[Chapter] 11: Islands

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Islands

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Key Messages

1. Islands are proven to deliver coastal resilience benefits, especially as part of a multiple-lines-of-defense strategy. Islands can be effective in areas where other, land-based natural and nature-based features (NNBF) are not feasible (e.g., urban areas).

2. Islands can simultaneously provide multiple services, including storm surge reduction, wave dissipation, erosion control, dredged material management, safe navigation and safe harbor, ecosystem diversity, recreation, and commercial opportunities.

3. Island features may have a regional influence and, therefore, must be placed in the regional context. For example, islands that provide coastal resilience benefits will significantly influence circulation, sediment transport, water quality, waves, and habitat within their domain of influence.

4. Habitat trade-offs are inevitable—island construction almost always involves changing habitat types from subtidal to intertidal and supratidal. Short-term impacts must be considered within the context of long-term ecosystem co-benefits, especially within the context of sea-level rise.

5. Islands may be multihabitat features; therefore, guidance from previous feature chapters may apply here. For example, large islands often include beach and dune, wetland, and upland plant community components.

Key Messages (Continued)

6. The complexity of physical processes at island NNBF settings, coupled with limited case studies for some conditions, results in significant uncertainty and risk during the construction process. Experienced contractors, capable of adaptively managing construction, are required to reduce risk and meet project goals within cost, regulations, and schedule.

7. Islands are typically dynamic features, and therefore, their success in achieving predefined objectives and observed metrics may fluctuate or change over time.

11.1 | Introduction

Islands in estuaries, major river deltas, and open-coast environments reduce the severity of hazards, including erosion and flooding from wind-driven waves and extreme water levels, on the nearby habitats and shorelines. Islands may also provide critical ecosystem function for threatened and endangered species and migratory birds while providing access to recreational opportunities and navigation co-benefits. This chapter will focus on islands as natural and nature-based features (NNBF) that support coastal resilience. Three types of islands will be discussed in this chapter—barrier islands, deltaic islands (including spits), and in-bay or in-lake islands. These islands may be new construction or, as in most cases, the restoration of island remnants. The degradation and loss of islands through combined processes such as sea-level rise, subsidence, and inadequate sediment input (e.g., upstream impoundments, navigation channels, evolving natural processes) are reducing the coastal resilience benefits of these features. This chapter does not include discussions of island reclamation solely for purposes of urban or agricultural development.

11.1.1 Background

Islands exist throughout coastal regions but are more common under specific conditions, including moderate tidal range and gentle foreshore slope. These islands can be a legacy of earlier geological and hydrological processes or sustained through ongoing processes. The latter are sustained through a combination of fluvial and marine processes that continually erode, nourish, and shape islands. Sediment transport, waves, river and coastal hydrology, littoral processes, climatology, episodic events, and vegetation are integral to island formation and sustenance. Although islands range in size from less than a hectare to millions of hectares, islands restored or created as NNBF are typically less than 20 kilometers (km) in length (shore parallel direction) and are relatively narrow (less than 1 km).

Islands are dynamic landscape features, constantly moving in response to both short-term and long-term regional circulation patterns, wave climate, habitat evolution, changes in sediment supply, subsidence, sea-level rise, and storm events. Islands are typically exposed to these processes from a broader range of directions than other NNBF. These characteristics result in special design requirements, discussed in Section 11.5. Further, changes in sediment supply due to natural or anthropogenic influences will influence island dynamics and resilience benefits. Additional details for the three island types (barrier, deltaic, in-bay and in-lake) are provided in the sections that follow. This classification system is broad, and island features may fall under more than one classification.

11.1.2 Types and Setting

11.1.2.1 Barrier Islands

Barrier islands are defined as “typically elongate, narrow land formations, composed of unconsolidated materials, lying parallel to the shoreline, and separated from the mainland coast by lagoons and/or bays” (Oertel 1985). Barrier islands are often the first line of defense, protecting the mainland coast from inundation (Figures 11.1 and 11.2) by waves, erosion, and the full force of the open-ocean environment. They have the capacity to alter surge pathways and attenuate waves in a wide variety of settings (Wamsley et al. 2009; Grzegorzewski, Cialone, and Wamsley 2011). Recent surveys based on satellite imagery indicate that there are more than 2,000 barrier islands in the world, with more than 20,000 km of shoreline (Stutz and Pilkey 2011). Although typically less than 100 km, barrier island length ranges over several orders of magnitude, with an average length of 15 km outside the Arctic (Stutz and Pilkey 2011) and a maximum length of 200 km (Garrison et al. 2010). There are extensive barrier island systems present in the United States, Mexico, Russia, and Australia, with smaller barrier island chains in equatorial Brazil, the North Sea (i.e., the Netherlands, Germany, Denmark), Canada, Mozambique, India, Madagascar, Columbia, and Nigeria (see Figure 11.1 and Stutz and Pilkey 2011) and less extensive islands in many other countries.

Figure 11.1. ***Barrier Island Setting and Features***

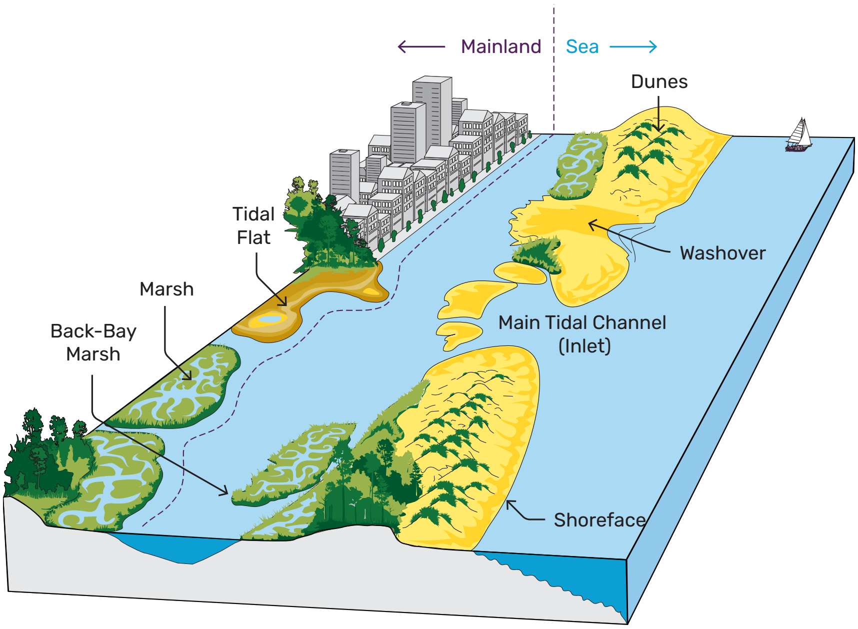
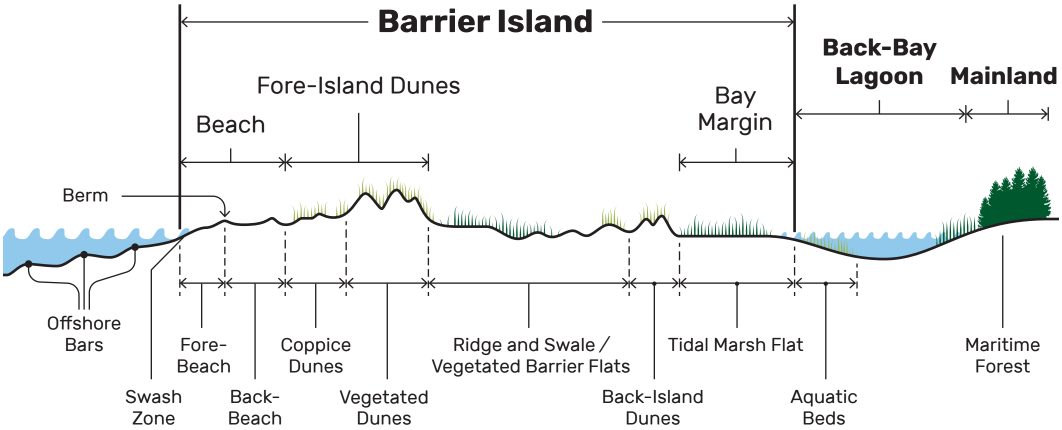


