Beach nourishment and the ecosystem response

Authors:

Paul Paris 1,3

parisp15@ecu.edu

D. Reide Corbett1

corbettd@ecu.edu

J.P. Walsh2

Anya Leach1

J. Spencer Wilkinson1

1 Coastal Studies Institute, East Carolina University

850 NC 345

Wanchese, NC 27981

<https://www.coastalstudiesinstitute.org>

22Coastal Resources Center

Graduate School of Oceanography

University of Rhode Island

Narragansett, RI 02882

3corresponding author

**Abstract**

Beach nourishment is the process of adding new sand to restore beach elevation and width lost to chronic shoreline recession and 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, longshore transport, 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 shoreline recession, beach 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 land and sea, 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 nearby. 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**

Hidden within the sands along and across most beaches are a broad, dense, and diverse array of interrelated 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 phytoplankton, zooplankton, amphipods, isopods, worms, mollusks, 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 (see Figure 2) that includes larger macro-species such as fish and crabs living in the nearshore (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 (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 2) (Brown and McLachlan 1990; Peterson and Manning 2001). While many species have been documented, common fish include anchovies (family *Engraulidae*), sardines (family *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).

**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 can 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).

**3.1 Direct impacts to the beach ecology**

Beach nourishment typically involves the placement of 1 to 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) 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 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 fill 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—thought exceptions do exist—it is assumed that the shallow beach and nearshore ecosystems will experience rapid, widespread mortality (van Egmond et al. 2018).

Following sand placement, heavy earth-moving equipment are often 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 (Figure 3) (Dean 2003; Basterretxea et al. 2007). The rate that 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 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**

Excess fine-grained (i.e., silt and clay sized particles) material present in nourishment sands can increase suspended particle concentrations within interstitial spaces across the beach (Naqvi and Pullen 1982), and in the surf zone and nearshore waters (Wilber 2003; Wilber et al. 2006). The 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 changes do no lasting damage, and in some cases may 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 (Figure 2). 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 surf and subtidal waters 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, potentially decreasing available dissolved oxygen (Goldberg 1988), blanketing grass beds and reefs with excess sediment (Jordan et al. 2010), and reducing 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 colonies 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 phytoplankton 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.

**3.3 Changes to 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 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 (Peterson et al. 2014). Morphological differences will reverberate into the intra-faunal community by altering species composition, abundance, and diversity on the post-nourished beach (McLachlan 1983; Grain et al. 1995). Greene (2002) asserts that these alterations 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**

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 each play a role in determining species composition, diversity, variability, and abundance in the beach ecosystem (Greene 2002).

Numerous studies published in the primary literature focusing on the potential ecosystem impacts of beach nourishment have asserted that differences in grain size between nourishment fill materials versus those from the original beach can yield large changes in the resulting beach ecology (Ryder 1991; Grain et al. 1995; Rakocinski et al. 1996; Ross and Lancaster 1996; Steinitz et al. 1998; Davis et al. 1999; Peterson et al. 2000; Peterson and Manning 2001; Rumbold et al. 2001; Benedet et al. 2004; Jackson et al. 2007; Schlacher et al. 2012; Voila et al. 2014; Woolridge et al. 2016; and others). For instance, 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 placement 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. Work along two North Carolina ocean beaches and in experimental wave tanks recognized this size-profile relationship while also observing a correlation between changes in sediment size and the survival/recovery of fauna on the nourished beach (Peterson and Manning 2001). 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 remerge quickly following nourishment (Peterson and Manning 2001). 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. Peterson et al. (2006) observed a rapid recovery for *Emerita talpoida*, while sp. *Donax* was much slower to recover along a recently nourished beach in North Carolina. 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). Davis et al. (1999), Steinitz et al. (1998) and later Rumbold et al. (2001) independently 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 Beaches. In each case evidence was found that suggested reduced nesting success attributable to differences between average pre and post-nourishment fill sediment particle sizes.

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**

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 sediments 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**

While grain-size is thought by many investigators 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). 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 these 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 were attributed to the local alongshore currents in the surf zone. The animals, the researchers observed, were able to use the littoral currents to relocate from the nourishment impact site to a safer location down-stream 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; van Gaalen et al. 2016). 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).

