never observed (Reilly and Bellis, 1983; Rakocinski et al. 1996; Peterson et al. 2000; Manning, 2003). The one common factor that differentiated the two groups was, according to Peterson et al, (2006), the longshore sediment transport rate. Beaches that recovered quickly, they observed, with little to no noticeable long-term impact were those where sediment transport rates were considered to be high, whereas those beaches with lower rates exhibited greater impact magnitudes and protracted recovery times. The authors did not provide specific definitions for what constituted high and low rates.

Evidence for the role that alongshore transport could play in the fate of the post-nourishment ecosystem can be found in studies dating to the 1970s. One such example investigated post-nourishment influences on mole crab *Emerita talpoida* abundance along a beach near Cape Hatteras, North Carolina (Hayden and Dolan. 1974). The investigators observed that while *talpoida* populations in the immediate impact area were significantly reduced these reductions did not reflect large scale burial and mortality but instead could be attributed to the local alongshore currents in the surf zone allowing the animals in the affected areas to relocate to a safer location down-current on the beach. This escape pathway provided an explanation for the lack of mortality evidence and for the short (2 days to a week) recovery times seen for *talpoida* in the nourished area. Net longshore transport along this part of the North Carolina coast has been estimated at approximately 300,000 cubic meters per year (Inman and Dolan, 1989). Gorzelany and Nelson, (1987) observed similar results for the coquina clams *Donax* *variabilis* and *Donax* *parvula* along Atlantic Ocean beaches in Brevard County, Florida. In this study the investigators were unable to detect an impact due to the nourishment that was distinguishable from the natural variability for these, and several other species, that populate the beach. Similar to the beaches near Cape Hatteras, alongshore transport rates on the Atlantic central coast of Florida are on the order of 250,000 cubic meters per year (van Gaalen et al 2016).

A more recent study along Bogue Banks, a barrier island on the North Carolina coast (Peterson et al., 2014) tracked macrofaunal recovery following beach nourishment. The researchers found that while *Emerita talpoida* reestablished after only a single season *Donax* recovery remained depressed to the end of the 3 year study. Sediment transport rates along Bogue Banks are estimated to be 50,000 cubic meters per year or less (van Gaalen et al 2016). One factor complicating the Peterson et al. (2014) study was the abundance coarse sediment and shell content in the nourishment fill used on Bogue Banks. Sp. *Donax* are thought to be more sensitive to changes in substrate grain-size than are *E. talpioda* (Manning et al. 2014) and so this factor likely accounts for some of the inhibited recovery.

Peterson et al. (2006) went on to propose two possible reasons for this difference in recovery as a function of alongshore sediment transport rates: 1.) higher alongshore transport rates promote a faster and more spatially extended redistribution of fill sediments across the impacted beach, a phenomenon which could force the mixing and dilution of the fill materials into the natural system which could amend the average sediment grain size and distribution to an average more in accord with the natural beach and 2.) that these alongshore currents may also more rapidly and consistently disperse potential new macroinvertebrate colonies and their larvae across larger areas of the nourished beach thus potentially accelerating the pace of recolonization in the new substrate (Peterson et al. 2006).

4.4 **Engineering design and planning** **controls on post-nourishment recovery**:

The objective of most beach nourishment projects is to widen the subaerial portion of the beach in order to maintain recreational benefit and provide infrastructure protection from storm waves (U.S. Army Corps of Engineers, 11994). This new width, the fill-design width, is dictated in large measure by the magnitude, where magnitude is based on the acceptable level of risk as governed by local shoreline recession rates and storm climate, and duration of protection desired (U.S. Army Corps of Engineers, 1994) and can involve fill augmentation on all or some part of the beach and/or dune surfaces (U.S. Army Corps of Engineers, 2002). This augmentation results in a wider, super-elevated subaerial beach surface that is typically nonuniform in thickness and variable in spatial extent.

Ecosystem impacts directly correlate with variability in fill distribution—both the fill volume thickness and horizontal coverage (Leewis et al. 2012; Voila et al. 2014). Differences in design objectives (i.e., fill thickness and extent) thus result in differing degrees of impact to the flora and fauna resident in the fill zone(s). Capobianco et al. (2002), illustrates some of these differences from the engineering perspective via four alternative beach-fill designs, each intended to address specific problems. These include: 1) dune only augmentation or re-construction; 2) subaerial berm elevation adjustment; 3) subaerial profile reshaping; and 4) nearshore-only fill. The extent of coverage and degree of impact will differ for each option. Options 2 and 3 can result in large areas of the beach surface being covered with new sediments. The extent of the ecosystem affected will be in direct proportion to this cover area. Differences in project design will have a direct 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; Peterson et al. 2014).

Stive et al. (2013) introduced another variant on beach 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 fill materials along the shoreline. Coverage can span 10 to 20 km of shoreline or more with a 20-year anticipated project lifespan (Stive et al. 2013). A 2011 mega-nourishment experiment was launched in 2011 along section of the Dutch coastline (Stive, 2013; van Egmond et al. 2018). Referred to as “the Sand Motor”, the project involved the placement of 21.5 million cubic yards on the beach near Dag Haag in the Netherlands (Stive et al. 2013). The approach is also thought to reduce ecosystem disturbance associated with sand placement by introducing new sediment to downstream beaches via natural littoral transport slowly over time, in lieu of the all at once replenishment associated with more conventional nourishment approaches (van Egmond et al. 2018). Natural distribution of fill material by littoral currents and its potential to reduce ecosystem impact is not a new discovery (see Hayden and Dolan, 1974; Peterson et al. 2006) but the scale of mega-nourishment is orders of magnitude larger than anything elsewhere attempted (Stive et al., 2013; van Egmond et al. 2018).

Along with application scale, the timing of a single nourishment event (Adriaanse and Coosen 1991), 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 peer-reviewed 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, and not the short term or lasting ecological impacts.

**5.0 Discussion**:

A successful beach nourishment project is gauged on how well it satisfies its principal design objectives. These may 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 beneficial use of dredge material. 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). 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). Economic and protection arguments notwithstanding, most of the controversy, uncertainty, and debate associated with nourishment is tied to its potential to adversely impact beach ecology (Greene 2002; Speybroeck et al. 2006; Peterson et al. 2014; Rosov et al. 2016). Many peer-reviewed studies have been conducted over the past half-century addressing many of these uncertainties and nourishment’s potential impacts to a resident beach ecology. Their findings, though far from complete, have yielded the following general conclusions:

1.) The 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 thought by many investigators to be the most influential factor deciding the morphology and ecology for a nourished beach. Differences in 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

3.) Composition of the fill sediment 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.) Alongshore sediment transport can play a role in post-nourishment outcomes, particularly as it is related to the pace of ecosystem recovery. Areas where sediment transport rates are considered high (<<<>>>) have been observed to recovery faster, often within one year, than areas where transport rates are lower, where recovery can take two or more years, or perhaps not at all.

5.) Quantity of sand placed on the beach is important. 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 ecosystem.

6.) 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 most desirable alternative to restore and protect the shoreline (USACOE, 1996; 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. Future work should thus also 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. References:

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