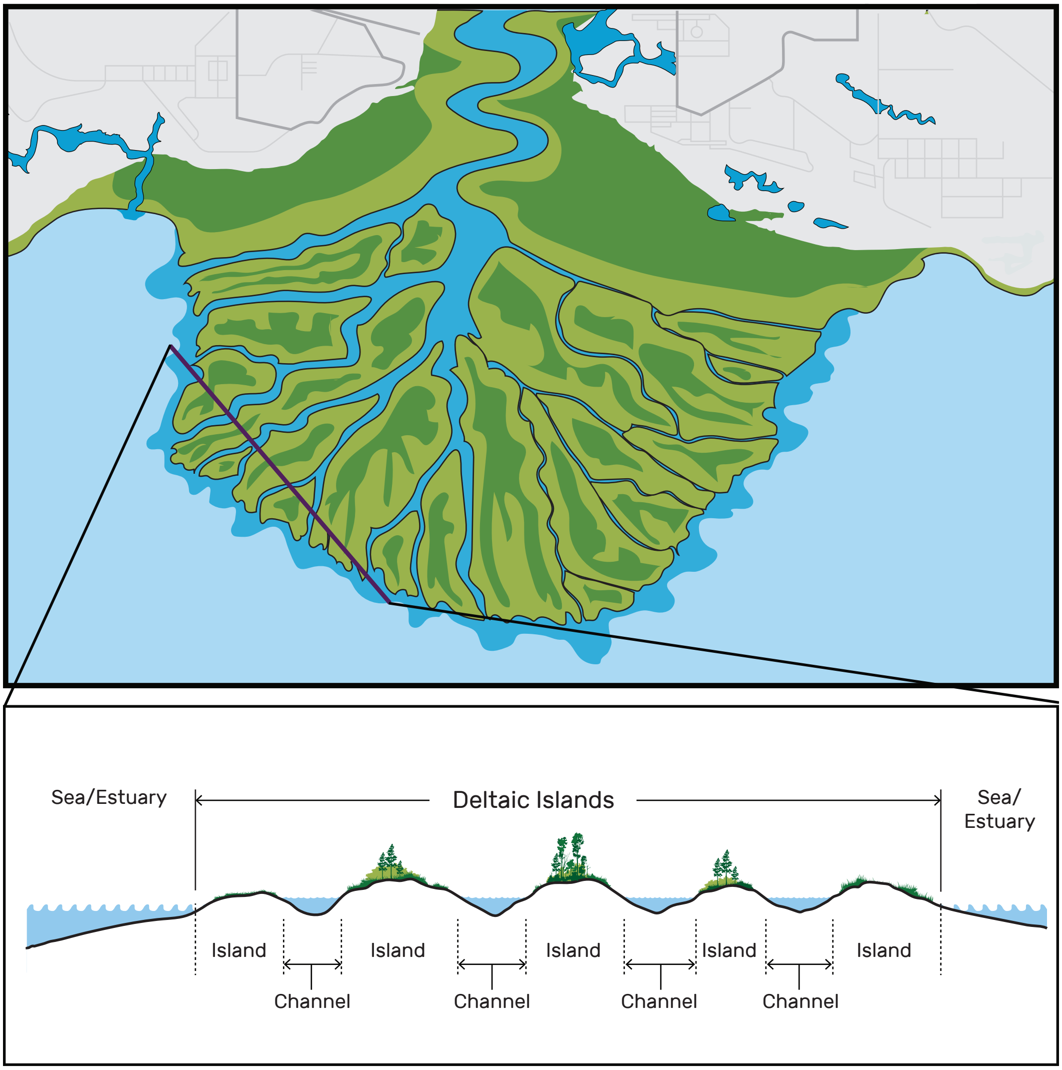
Figure 11.2. *Typical Barrier Island Cross Section*



11.1.2.2 Deltaic Islands

Deltaic islands are formed at the mouths of rivers, where fast-moving waters slow as the river meets a sea or lake, and the sediment carried by the river is deposited on the seabed or lakebed (Figure 11.3). Large river deltas (e.g., Danube, Niger, Nile, Rhine, Ganges, Mississippi, Mekong, Fraser, Saskatchewan, Mackenzie, Peace-Athabasca, Sacramento-San Joaquin, and Patía) consist of networks of islands and distributary channels, which can incorporate sensitive and biologically diverse habitats such as salt marshes, tidal mudflats, wetlands, and beaches. Stutz and Pilkey (2002) identified three essential requirements for deltaic island formation—adequate sediment supply, low foreshore slope, and sufficient wave energy to support island building. Tidal range is another factor affecting deltaic island formation, with very large tidal ranges unfavorable for island formation. Deltaic island morphology is highly variable and depends on interactions between fluvial and coastal processes, and sediment characteristics (Stutz and Pilkey 2002, 2011). Deltaic sediments deposited at the mouth of a river naturally consolidate and subside over time, and the exposure of islands to flood and erosion hazards is often governed by balances between rates of subsidence and sediment supply, as well as relative sea- and lake-level changes and vegetation establishment and survival. Stutz and Pilkey (2002) point out that the stability of deltaic islands is critically dependent on a stable supply of fluvial sediment, and that many existing deltaic islands are threatened by interruptions of the natural sediment pathways (e.g., hydropower dams, dredging for navigation, channelization, and levee building). Deltaic channels (active or abandoned) and islands provide flood risk management (FRM) function through flood storage and by acting as barriers to attenuate waves and storm surges. Deltaic islands and deltaic systems may also be a source of sediment supply to downdrift coastal barrier islands, and so they may indirectly influence coastal resilience and ecosystem function over significant distances.

Figure 11.3. *Deltaic Island Conceptual Figure*



11.1.2.3 In-Bay or In-Lake Islands

In-bay or in-lake islands differ from their barrier and deltaic counterparts in that the processes they are exposed to are constrained by the scale of the waterbody. Also referred to as fetch-limited islands, they typically exist outside the deltaic and barrier island network in more protected areas and are formed by lagoon, bay, estuary, or lake hydrodynamics and sediment dynamics (Lewis, Cooper, and Pilkey 2005). Globally there are approximately 7,500 islands within lagoons, bays, and other waterbodies, making them more abundant than open-ocean barrier islands. However, they are usually much shorter, typically less than 1 km long. In the Chesapeake and Delaware Bays of the United States, more than 300 fetch-limited islands have been identified (Lewis, Cooper, and Pilkey 2005). These vegetation-dominated islands protect the mainland from erosion and direct wave attack by attenuating short waves and providing greater shore and bank stabilization.