In contrast, 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 of 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 at least 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. This mixing could adjust the average sediment grain size and distribution to an average more in accord with the natural beach. 2.) alongshore surf zone currents may also more rapidly and consistently disperse potential new macroinvertebrate colonies and their larvae from adjacent areas across larger extents 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**

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 1994). This new width, the fill-design width, can involve 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 also 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 this relationship 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 vary 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 large volumes of sand placed at a strategic location along the beach. This large volume of material provides a large-volume sediment resource that leverages littoral currents for redistribution of fill materials slowly and potentially across large spans of shoreline, over time. Such an approach is also thought to minimize overall ecosystem disturbance, both in the immediate and longer-terms as compared to more conventional methods where smaller volumes of fill are applied over shorter renourishment intervals (van Egmond et al. 2018). Coverage can span 10 to 20 km of shoreline or more with a 20-year or greater anticipated project lifespan (Stive et al. 2013). Leveraging the local waves and winds to handle redistribution following initial deposition of nourishment fill materials on the beach is not a new idea; Hayden and Dolan (1974) discussed ecosystem impacts associated with such a project along the North Carolina Outer Banks more than 40 years ago. What makes mega-nourishment unique is the volume of sediments used. For instance, an experiment in 2011 along a section of the Dutch coastline (Stive et al. 2013; van Egmond et al. 2018), referred to as “the Sand Motor”, involved the placement of 21.5 million cubic yards of new fill material on the beach near Dag Haag in the Netherlands (Stive et al. 2013). In contrast, the 1974 project in North Carolina used only 239,000 cubic yards of fill (Hayden and Dolan 1974).

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 chronic erosion and beach loss from local effects and long-term sea level rise, with conclusions in both reports suggesting that regular renourishment can offset and even reverse erosive narrowing 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 Conclusion**

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 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 findings:

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 the 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 recover faster, often within one year, than areas where transport rates are lower, where reestablishing the beach ecology can take two or more years, or perhaps in some circumstances, not at all.

5.) The 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 high mortality for 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.

Although beach nourishment has become the most desirable alternative to restore and protect the shoreline (U.S. Army Corps of Engineers 1996; Finkl and Walker 2004), there is 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, and how they interact with and respond to changes in their respective natural environments. **6.) References**

Able, K.W., Wuenschel, M.J., Grothues, T.M., Vasslides, J.M., Rowe, P.M., 2013. “Do surf zones in New Jersey provide “nursery” habitat for southern fishes?” *Environ Biol Fish* 96, 661–675.

Adriaanse, L.A., Coosen, J., 1991. “Beach and dune nourishment and environmental aspects.” *Coastal Engineering* 16, 129–146.

Airoldi, L., Abbiati, M., Beck, M.W., Hawkins, S.J., Martin, D., Moschella, P.S., Sundelöf, A., Thompson, R.C., Aberg, P., 2005. “An ecological perspective on the deployment and design of low-crested and other hard coastal defence structures.” *Coastal Engineering* 52, 1073–1087.

Armstrong, S.B., Lazarus, E.D., 2019. Masked Shoreline Erosion at Large Spatial Scales as a Collective Effect of Beach Nourishment. Earth’s Future 7, 74–84.

Ballesta, L., Pergent, G., Pasqualini, V., Pergent-Martini, C., 2000. “Distribution and dynamics of *Posidonia oceanica* beds along the Albères coastline.” *Comptes Rendus de l’Académie des Sciences*-Series III-Sciences de la Vie 323, 407–414.

Basterretxea, G., Orfila, A., Jordi, A., Fornós, J.J., Tintoré, J., 2007. “Evaluation of a small volume renourishment strategy on a narrow Mediterranean beach.” *Geomorphology* 88, 139–151.

Bender, E.A., Case, T.J., Gilpin, M.E., 1984. “Perturbation Experiments in Community Ecology: Theory and Practice.” *Ecology* 65, 1–13.

Benedet, L., Finkl, C.W., Campbell, T., Klein, A., 2004. “Predicting the effect of beach nourishment and cross-shore sediment variation on beach morphodynamic assessment. “*Coastal Engineering*, Coastal Morphodynamic Modeling 51, 839–861.

Beyst, B., Hostens, K., Mees, J., 2002. “Factors influencing the spatial variation in fish and macrocrustacean communities in the surf zone of sandy beaches in Belgium.” *Journal of the Marine Biological Association of the United Kingdom* 82, 181–187.

Bilodeau, A.L., Robert P. Bourgeois, 2004. “Impact of Beach Restoration on the Deep-Burrowing Ghost Shrimp, *Callichirus islagrande*.” *Journal of Coastal Research* 20, 931–936.

Bird, E.C.F., 1985. *Coastline Changes*. Wiley-Interscience, Chichester.

Bitan, M., Galili, E., Spanier, E., Zviely, D., 2020. “Beach Nourishment Alternatives for Mitigating Erosion of Ancient Coastal Sites on the Mediterranean Coast of Israel.” *Journal of Marine Science and Engineering* 8, 509.