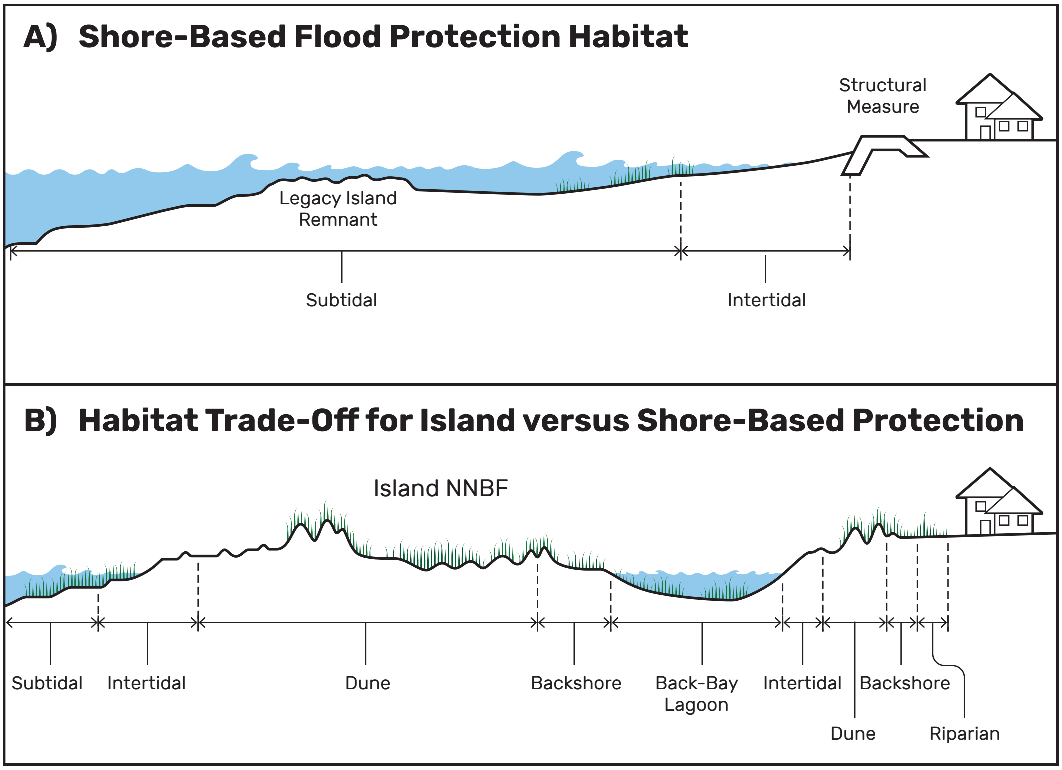
11.1.3 Values and Contexts for Application

Islands serve multiple functions, including storm surge reduction, wave dissipation, erosion control, dredged material management, safe navigation and safe haven, ecosystem diversity, wildlife habitat, recreation, and commercial opportunities (e.g., tourism and fisheries). Islands often comprise multiple habitat types (e.g., reef, beach, dune, upland plant community, wetland, and submerged aquatic vegetation [SAV] bed) and have a hydrodynamic footprint that influences the formation and protection of adjacent coastal habitats. Islands are a critical element in the multiple-lines-of-defense strategy (Lopez 2009). This strategy describes how multiple features in a sequence, from offshore to onshore, provide greater coastal resilience benefits than a single feature (Lopez 2009; Guannel et al. 2016; Arkema et al. 2017). For example, overwash and windblown sand can nourish dunes and marshes on the back side of islands, and the protective environment in back bays can facilitate the formation of beds of SAV (see Chapter 13), salt marsh (see Chapter 10), and other habitat that requires protection from large waves (Walters et al. 2014; Harkers Island in North Carolina is an example). In turn, SAV beds, salt marsh, and dune vegetation interact with, and can exert a strong influence on, the hydrodynamics and morphology of barrier islands and back-bay systems through biostabilization of sediment and wave attenuation (Duck and da Silva 2012; Stallins 2005; Rupprecht et al. 2017). Back-bay marsh subsequently reduces loss of beach and dune sediment during overtopping or high wind events. However, most studies focus on the benefits (e.g., wave and storm protection benefits) of single habitat types like wetlands, coral reefs, or mangroves (Narayan et al. 2016, 2017; Arkema et al. 2017).

Islands may be an efficient and cost-effective FRM measure, where other shore-based solutions are not feasible or are ineffective (e.g., high-energy areas or urbanized shorelines), especially in areas near navigation channels, where clean dredged sediments are available for construction and maintenance. Many islands are at risk due to sea-level rise, subsidence, and inadequate sediment supply such as in the Chesapeake Bay (Wray, Leatherman, and Nicholls 1995), eastern Canada (Carter et al. 1989; Forbes et al. 2004), and the Isles Dernières island chain in Louisiana, United States (CECI 2013). If evolving conditions are captured in design and maintenance, considering processes such as sediment budget (source and net transport), expected sea-level rise, and island nourishment requirements, resilient island features can be created.

Habitat trade-offs when restoring and creating island features are inevitable. The process typically requires switching from subtidal to intertidal and supratidal habitat and may replace a single habitat with multiple habitats, simultaneously increasing diversity and resilience (Figure 11.4). Therefore, short-term changes to the ecosystem must be considered and communicated within the context of historical conditions, long-term benefits, biodiversity trends, and system trajectories such as sea-level rise (see Sections 11.2.4 and 11.4).

Figure 11.4. ***Conceptual Illustration of Habitat Switching Components***



Given the relatively narrow set of conditions that support sustainable island features (e.g., sediment budget, tidal range, and foreshore slope), there is limited context under which islands are preferred to shore-based NNBF. Islands might be used to stabilize shorelines in locations where transport gradients are significant or longshore sediment transport dominates, where the foreshore slope is gentle and water depths small (making island construction or restoration feasible), or where appropriate material is available; otherwise, reefs or other alternatives may be appropriate. Island construction usually requires an existing platform to manage costs and optimize sediment capture. These platforms are typically remnants of islands that have either subsided or eroded over time due to changing climatic and sediment loading conditions. However, there are conditions where dynamic shorelines result in legacy platforms outside the present sediment transport system. In these cases, island creation on legacy platforms may be infeasible (due to lack of sediment source) or ill-advised. Under these conditions, other options that locate the island closer to the new shoreline (where benefits are maximized) should be evaluated.