Bocamazo, L.M., Grosskopf, W.G., Buonuiato, F.S., 2011. “Beach Nourishment, Shoreline Change, and Dune Growth at Westhampton Beach, New York, 1996-2009.” *Journal of Coastal Research* 59, 181–191.

Bowman, M.L., Dolan, R., 1985. “The relationship of *Emerita talpoida* to beach characteristics.” *Journal of Coastal Research* 1, 151–163.

Brock, K.A., Reece, J.S., Ehrhart, L.M., 2009. “The effects of artificial beach nourishment on marine turtles: differences between loggerhead and green turtles.” *Restoration Ecology* 17, 297–307.

Brown, A.C., McLachlan, A., 1990. *Ecology of sandy shores*. Elsevier, New York, 372 pp.

Capobianco, M., Hanson, H., Larson, M., Steetzel, H., Stive, M.J.F., Chatelus, Y., Aarninkhof, S., Karambas, T., 2002. “Nourishment design and evaluation: applicability of model concepts.” *Coastal Engineering* 47, 113–135.

Charvat, D.L., Nelson, W.G., Allenbaugh, T., 1990. “Composition and seasonality of sand-beach amphipod assemblages of the east coast of Florida.” *Journal of Crustacean Biology* 10, 446–454.

Cooke, B.C., Jones, A.R., Goodwin, I.D., Bishop, M.J., 2012. “Nourishment practices on Australian sandy beaches: A review.” *Journal of Environmental Management* 113, 319–327.

Davis Jr, R.A., FitzGerald, M.V., Terry, J., 1999. “Turtle nesting on adjacent nourished beaches with different construction styles: Pinellas County, Florida.” *Journal of Coastal Research, 15,* 111–120.

Dean, R.G., 2003. *Beach Nourishment: Theory and Practice*. World Scientific Publishing Company, River Edge, NJ.

Dean, R.G., 2001. “Storm damage reduction potential via beach nourishment,” in: Coastal Engineering 2000, *27th International Conference on Coastal Engineering (ICCE)*. Sydney, Australia, pp. 3305–3318.

Defeo, O., McLachlan, A., Schoeman, D.S., Schlacher, T.A., Dugan, J., Jones, A., Lastra, M., Scapini, F., 2009. “Threats to sandy beach ecosystems: A review.” *Estuarine, Coastal and Shelf Science* 81, 1–12.

Degraer, S., Volckaert, A., Vincx, M., 2003. “Macrobenthic zonation patterns along a morphodynamical continuum of macrotidal, low tide bar/rip and ultra-dissipative sandy beaches.” *Estuarine, Coastal and Shelf Science* 56, 459–468.

Dugan, J.E., Defeo, O., Jaramillo, E., Jones, A.R., Lastra, M., Nel, R., Peterson, C.H., Scapini, F., Schlacher, T., Schoeman, D.S., 2010. “Give beach ecosystems their day in the sun.” *Science* 329, 1146–1146.

Erftemeijer, P.L.A., Riegl, B., Hoeksema, B.W., Todd, P.A., 2012. “Environmental impacts of dredging and other sediment disturbances on corals: A review.” *Marine Pollution Bulletin* 64, 1737–1765.

Essink, K., 1999. “Ecological effects of dumping of dredged sediments; options for management.” *Journal of Coastal Conservation* 5, 69–80.

Fanini, L., Marchetti, G.M., Scapini, F., Defeo, O., 2007. “Abundance and orientation responses of the sandhopper *Talitrus saltator* to beach nourishment and groynes building at San Rossore natural park, Tuscany, Italy.” *Marine Biology* 152, 1169–1179.

Farley, P.P., 1923. “Coney Island public beach and boardwalk improvements.” *The Municipal Engineers* Journal 9.

Fenster, M.S., Knisley, C.B., Reed, C.T., 2006. “Habitat preference and the effects of beach nourishment on the federally threatened northeastern beach tiger beetle, *Cicindela dorsalis*: Western Shore, Chesapeake Bay, Virginia.” *Journal of Coastal Research* 22, 1133–1144.

Finkl, C.W., Walker, H.J., 2005. “Beach Nourishment.” *The Encyclopedia of Coastal Science, Springer,* 147-161.

French, P., 2002. *Coastal and Estuarine Management*. Routledge, London and New York.

Galgano, F.A., 2004. “Long-term effectiveness of a groin and beach fill system: a case study using shoreline change maps.” *Journal of Coastal Research, SI 33,* 3–18.

Gambi, M., Dappiano, M., Lorenti, M., Iacono, B., Flagella, S., Buia, M., 2005. “Chronicle of a death foretold”-Features of a *Posidonia oceanica* bed impacted by sand extraction,” in: *Proceedings of the Seventh International Conference on the Mediterranean Coastal Environment*, MEDCOAST. pp. 441–450.