11.2 | Conceptual System Understanding

11.2.1 Introduction

In addition to diverse habitat on the island, changing circulation and wave climate within the island's domain of influence may permit establishment or construction of additional aquatic habitats, such as reefs, fish spawning grounds, or SAV, which are not part of the island but provide additional resilience and ecosystem co-benefits. Like other coastal features, they are often at risk from degradation due to sea-level rise, lack of sediment sources, and erosion from storm events. A conceptual understanding of the regional system processes that influence or will be affected by the island feature is required for successful implementation. This begins with an understanding of the coastal classification and physical processes that govern the type of naturally occurring islands within an area; this understanding can be obtained from surveying local analogous features. Examining existing, local and regional, and natural analogues to support assessments of what can and cannot work at a given site is critical to successful restoration or construction of islands. Besides analogues, proper understanding of local circulation, wave climate, and predominant sediment transport patterns are critical to evaluating sustainability and maintenance requirements. An intensive survey of available system data (e.g., morphology, bathymetry, reports) can help understand historical conditions (what the system used to be) and system evolution.

11.2.2 Natural System

Island features can play important roles in healthy ecological systems, in part due to the variety and diversity of habitats that they support (Figure 11.4). Barrier island-lagoon ecosystems exhibit significant biotic diversity (Gilmore 1995), deltaic islands are common features of estuarine wetland systems that encompass some of the world's most productive ecosystems (Elliott et al. 2019), and in-bay and in-lake islands can provide similarly diverse habitat, including beach and dune, upland plant community, high marsh, and low marsh. Islands may also provide predator-free habitat for nesting birds depending on their distance from the mainland and their size (Erwin et al. 2011) and may also protect local, diverse aquatic habitat such as SAV and fish spawning grounds (see Swan Island Restoration Project case study in Section 11.2.2.3) (Fullarton et al. 2006). Steep gradients and temporal disturbances or changes in environmental parameters tend to occur in the vicinity of island features, such as variations in wave and current exposure, water temperature and salinity, topography (elevation and aspect), light and shade, sediment characteristics and dynamics, and habitat. The primary factors influencing island development, migration, and erosion and accretion dynamics are the relict lithology, hydrodynamics, wave energy, sediment availability, sediment type and source, slope, and drainage of the mainland (Oertel 1985; Riggs et al. 2008). In addition, subsidence and sea-level rise are factors that increase susceptibility to loss of island features and associated coastal resilience function (Carter et al. 1989).

These processes, in turn, govern the feature characteristics that form or can be constructed or adaptively managed on an island. Islands may be a combination of beaches and dunes, high and low wetlands (marshes and mangroves), or upland vegetation and forest, suggesting that all these features can be used in isolation or combined to form the island features. Subtidal and intertidal features such as oyster reefs or SAV may also be part of the seascape that surrounds the island. These features increase ecosystem diversity, increase sediment retention, and support wave attenuation. Both sediment supply and sediment stabilization benefits of island vegetation are required to sustain the island as a system that provides coastal resilience benefits.

11.2.2.1 Barrier Islands

Geological and morphological origins of barrier islands are diverse. Some are glacial remnants from drowned river valleys (Long Island Sound and Cape Cod on the U.S. Northeast Coast), some are continuously being nourished by ongoing river discharge (Mississippi and Alabama on the U.S. Gulf Coast), and others are a combination of both (the Outer Banks in North Carolina, on the U.S. East Coast). Independent of the origin, islands provide coastal resilience benefits by trapping sediments, reducing storm surge, and protecting open coasts from waves.

Five environments generally characterize the island system—beach and dune, barrier island, inlet and inlet deltas, back-bay lagoon, and mainland (Figures 11.1 and 11.2). The lithology, sediment type and supply, slope, and drainage of the mainland all influence barrier island dynamics (Oertel 1985; Hequette and Ruz 1991; Riggs et al. 2008). For example, on the sediment-rich northern stretch of the Outer Banks in North Carolina, United States, the barrier islands are longer, wider, and with higher elevation, and the back-barrier lagoon is also wider and forms a somewhat deeper embayment than the sediment-limited southern portion (Riggs et al. 2008).

The Outer Banks example illustrates the physical processes that lead to a variety of barrier island forms. During storm events, overwash removes sediment from the shoreface and deposits it on the back side of the island. This process erodes the front side and supports accretion on the back side; it is referred to as rolling over, a process of island migration, usually in the landward direction. Post-storm, long-term littoral and eolian transport may permit renourishment of the shoreface. Islands that have sufficient sediment supply may roll over and migrate intermittently during storm events instead of narrowing on the front and back sides. However, this process can be highly variable in response to individual storms, which can cause local, rapid erosion. Over longer time periods, rates of relative sea-level change exert considerable influence on the evolution and sustainability of barrier island systems (Carter et al. 1989). To understand the natural system and develop sustainable island features, it is critical to understand the role of vegetation in trapping sediments, both during events (trapping in the back bay) and during recovery of the shoreface (stabilization benefits of dune vegetation). Therefore, there is a feedback loop between healthy sediment transport and vegetation processes. Sediment supplied to island backshore wetlands (Figure 11.4 [B]) during overwash is critical to maintaining intertidal elevation for healthy wetland growth. This is complemented by the demonstrated efficient trapping of sediments from open water by wetland vegetation during storms and flood tide (Kirwan et al. 2016). Similarly, dune and upland plant communities are critical to trapping sediment from eolian transport and storm surge. In addition, vegetation creates biomass, as described in Chapter 10. Without this island and wetland vegetation, barrier islands would quickly dissipate during storms as sediment is transported beyond the island platform. Similarly, sediment supply is critical to maintaining backshore wetland and dune elevation. Barrier island systems are susceptible to sediment deficits caused by natural and anthropogenic changes or interruptions in sediment supply (e.g., shoreline armoring, navigation channels acting as sediment traps, and reduced river sediment load).

Depending on rates of sediment supply, recovery of overwash beaches and shoreface (including beach and dune) can take many years or decades, such that islands can be more vulnerable to subsequent storm events or relative sea-level rise (Carter et al. 1989). Storm clustering over timescales of weeks to years can affect barrier island resilience (Forbes et al.

2004). The potential effects of climate change on storm clustering are, therefore, a concern for barrier island systems such as those on the coasts of the southern Gulf of Saint Lawrence, where sea-level rise and subsidence are already significant factors driving shoreline recession.

11.2.2.2 Deltaic Islands

Deltaic systems, which may include islands, occur where a river enters the sea. Deltaic systems often include a network of islands, wetlands, and both abandoned and active distributaries. Deltaic islands form and degrade through a combination of fluvial and coastal processes as well as subsidence. There are approximately 30 to 35 major deltas (i.e., with land areas exceeding 1,000 square kilometers) in the world (Well and Coleman 1985), and numerous smaller deltas.

Deltaic islands fronting the coast, where coastal processes are dominant, may have more in common with barrier islands than islands further upstream in the delta, and these islands are often defined as either deltaic or barrier, or both (e.g., the Nile River and Mississippi River deltas). High river discharge events both erode islands and nourish island platforms with sediment critical to compensate for subsidence. These events continually rework deltaic systems, creating new distributaries while cutting off others (Figure 11.3) and altering local processes that sustain and degrade islands and wetlands. Storm events in the open ocean have similar effects on the near-coast portion of the delta. Sediment from the river and coastal islands in the delta often help to sustain barrier islands downdrift. Anthropogenic activity has significantly reduced or diverted sediment into and within many of the world's deltas. Decreases in sediment load can deprive deltaic islands of material needed to rebuild them following storm-driven erosion events.

Deltaic islands and the nearby land are prime locations for agriculture due to rich soil sustained by episodic flooding, as well as convenient locations for cities engaged in commerce and trade. In addition to global sea-level rise, sediment deficits and the subsequent impact on delta evolution have made cities and cropland more vulnerable to flooding from both the sea and river. As humans intervene to sustain islands that are critical to resilience, these activities must account for the reduced sediment loads that sustained the original deltaic island systems. Over time, deltaic island formation or erosion can be affected by the following:

- River hydrology and hydraulics (and related climate change influences)
- Sediment availability in river watersheds
- Tidal range
- Waves and coastal sediment transport processes

- Land use changes and anthropogenic activities (e.g., dredging, channelization, levee and dike construction, deforestation, and urbanization)
- Relative sea- and lake-level change (including climate change-related sea-level rise and uplift or subsidence)
- Density differences between river water and receiving waters (e.g., due to salinity or temperature differences)

11.2.2.3 In-Bay or In-Lake Islands

In-bay or in-lake islands respond to similar physical processes as their barrier and deltaic island counterparts. For example, Lewis, Cooper, and Pilkey (2005) found dominantly landward migration of these islands as a result of shoreface erosion on the open-water side and accretion along the back side (i.e., mainland side), a result of similar rollover processes that occur in open-ocean barrier islands. However, there are key morphological differences—in-bay and in-lake islands are usually much shorter, narrower, and lower elevation and are strongly controlled by intertidal and upland vegetation dynamics (Pilkey, Cooper, and Lewis 2009). Islands within the Chesapeake Bay are examples of in-bay islands that fit these criteria. These islands are degrading and at risk of erosion into submerged shoals (Erwin et al. 2011; Wray, Leatherman, and Nicholls 1995). Their relatively small size and proximity to maintained navigation channels makes them prime candidates for restoration through beneficial use of dredged sediments (see Swan Island Restoration Project case study). In-bay and in-lake islands have been classified by Lewis, Cooper, and Pilkey (2005) into the following three main categories:

1. **Classic islands.** These islands undergo similar processes as open-ocean barrier islands, such as overwashing, cross-shore migration, and longshore migration, to form recurved spits and inlets.
2. **Marsh fringe islands.** The most common type, these islands are created by sediment trapping on existing high marsh. The high marsh acts as an anchor point for additional sediment accretion and subsequent island formation. They often exhibit a crescent-shaped sandy beach that is oriented concave to the primary flow of water and are backed by a fringe marsh.
3. **Two-sided islands.** These islands experience similar physical processes on both the lagoon and the open-water side. Tangier Island located in the Chesapeake Bay is a good example of a two-sided island type. There is considerable variability among and within these island types, and although they are often dominated by intertidal and upland vegetation, they may also have beach and dune features.

CASE STUDY:

Swan Island Restoration Project (Maryland, United States)

Chesapeake Bay islands reduce erosion and wave run-up to adjacent habitats and communities while providing habitat for migratory birds and other wildlife (Erwin et al. 2011). These islands are disappearing at an alarming rate. Use of dredged sediment from navigation channels is one method applied by the U.S. Army Corps of Engineers (USACE) Baltimore District to restore the physical features of Chesapeake Bay islands (Blama 2012).To restore one such island, the USACE Baltimore District employed beneficial use of dredged sediments from a nearby navigation channel as a cost-effective way to build resilience for nearby coastal communities and maintain shallow-water channels. From October 2018 to April 2019, the USACE Baltimore District placed approximately 61,000 cubic yards of dredged sediment on Swan Island, a natural wave break for the Town of Ewell on Smith Island, within Chesapeake Bay. This area has been experiencing erosion rates of up to 3 meters per year over the past 75 years. In June and July 2019, approximately 200,000 high and low marsh and dune plants were installed (see Figure 11.5).

The restoration of Swan Island is expected to produce significant benefits in terms of ecosystem services, increased resilience to future sea-level rise, and abatement of erosive losses for adjacent communities and habitats. The pre- and post-restoration monitoring and integrated hydrodynamic and ecological model development by project partners will serve to quantify the benefits and efficacy of the island restoration and inform adaptive management actions (Herman et al. 2020).

Figure 11.5. ***2018 Pre-Placement and 2019 Post-Placement Photographs***

Note: The photograph on the left shows pre-placement in 2018, and the photograph on the right shows post-placement in 2019.

Source: Left photograph courtesy of U.S. Fish and Wildlife Service; right photograph courtesy of National Oceanic and Atmospheric Administration

11.2.3 Socioeconomic System

Island features provide services that protect people, property, and coastlines from the destructive power of storms (Costanza et al. 2008; Arkema et al. 2013; Bridges et al. 2015; Narayan et al. 2016; Guannel et al. 2016; Narayan et al. 2017). Whether formed within bays, as barrier islands, or as a result of deltaic processes, islands have the potential to deliver diverse socioeconomic services that benefit both people and wildlife (marine and terrestrial) (Arkema et al. 2017; Reguero et al. 2018). Island resilience benefits that protect people and property are derived, in part, because islands comprise multiple complementary habitats that, in combination, are well suited to resist and recover during and after storm events. These habitats provide socioeconomic co-benefits such as coastal protection (including wave dampening, storm surge reduction, and erosion control), recreation, commercial opportunities (fisheries, agriculture, shipping, and ecotourism), and habitat for threatened and endangered species (Arkema et al. 2017). However, the exact socioeconomic co-benefits depend on the location, size (width and length), elevation, and distance from shore, among other island attributes.

The benefits of barrier island restoration in the Gulf of Mexico as measured by averted or avoided damages (a standard insurance industry risk modeling approach) and cost-benefit analysis are estimated to be valued at $5.9 million U.S. dollars (USD) and with a 5.1 benefit-cost ratio (BCR), respectively (Reguero et al. 2018). This is lower than the damages avoided and a lower BCR than other natural features in the Gulf of Mexico such as oyster reefs (USD$9.7 million and 7.3 BCR) and wetlands in high-risk areas (USD$18.2 million and 8.7 BCR), which are cheaper to construct and often more extensive in size but similar to the damages averted for wetlands in conservation areas (USD$5.9 million). However, islands have a greater overall BCR (5.1 BCR) than wetlands in conservation areas (1.9 BCR) and beach nourishment in the eastern (1.7 BCR) and western Gulf of Mexico (0.2 BCR). This is likely due to the lower property values or the relatively high cost of beach nourishment projects, or both (Reguero et al. 2018). However, as stated previously, island features may be an option in regions where mainland-adjacent NNBF are not feasible due, for example, to mainland urbanization or other factors. Under these conditions, islands can also provide diverse habitat co-benefits to replace those lost to urbanization or other anthropogenic land use on the mainland.

Although studies such as Reguero et al. 2018 generally take a single-habitat approach to assessing coastal protective services, this ignores the potential combined, complementary effect of integrated offshore to onshore habitat types in terms of short-term and long-term protective benefits (Lopez 2009; Guannel et al. 2016; Arkema et al. 2017). Further, as large natural features encompassing many habitat types, islands may be designed and adaptively managed to provide multiple socioeconomic co-benefits (also see CPRA 2007; Lopez 2009; Guannel et al. 2016; Grouthes and Able 2016).