Goldberg, W.M., 1988. “Biological effects of beach restoration in South Florida: the good, the bad, and the ugly.” *Beach Preservation Technology* 88, 19–28.

Gopalakrishnan, S., Smith, M.D., Slott, J.M., Murray, A.B., 2011. “The value of disappearing beaches: A hedonic pricing model with endogenous beach width.” *Journal of Environmental Economics and Management* 61, 297–310.

Gorzelany, J.F., Nelson, W.G., 1987. “The effects of beach replenishment on the benthos of a sub-tropical Florida beach.” *Marine Environmental Research* 21, 75–94.

Grain, D.A., Bolten, A.B., Bjorndal, K.A., 1995. “Effects of beach nourishment on sea turtles: review and research initiatives.” *Restoration Ecology* 3, 95–104.

Greene, K., 2002. “Beach Nourishment: A Review of the Biological and Physical Impacts” (No. 7), *ASMFC Habitat Management Series*. Atlantic States Marine Fisheries Commission, Washington, DC.

Grippo, M.A., Cooper, S., Massey, A.G., 2007. “Effect of Beach Replenishment on Waterbird and Shorebird Communities.” *Journal of Coastal Research* 23, 1088–1096.

Guidetti, P., Fabiano, M., 2000. “The use of lepidochronology to assess the impact of terrigenous discharges on the primary leaf production of the Mediterranean seagrass *Posidonia oceanica*.” *Marine Pollution Bulletin* 40, 449–453.

Hackney, C., Posey, M., Ross, S., Norris, A., 1996. *A review and synthesis of data on surf zone fishes and invertebrates in the South Atlantic Bight and the potential impacts from beach renourishment*. US Army Corps of Engineers, Wilmington, NC, Technical Report.

Haddad, T.C., Pilkey, O.H., 1998. “Summary of the New England beach nourishment experience (1935-1996).” *Journal of Coastal Research* 14, 1395–1404.

Hall, S.C., Parmenter, C.J., 2006. “Larvae of two signal fly species (*Diptera: Platystomat*idae), *Duomyia foliata* McAlpine and *Plagiostenopterina enderlein*i Hendel, are scavengers of sea turtle eggs.” *Australian Journal of Zoology* 54, 245–252.

Hamm, L., Capobianco, M., Dette, H., Lechuga, A., Spanhoff, R., Stive, M., 2002. “A summary of European experience with shore nourishment.” Co*astal Engineering* 47, 237–264.

Hanson, H., Brampton, A., Capobianco, M., Dette, H.H., Hamm, L., Laustrup, C., Lechuga, A., Spanhoff, R., 2002. “Beach nourishment projects, practices, and objectives—a European overview.” *Coastal Engineering* 47, 81–111.

Hawkes, L.A., Broderick, A.C., Godfrey, M.H., Godley, B.J., 2009. “Climate change and marine turtles.” *Endangered Species Research* 7, 137–154.

Hayden, B., Dolan, R., 1974. “Impact of beach nourishment on distribution of *Emerita talpoida*, the common mole crab.” *Journal of the Waterways, Harbors and Coastal Engineering Division* ASCE 100, 123–132.

Hoagland, P., Jin, D., Kite-Powell, H., 2012. “The Costs of Beach Replenishment along the U.S. Atlantic Coast.” *Journal of Coastal Research* 28, 199–204.

Houston, J., 2020. “Beach nourishment versus sea level rise on Florida’s coasts.” *Shore & Beach* 3–13.

Houston, J.R., 2016. “Beach nourishment as an adaptive strategy for sea level rise: A Florida east coast perspective.” *Shore and Beach* 84, 3–12.

Houston, J.R., 2008. “The economic value of beaches--a 2008 update.” *Shore and Beach* 76, 22–26.

Inman, D.L., Dolan, R., 1989. “The Outer Banks of North Carolina: Budget of Sediment and Inlet Dynamics along a Migrating Barrier System.” *Journal of Coastal Research* 5, 193–237.

Jackson, D., Cooper, J., Del Rio, L., 2005. “Geological control of beach morphodynamic state.” *Marine Geology* 216, 297–314.

Jackson, N.L., Smith, D.R., Tiyarattanachai, R., Nordstrom, K.F., 2007. “Evaluation of a small beach nourishment project to enhance habitat suitability for horseshoe crabs.” *Geomorphology*, 36th Binghamton Geomorphology Symposium 89, 172–185.

Jones, A.R., Murray, A., Lasiak, T.A., Marsh, R.E., 2008. “The effects of beach nourishment on the sandy-beach amphipod *Exoediceros fossor*: impact and recovery in Botany Bay, New South Wales, Australia.” *Marine Ecology* 29, 28–36.

Jordan, L.K.B., Banks, K.W., Fisher, L.E., Walker, B.K., Gilliam, D.S., 2010. “Elevated sedimentation on coral reefs adjacent to a beach nourishment project.” *Marine Pollution Bulletin,* 60, 261–271.

Klein, Y.L., Osleeb, J.P., Viola, M.R., 2004. “Tourism-generated earnings in the coastal zone: a regional analysis.” *Journal of Coastal Research* 20, 1080–1088.

Knott, D.M., Calder, D.R., Van Dolah, R.F., 1983. “Macrobenthos of sandy beach and nearshore environments at Murrells Inlet, South Carolina, USA.” *Estuarine, Coastal and Shelf Science* 16, 573–590.

Landry, C.E., Hindsley, P., 2011. “Valuing beach quality with hedonic property models.” *Land Economics* 87, 92–108.

Leewis, L., van Bodegom, P.M., Rozema, J., Janssen, G.M., 2012. “Does beach nourishment have long-term effects on intertidal macroinvertebrate species abundance?” *Estuarine, Coastal and Shelf Science* 113, 172–181.

Lindquist, N., Manning, L., 2001. *Impacts of beach nourishment and beach scraping on critical habitat and productivity of surf fishes*. NC Sea Grant, Fisheries Resource Grant Program.

Luijendijk, A., Hagenaars, G., Ranasinghe, R., Baart, F., Donchyts, G., Aarninkhof, S., 2018. “The state of the world’s beaches.” *Scientific Reports* 8, 1–11.

Madden, D., Ballestero, J., Calvo, C., Carlson, R., Christians, E., Madden, E., 2008. “Sea Turtle Nesting as a Process Influencing a Sandy Beach Ecosystem.” *Biotropica* 40, 758–765.

Manning, L.M., Peterson, C.H., Bishop, M.J., 2014. “Dominant macrobenthic populations experience sustained impacts from annual disposal of fine sediments on sandy beaches.” *Marine Ecology Progress* Series 508, 1–15.

McLachlan, A., 1996. “Physical factors in benthic ecology: effects of changing sand particle size on beach fauna.” *Marine Ecology Progress* Series 131, 205–217.

McLachlan, A., 1991. “Ecology of coastal dune fauna.” *Journal of Arid Environments* 21, 229–243.

McLachlan, A., 1983. “Sandy beach ecology—a review,” in: *Sandy Beaches as Ecosystems*. Springer, pp. 321–380.

McLachlan, A., Defeo, O., 2018. *The Ecology of Sandy Shores*, 3rd ed. Academic Press.

McLachlan, A., Dorvlo, A., 2005. “Global Patterns in Sandy Beach Macrobenthic Communities.” *Journal of Coastal Research* 214, 674–687,

McLachlan, A., Jaramillo, E., 1995. “Zonation on sandy beaches.” *Oceanography and Marine Biology*: an annual review 33, 305–335.

Melvin, S.M., Griffin, C.R., Macivor, L.H., 1991. “Recovery strategies for piping plovers in managed coastal landscapes.” *Coastal Management* 19, 21–34.

Menn, I., Junghans, C., Reise, K., 2003. “Buried alive: Effects of beach nourishment on the infauna of an erosive shore in the North Sea.” *Senckenbergiana maritima* 32, 125–145.

Micheli, C., Cupido, R., Lombardi, C., Belmonte, A., Peirano, A., 2012. “Changes in Genetic Structure of *Posidonia oceanica* at Monterosso al Mare (Ligurian Sea) and Its Resilience Over a Decade (1998-2009). “*Environmental Management* 50, 598–606.

Modde, T., Ross, S.T., 1981. “Seasonality of fishes occupying a surf zone habitat in the northern Gulf of Mexico.” *Fishery Bulletin* 78, 911–922.

Moore, L.J., Benumof, B.T., Griggs, G.B., 1999. “Coastal erosion hazards in Santa Cruz and San Diego Counties, California.” *Journal of Coastal Research* SI28, 121–139.

Morton, R.A., McKenna, K.K., 1999. “Analysis and projection of erosion hazard areas in Brazoria and Galveston Counties, Texas.” *Journal of Coastal Research* 81, 106–120.

Myers, J.P., Morrison, R.I.G., Antas, P.Z., Harrington, B.A., Lovejoy, T.E., Sallaberry, M., Senner, S.E., Tarak, A., 1987. “Conservation strategy for migratory species.” *American Scientist* 75, 19–26.

Naqvi, S.M., Pullen, E.J., 1982. *Effects of beach nourishment and borrowing on marine organisms*. Coastal Engineering Research Center, Vicksburg MS.