Islands and their interconnected waterways are essential to the livelihoods and cultural heritage of Indigenous people and historical working waterfronts worldwide (Jones and Garza 1998). Similarly, depending on their location, islands have the potential to significantly alter waterfront recreation, access, and visual appearance for adjacent communities. Therefore, considering these socioeconomic aspects during the Scoping Phase and Planning Phase (discussed in Section 11.2.4) may be critical to community advocacy and overall project success.

11.2.4 Governance Context

The governance context has a significant bearing on the feasibility and success of island NNBF projects, decision-making, and the processes by which islands are restored, constructed, and maintained. Jurisdiction and permitting requirements often depend on island and sediment borrow area location and scale; the landowner (island and borrow area); locally applicable regulatory frameworks; and interested or affected parties (e.g., users of the site and surrounding areas). Given these potential variables, the governance process necessarily includes numerous stakeholders from government, nonprofits, and private sectors.

Island construction generally involves dredging of sediments from a borrow area and placement of that material to form or restore an island in another area that may or may not have been present historically. Typically, this introduces regulatory and permitting considerations applicable to both the borrow area and placement sites. The former may be eliminated or streamlined in cases where sediment dredged for navigation (or other) purposes provides opportunities for beneficial use in island construction. Construction or restoration of an island generally requires placing sediment within a subtidal area to raise the elevation above the mean high tide mark. The process of replacing one habitat type for another, such as when subtidal seafloor is converted to intertidal marsh, is often referred to as habitat switching. Due to the well-recognized value of most subtidal areas as habitat (e.g., seagrasses, reefs, and mudflats) critical to the maintenance of fisheries' productivity, most developed countries have legal requirements that must be completed prior to initiation of dredge and placement operations. The amount and type of existing habitat proposed to be switched may be part of the regulatory framework, depending on the location, and should be addressed early in the planning and stakeholder engagement process, prior to the development of final planning and environmental assessment documents for the regulatory agency review.

For example, in the United States, Section 404 of the Clean Water Act, the Essential Fish Habitat provisions of the Magnuson-Stevens Act, the Endangered Species Act, and the Fish and Wildlife Coordination Act (among others) govern activities that may impact U.S. waters and wildlife. In Canada, the Fisheries Act requires that projects near water avoid harmful alteration, disruption, or destruction of fish habitat unless authorized by the minister of Fisheries and Oceans Canada (DFO). In Bahrain, there is environmental legislation pertaining to dredging and island-building activities that typically culminates in the requirement for an environmental impact assessment (Deltares and Delft Hydraulics 2008). Although the laws governing these activities vary by country, the process generally involves coordination across multiple stakeholders, jurisdictions, and agencies to gain approvals and obtain the required permits.

The most relevant steps in the process for gaining final approvals and permits are outlined in Phases 1 through 4 (i.e., Scoping Phase, Planning Phase, Decision-Making Phase, and Implementation Phase) of the five phases (note that Phase 5 is the Operations Phase) of the NNBF project development framework (described in detail in Chapter 2). However, the following list adds details relevant to governance, permitting, and approvals for island construction projects (this list is also adapted from Deltares and Delft Hydraulics [2008]):

1. **Scoping Phase.** The Scoping Phase includes problem identification and identification and organization of stakeholders and applicable regulatory requirements. The Scoping Phase usually begins with the identification of a site or a problem that requires an action to resolve (e.g., an eroding island in front of a waterfront community). Next, ownership of the island site and surrounding areas, including borrow areas, where construction will occur, should be identified along with the potential regulatory requirements and stakeholders. Stakeholder engagement allows all regulatory agencies and local communities who live and work in the project area to provide input. This improves system understanding and supports refinement of objectives and methods. Local stakeholders, in particular, should be involved throughout subsequent phases to improve design and implementation and increase community awareness and advocacy. Stakeholders may include the following:
    a. Landowners
    b. Government bodies (federal, state, provincial, and local municipalities)
    c. Financial institutions
    d. Other partners (e.g., nonprofits, commercial interests, local community groups)
2. **Planning Phase.** During this phase, a preliminary project description and design are developed to determine the regional environmental, cultural, and socioeconomic co-benefits and impacts. Preliminary description and design alternatives should be shared with regulators and stakeholders to identify and address relevant issues such as endangered species, essential fish habitat, and cultural resources. This will help to facilitate project approvals through the regulatory process.
3. **Decision-Making Phase.** During the Decision-Making Phase, a final project description with alternatives is presented and reviewed by the relevant stakeholders. Criteria and basis for the selected alternatives should be clearly presented to justify recommendations and typically include relevant information such as cost, habitat trade-offs, technical performance, and benefits for each alternative.

4. **Implementation Phase (specific to permit and license regulatory approvals)**. As part of project implementation, the regulatory approval process and permits must be completed. At this stage, decisions on the final project design and implementation strategy, along with associated adaptive management or monitoring procedures, are documented (in country- and region-specific format) for final approval and issuance of permits. Depending on the regulatory framework, permits or licenses could take the following forms and may include mitigation actions or conservation recommendations prescribed by the regulatory entities:
    a. Dredging or extraction permits from the borrow area
    b. Island construction or reclamation permit (sediment placement)

Environmental Permits and Authorizations in Canada

In Canada, the Fisheries Act requires that projects near water avoid harmful alteration, disruption, or destruction of fish habitat and prohibits activities, other than fishing, that cause the death of fish. The Fisheries Act recently underwent a significant overhaul, with potentially significant implications for permitting and authorization of island NNBF projects. For example, the updated act contains new provisions for the development of regulations for permitting of larger-scale ("designated") projects, and codes of practice for smaller, more routine projects; habitat restoration; preservation of marine biodiversity; and participation of Indigenous peoples in project reviews. DFO publishes recommended measures to protect fish and fish habitat. However, these measures include avoiding work in water, or placing fill below the high water mark, which are inevitably involved in island NNBF construction. Thus, island projects will almost always require, at a minimum, the proponent to submit a request for review to DFO's Fish and Fish Habitat Protection Program. The review determines the following: (1) if the project would impact an aquatic species at risk; (2) if the activity could result in the death of fish and the harmful alteration, disruption, or destruction of fish habitat; and (3) if the project will need ministerial authorization under the Fisheries Act. If a Fisheries Act authorization is applied for, and granted, it will include terms and conditions that the proponent must follow to avoid, mitigate, offset (counterbalance impacts), and monitor the impacts to fish and fish habitat resulting from the project.

11.3 | Objectives and Metrics

An NNBF island can be a potential solution for meeting an overall project objective or strategic goal (see Chapters 2 and 9). This section seeks to define objectives that may be addressed by NNBF island solutions within the context of an overall coastal resilience or shoreline management strategy (see Chapter 9). Due to the complexity and dynamic nature of island ecosystems and the limited number of case studies, a certain degree of flexibility is often desired when setting environmental objectives and metrics, and planning for adaptive management of island NNBF. Nevertheless, it is possible (and desirable) to establish quantitative objectives and performance metrics (Table 11.1).