Nelson, D.A., Mauck, K., Fletemeyer, J., 1987. “Physical effects of beach nourishment on sea turtle nesting, Delray Beach, Florida” (*Technical Report EL-87-15*). US Department of the Army, U.S. Army Corps of Engineers, Jacksonville, FL.

Nelson, W.G., 1989. “An overview of the effects of beach nourishment on the sand beach fauna.” *Beach Preservation Technology* 88, 295–310.

Nicoletti, L., Paganelli, D., Gabellini, M., 2006. “Environmental aspects of relict sand dredging for beach nourishment: proposal for a monitoring protocol.” (No. 5), *Quaderno* ICRAM.

Nordstrom, K.F., 2005. Beach Nourishment and Coastal Habitats: Research Needs to Improve Compatibility. *Restoration Ecology* 13, 215–222.

Nordstrom, K.F., Jackson, N.L., Kraus, N.C., Kana, T.W., Bearce, R., Bocamazo, L.M., Young, D.R., Butts, H. a. D., 2011. “Enhancing geomorphic and biologic functions and values on backshores and dunes of developed shores: a review of opportunities and constraints.” *Environmental Conservation* 38, 288–302.

North Carolina Coastal Resources Commission, 2014. *CAMA Handbook for Coastal Development*.

Peterson, C., Laney, W., Rice, T., 2001. “Biological impacts of beach nourishment,” in: *Workshop on the Science of Beach Renourishment*. Pine Knoll Shores, North Carolina.

Peterson, C., Manning, L., 2001. “How beach nourishment affects the habitat value of intertidal beach prey for surf fish and shorebirds and why uncertainty still exists,” in: *Proceedings of the Coastal Ecosystems and Federal Activities Technical Training Symposium*. p. 2.

Peterson, C.H., Bishop, M.J., 2005. “Assessing the Environmental Impacts of Beach Nourishment.” *BioScience* 55, 887.

Peterson, C.H., Bishop, M.J., D’Anna, L.M., Johnson, G.A., 2014. “Multi-year persistence of beach habitat degradation from nourishment using coarse shelly sediments.” *Science of the Total Environment* 487, 481–492.

Peterson, C.H., Bishop, M.J., Johnson, G.A., D’Anna, L.M., Manning, L.M., 2006. “Exploiting beach filling as an unaffordable experiment: Benthic intertidal impacts propagating upwards to shorebirds.”’ *Journal of Experimental Marine Biology and Ecology* 338, 205–221.

Peterson, C.H., Hickerson, D.H.M., Johnson, G.G., 2000. “Short-Term Consequences of Nourishment and Bulldozing on the Dominant Large Invertebrates of a Sandy Beach.” *Journal of Coastal Research* 16, 368–378.

Phillips, M.R., Jones, A.L., 2006. “Erosion and tourism infrastructure in the coastal zone: Problems, consequences and management.” *Tourism Management* 27, 517–524.

Pilkey, O.H., Wright, H.L., 1989. “Seawalls versus beaches.” *Journal of Coastal Research* 4, 41–67.

Rakocinski, C.F., Heard, R.W., Lecroy, S.E., McLelland, J.A., Simons, T., 1996. “Responses by macrobenthic assemblages to extensive beach restoration at Perdido Key, Florida, U.S.A.” *Journal of Coastal Research* 12, 326–353.

Rice, T., 2001. “The Big Picture: An Overview of Coastal Resources and Federal Projects,” in: *Proceedings of the Coastal Ecosystems & Federal Activities Technical Training Symposium*. Presented at the Coastal Ecosystems & Federal Activities Technical Training Symposium, Gulf Shores, Alabama.

Rimkus, T.A., 1992. *The hydric and physical properties of natural and nourished beach sands along the Atlantic Coast of Florida* (Master's thesis), Iowa State University, Ames, IA.

Roberts, T.M., Wang, P., 2012. “Four-year performance and associated controlling factors of several beach nourishment projects along three adjacent barrier islands, west-central Florida, USA.” *Coastal Engineering* 70, 21–39.

Rodil, I., Lastra, M., 2004. “Environmental factors affecting benthic macrofauna along a gradient of intermediate sandy beaches in northern Spain.” *Estuarine, Coastal and Shelf Science* 61, 37–44.

Rosov, B., Bush, S., Roberts Briggs, T., Elko, N., 2016. “The state of understanding the impacts of beach nourishment activities on infaunal communities.” *Shore & Beach* 84, 51–55.

Ross, S., Lancaster, J., 1996. *Movements of juvenile fishes using surf zone nursery habitats and the relationship of movements to beach nourishment along a North Carolina beach: pilot project*. Wilmington, NC: North Carolina National Estuarine Research Reserve.

Ruiz, J., Romero, J., 2003. “Effects of disturbances caused by coastal constructions on spatial structure, growth dynamics and photosynthesis of the seagrass *Posidonia oceanica*.” *Marine Pollution Bulletin* 46, 1523–1533.

Rumbold, D., Davis, P., Perretta, C., 2001. “Estimating the effect of beach nourishment on *Caretta caretta* (loggerhead sea turtle) nesting.” *Restoration Ecology* 9, 304–310.

Ryder, C., 1991. *The Effects of Beach Nourishment on Sea Turtle Nesting and Hatch Success*. Unpublished Report to Sebastian Inlet Tax District Commission.

Schlacher, T.A., Dugan, J., Schoeman, D.S., Lastra, M., Jones, A., Scapini, F., McLachlan, A., Defeo, O., 2007. “Sandy beaches at the brink.” *Diversity and Distributions* 13, 556–560.

Schlacher, T.A., Noriega, R., Jones, A., Dye, T., 2012. “The effects of beach nourishment on benthic invertebrates in eastern Australia: Impacts and variable recovery.” *Science of The Total Environment* 435, 411–417.

Slott, J.M., Smith, M.D., Murray, A.B., 2008. “Synergies between adjacent beach-nourishing communities in a morpho-economic coupled coastline model.” *Coastal Management* 36, 374–391.

Speybroeck, J., Bonte, D., Courtens, W., Gheskiere, T., Grootaert, P., Maelfait, J.-P., Mathys, M., Provoost, S., Sabbe, K., Stienen, E.W.M., Lancker, V.V., Vincx, M., Degraer, S., 2006. “Beach nourishment: an ecologically sound coastal defence alternative? A review.” *Aquatic Conservation: Marine and Freshwater Ecosystems* 16, 419–435.

Steinitz, M.J., Salmon, M., Wyneken, J., 1998. “Beach renourishment and loggerhead turtle reproduction: A seven-year study at Jupiter Island, Florida.” *Journal of Coastal Research* 14, 1000–1013.

Stive, M.J.F., de Schipper, M.A., Luijendijk, A.P., Aarninkhof, S.G.J., van Gelder-Maas, C., van Thiel de Vries, J.S.M., de Vries, S., Henriquez, M., Marx, S., Ranasinghe, R., 2013. “A New Alternative to Saving Our Beaches from Sea-Level Rise: The Sand Engine.” *Journal of Coastal Research* 290, 1001–1008.

Stull, K.J., Cahoon, L.B., Lankford, T.E., 2016. “Zooplankton Abundance in the Surf Zones of Nourished and Unnourished Beaches in Southeastern North Carolina, U.S.A.” *Journal of Coastal Research* 32, 70–77.

U.S. Army Corps of Engineers, 1994. S*horeline protection and beach erosion control study. Phase 1: Cost comparison of shoreline protection projects of the US Corps of Engineers*. Water Resources Support Center, Washington, DC.

U.S. Army Corps of Engineers, 2002. *Coastal Engineering Manual*. EM-1110-2-1100, Chapter 4, Dept. of the Army.

Valverde, H.R., Trembanis, A.C., Pilkey, O.H., 1999. “Summary of Beach Nourishment Episodes on the U.S. East Coast Barrier Islands.” *Journal of Coastal Research* 15, 1100–1118.

van de Koppel, J., Herman, P.M., Thoolen, P., Heip, C.H., 2001. “Do alternate stable states occur in natural ecosystems? Evidence from a tidal flat.” *Ecology* 82, 3449–3461.

Van der Putten, W.H., Peters, B.A.M., 1997. “How Soil-Borne Pathogens May Affect Plant Competition.” *Ecology* 78, 1785–1795.

Van Der Wal, D., 1998. “The impact of the grain-size distribution of nourishment sand on aeolian sand transport.” *Journal of Coastal Research* 14, 620–631.

Van Dolah, R., Martore, R., Lynch, A., Levisen, M., Wendt, P., Whitaker, D., Anderson, W., 1994. *Environmental evaluation of the Folly Beach nourishment project. Final Report*. Prepared by the Marine Resources Division, South Carolina Department of Natural Resources, Charleston, SC for the US Army Corps of Engineers, Charleston District.

van Egmond, E.M., Bodegom, P.M. van, Berg, M.P., Wijsman, J.W.M., Leewis, L., Janssen, G.M., Aerts, R., 2018. “A mega-nourishment creates novel habitat for intertidal macroinvertebrates by enhancing habitat relief of the sandy beach.” *Estuarine, Coastal and Shelf Science* 207, 232–241.

van Gaalen, J.F., Tebbens, S.F., Barton, C.C., 2016. “Sediment Transport Directions and Rates from Northern Maine to Tampa Bay, Florida: Literature Compilation and Interpretation.” *Journal of Coastal Research* 32, 1277–1301.