Objectives and metrics should be defined to enable unbiased assessment of project performance and to support adaptive management (i.e., specific, measurable, achievable, relevant, and time-bound [SMART] objectives—see Chapter 9). Project objectives are defined as the project goals (Table 11.1), and performance metrics are measures of success in achieving project objectives. Performance metrics should be aligned with stakeholder risk mitigation objectives and risk tolerances (e.g., island feature is dynamically stable and provides acceptable flood protection for design events with specified probabilities). The objectives established for a project will guide the monitoring, maintenance, and adaptive management of the island NNBF (Section 11.6). For example, Davis et al. (forthcoming) identified specific goal statements and performance metrics that reflect the primary project objective of quantifying coastal resilience performance of Swan Island, in Chesapeake Bay (see Swan Island Restoration Project case study in Section 11.2.2.3); this includes goals such as determine how the restoration actions have influenced the capacity of Swan Island to provide protection from wave energy to the Town of Ewell, Maryland, United States, and a performance measure of "maintain or increase relative to designed elevations." One potential scenario, then, is that decreased designed elevations over time may be cause for an adaptive management action, such as placement of more sediment or planting vegetation to stabilize elevations (Davis et al., forthcoming; see "Simplified Resilience Conceptual Model for Swan Island Restoration Project [Maryland, United States]" in Section 11.6). Therefore, the selection of monitoring parameters, maintenance, and adaptive management of the island NNBF will naturally stem from the project objectives and performance metrics identified to evaluate project success.

Table 11.1. *Potential Project Objectives Satisfied by Islands and Associated Performance Metrics*

Range of project objectives	Island function	Example objective	Example performance metric or measure of success
Engineering	Wave attenuation	• Reduce storm wave exposure and associated risk • Reduce erosion risk	• Wave energy and height reduction during a storm • Reduction in erosion rate • Wave run-up elevations • Mean wave overtopping discharges • Survival of vegetation
	Surge attenuation	• Reduce flood risk associated with inundation	• Surge reduction during a storm • Reduction in inundated land area during a storm • Survival of vegetation
	Sediment trapping and land building	• Increase land elevation • Increase acreage • Reduce erosion • Stabilize shoreline in lee of island	• Temporal increase in surface elevation • Temporal reduction in erosion or accretion • Beach profiles that are stable over time
	Mainland shore stabilization	• Protect infrastructure and land-based natural features (wetlands, for example)	• Shoreline position
	Beneficial placement of sediment	• Provide cost-effective disposal option for sediment dredged for other purposes • Reduce other maintenance requirements (nourishment with mined material)	• Savings in dredging cost • Measured reduction in frequency and magnitude of other construction and nourishment activities
	Provide physical conditions consistent with environmental objectives	• Provide required land area and range of elevations to support colonization by flora and fauna • Provide appropriate exposure to fresh- and saltwater conditions (overwash), waves, and currents • Provide for appropriate supply of natural sediment and nutrients • Provide appropriate water renewal or flushing, drainage, and water quality • Control exposure to waterborne debris	• Land area at different elevations • Changes in land area at different elevations • Island crest elevations • Observed frequency and duration of overwash events • Wave and current speeds at locations near the island • Water residence times • Water quality parameters (temperature, salinity, suspended sediment concentrations) • Quantities and distribution of debris

Range of project objectives	Island function	Example objective	Example performance metric or measure of success
Environmental	Provide habitat diversity	• Provide range of habitat types (flora and fauna) • Provide space for migratory bird resting and nesting	• Habitat ranges • Species utilization • Presence or rate of protected species • Migratory bird seasonal population
	Provide habitat area	• Provide habitat for species of interest	• Habitat area or type • Inundation period
	Provide sustainable, self-sustaining habitat	• Provide stability or growth of vegetation	• Area covered by vegetation • Vegetation density, percent survival
Socioeconomic	Education	• Increase education facilities	• Number of visitors to visitor centers • Number of signs installed • Number of presentations given to local community
	Tourism	• Attract visitors	• Business transactions • Number of visitors
	Navigation	• Provide safe harbor • Provide sustainable and cost-effective dredged sediment management	• Use by small vessels during non-events • Damage to vessels during events • Risk reduction to large ships entering ports • Quantity of dredged sediment used beneficially • Island sediment budget
	Recreational	• Provide recreational opportunities • Increase public well-being	• Usage levels • Concession levels • Social science metrics • Recreational fish populations
	Fisheries	• Increase commercial fishing productivity	• Commercial species population • Commercial fishing take
	Avoided damages	• Protect area from flood hazards • Reduce flood risk to communities	• Stabilization or decrease in damage to buildings in infrastructure over time • Measured reduction in injuries or fatalities due to extreme events • Decrease in flood insurance premiums or emergency response costs

Islands are dynamic features; therefore, their success in achieving predefined objectives and observed metrics may fluctuate. Changes in performance may be gradual, may be sudden and dramatic (e.g., in response to tipping points or storm events that exceed design criteria), or may change over time. In particular, islands are naturally exposed to waves and hydrodynamic processes from a broader range of directions than shore-based NNBF, and, therefore, may experience higher susceptibility to changes in climate variables (e.g., direction of wave incidence). Also, overwash may reduce dune height, which temporarily reduces storm surge mitigation benefits to the mainland. However, natural accretion of dunes post-storm (recovery) may reinstate coastal resilience performance. These processes must be considered when establishing performance objectives and metrics, and monitoring may be required to re-evaluate performance after post-storm recovery.

Island features can be designed to help achieve multiple environmental objectives related to the provision of habitat and species diversity. The complex feedback and interactions between physical and biological processes determine island ecosystem function (Brantley et al. 2014) and the extent to which environmental objectives and metrics for island NNBF can be satisfied. Positive correlations between island area and species richness have been widely documented (Ricklefs and Lovette 1999, and references therein).

As stated previously, construction of island features typically requires placement of sediment in subtidal or intertidal areas, resulting in habitat switching. This trade-off inevitably leads to short-term losses of marine habitat (see discussion of recovery versus disturbance in Chapter 9, Section 9.5.3.7), which must be balanced against longer-term objectives (e.g., increased habitat diversity with greater coastal protection capacity; Figure 11.4).

Objectives, metrics, and performance can be expected to change over time, or have temporal components. For example, tighter control on wave exposure may be required during the initial stages following construction or restoration of an island feature to allow time for vegetation to establish. Beyond this initial period, objectives for wave exposure may be relaxed. Similarly, periods of strong habitat and ecosystem growth and establishment may be interspersed with periods of stagnation or decline, depending on system-wide changes and natural (e.g., seasonal or decadal) fluctuations.