Van Tomme, J., Eede, S.V., Speybroeck, J., Degraer, S., Vincx, M., 2013. “Macrofaunal sediment selectivity considerations for beach nourishment programmes.” *Marine Environmental Research* 84, 10–16.

Vanden Eede, S., Van Tomme, J., De Busschere, C., Vandegehuchte, M.L., Sabbe, K., Stienen, E.W.M., Degraer, S., Vincx, M., Bonte, D., 2014. “Assessing the impact of beach nourishment on the intertidal food web through the development of a mechanistic-envelope model.” *J Appl Ecol* 51, 1304–1313.

Viola, S.M., Hubbard, D.M., Dugan, J.E., Schooler, N.K., 2014. “Burrowing inhibition by fine textured beach fill: Implications for recovery of beach ecosystems.” *Estuarine, Coastal and Shelf Science* 150, 142–148.

Wilber, D., Clarke, D., Ray, D., Van Dolah, R., 2009. “Lessons learned from biological monitoring of beach nourishment projects,” in: *Proceedings of the Western Dredging Association’s Twenty-Ninth Technical Conference*. pp. 262–274.

Wilber, D., Clarke, D., Ray, G., Burlas, M., 2003. “Response of surf zone fish to beach nourishment operations on the northern coast of New Jersey, USA.” *Marine Ecology Progress* Series 250, 231–246.

Wilber, D.H., Clarke, D.G., Burlas, M.H., 2006. “Suspended Sediment Concentrations Associated with a Beach Nourishment Project on the Northern Coast of New Jersey.”*Journal of Coastal Research* 22, 1035–1042.

Wood, D.W., Bjorndal, K.A., 2000. “Relation of temperature, moisture, salinity, and slope to nest site selection in loggerhead sea turtles.” *Copeia* 2000, 119–119.

Wooldridge, T., Henter, H.J., Kohn, J.R., 2016. “Effects of beach replenishment on intertidal invertebrates: A15-month, eight beach study.” *Estuarine, Coastal and Shelf Science* 175, 24–33.

Woolridge, T.B., 2015. *Long-term effects of beach nourishment on intertidal invertebrates* (Masters of Science in Biology). University of California, San Diego, San Diego, CA.

World Travel and Tourism Council, 2020. *Travel and Tourism: Global Economic Impact & Trends 2020*.

Zhang, K., Douglas, B.C., Leatherman, S.P., 2004. “Global Warming and Coastal Erosion.” *Climatic Change* 64, 41.

Figures

A picture containing text, outdoor

Description automatically generated

A picture containing text, outdoor

Description automatically generated

Figure 1: The approximate subaerial and subaqueous floral and faunal habitat provinces found across the sandy beach as mentioned in the text. While the swash zone is often the smallest of the provinces in cross-shore width, it is typically the most prolific and densely populated in terms of invertebrate species.

Diagram

Description automatically generated

Diagram

Description automatically generated

Figure 2: A simplified beach ecosystem food web graphic showing select species, their relative trophic positions, and common habitats along the beach. The graph shown here is specific to the various species mentioned in the paper.

Diagram

Description automatically generated

Diagram

Description automatically generated

Figure 3: Beach in elevation at three stages of nourishment evolution. Profile A shows an idealized typical beach cross-shore profile prior to nourishment. Profile B depicts the beach profile, with the new sand volume added in the immediate aftermath of nourishment. The placed fill sand volume is positioned principally on the subaerial beach and is bulldozed into an initial design profile from which natural processes driven by local winds and waves will continue with redistribution toward equilibrium with local conditions. Profile C shows the profile after placement at a point where sand has been naturally redistributed onshore and offshore toward a profile geometry that is equilibrated to local conditions.

A picture containing outdoor, shore, nature, sandy

Description automatically generated

A picture containing outdoor, sky, nature, ground

Description automatically generated

Figures 4a and b: Beach scarps along Pea Island on the North Carolina Outer Banks. Scarps form when the beach profile is out of equilibrium with wave conditions--in such cases wave energies in the adjacent surf zone are sufficiently high to erode sands from the subaerial beach, moving them offshore leaving behind steeply sloped scarp features along the beach. Scarp elevations can range from a few centimeters to three meters or more—in Figure 4a the scarp height is approximate 40 cm; in Figure 4b the scarp height is approximately 1 m. Such features are commonplace under erosive conditions such as during storms. They are also common following nourishment sand placement as the unstable beach profile undergoes morphological adjustment.