11.4 | Design Considerations

The design process for island features generally follows established frameworks for coastal engineering design (e.g., Part V of USACE 2002; CIRIA 2010) and other coastal NNBF (Chapter 2). Design considerations for islands will necessarily draw on those for other coastal features (e.g., beaches, dunes, and wetlands), because islands are typically composite features. However, there are some unique design considerations for islands, particularly with respect to the physical processes in an open-water setting, habitat diversity, and interactions with surrounding areas and other processes (e.g., vegetation and sediment dynamics). The design team should be multidisciplinary, consisting of engineers, ecologists, oceanographers, dredgers, and others. Furthermore, there are a limited number of case studies for island NNBF that capture the wide range of conditions (e.g., hydrology, wave, climatology, vegetation, geomorphology) in which island NNBF will be constructed. This section identifies some key considerations for island NNBF at each of the following five identified design phases:

- Establishing design criteria
- Site characterization
- Conceptual design
- Evaluation and analysis of design alternatives
- Detailed design development

11.4.1 Design Criteria

Similar to other NNBF, the design process for island features typically begins with establishing basic design criteria to meet and confirm the overall project objectives (see Section 11.3). These criteria may include but are not limited to the following:

- Regulatory criteria and project constraints
- Project coordinate systems and datums
- Design life, design return period, or acceptable risk of design storm encounter
- Role of the island feature within the overall resilient system (because islands are often key components of multiple-lines-of-defense systems) and areas where the island is intended to provide FRM benefits
- Geotechnical and seismic design criteria
- Island and shore stability criteria
- Wave, water level (including relative sea-level change considerations), current, and wave overtopping criteria
- Water quality and circulation and renewal criteria, both from the perspective of providing for healthy island ecosystems and avoiding negative impacts by altering circulation patterns in surrounding waters
- Habitat criteria (shade, aspect, exposure, substrate, vegetation types, woody debris, water velocities, depths, and habitat suitability)

- Vegetation ecology criteria (elevations, salt tolerance, aspect, tolerable slopes, frequency and duration of inundation, wave exposure, and control of invasive species)
- Beach quality criteria (if applicable), including wave exposure, stability, safety, debris, materials, and tolerances
- Ability of the system to recover from events through natural processes
- Monitoring and maintenance criteria
- Navigation criteria, if applicable (i.e., preserving minimum fairway widths and exposure to ship wake)
- Criteria for engineered control structures (if applicable)
- Approaches to short- and long-term phasing and adaptation (e.g., sequencing to align with overall coastal resilience strategy and flexibility in the design for adaptation to sea-level rise)
- Life-cycle cost considerations (e.g., preference for capital versus maintenance investment)

Establishing design criteria may involve multiple iterations and discussion among the owner, designer, regulators, subject matter specialists, and stakeholders (see Chapters 2 and 3). This step also serves to identify requirements and details for studies, field data collection, and analysis conducted at later design stages.

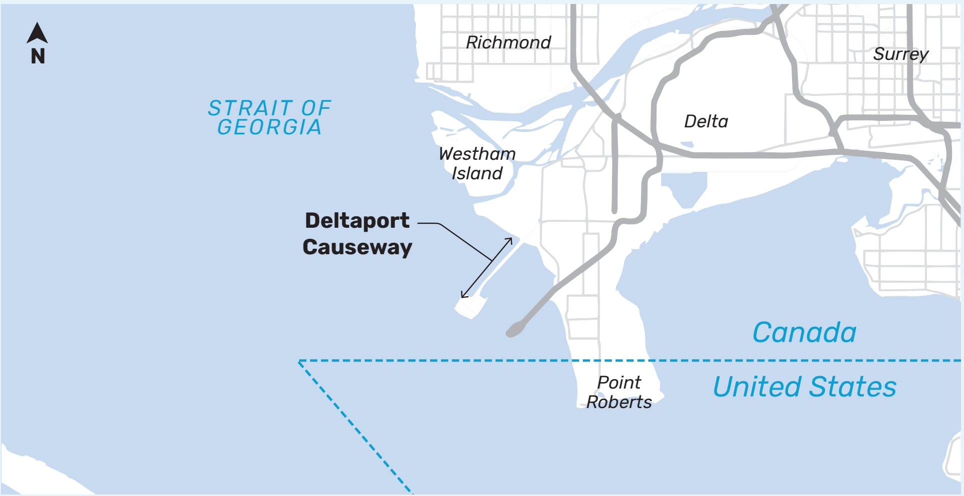
Design criteria for island NNBF can differ in a number of ways from those for conventional offshore structures (e.g., breakwaters) and shore-based NNBF. For example, key objectives of barrier island NNBF are typically to attenuate waves and storm surges or stabilize mainland shorelines. However, it is also recognized that some overwash and inundation of barrier islands is needed to replicate the natural processes that contribute to island building (Leatherman 1976) and sustainable backshore wetland growth and survival (Walters et al. 2014; Schupp et al. 2013). Careful consideration should, therefore, be given to balance competing objectives when establishing design wave and water level criteria, and wave overtopping and transmission criteria for an island NNBF. Balancing these competing objectives directly influences island design profiles (crest levels and widths, seaward slope), the sediment characteristics required to meet stability criteria, and the types of habitats and ecosystems that can be supported. For example, the design criteria for beach crest elevations of the Deltaport East Causeway barrier islands (see Deltaport East Causeway Barrier Island Features case study) were set by considering local wave and water level conditions, as well as local, natural barrier beach analogues.

CASE STUDY:

Deltaport East Causeway Barrier Island Features (British Columbia, Canada)

Deltaport East Causeway is on the west shore of the Fraser River delta (Figure 11.6) and is the road and rail link connecting the Port of Vancouver's largest container terminal to mainland British Columbia, Canada. In 2010, Vancouver Fraser Port Authority constructed habitat features along the shore of the causeway as a condition of the Fisheries Act authorization for a port expansion. The features were integrated with the causeway shore protection structures that provide FRM functions to this critical transportation corridor. Post-construction, compliance monitoring of physical and biological metrics indicated that wave and wind exposure was inhibiting habitat function. Performance deficiencies were primarily related to salt marsh productivity and retention of sediment.

Figure 11.6. ***Location of Deltaport Causeway Site***



In 2016, a remedial concept was developed to address these performance deficiencies. Several barrier beach and back-beach marsh features were constructed, making use of on-site materials, to create and enhance habitat. The barrier islands now provide FRM functions for sections of the causeway where rock armoring is not present.

The barrier island feature designs were developed considering the local wave climate and geomorphological principles applicable to crenulate beaches, and by drawing on observations from several local, natural analogues. The barrier beaches and artificial headlands provide a dynamically stable framework on which to support diverse habitat, even under conditions where sediment supply has been interrupted. One year following construction, the beaches and marshes had performed well morphodynamically (see Figure 11.7). Establishment of new salt marsh has required adaptive management due to challenges including accumulation of eelgrass wrack from adjacent subtidal flats and large woody material (logs), and scour of back-beach marshes during strong southeasterly winter storms. Field monitoring has demonstrated the need for adaptive management and provided the following valuable insights:

- **Salt marsh establishment takes time.** Even small waves generated along short, nearshore fetches can have significant impacts on substrate stability and vegetation survival during the initial stages of marsh establishment. This is a key consideration for island NNBF, which are exposed to waves from a broader range of directions than other features. Cluster plantings offer some resistance to wave action.
- **Wrack and large woody material accumulation can inhibit drainage and vegetation survival in the early stages of marsh establishment.** Floating barriers can be effective but must be designed to withstand wrack, debris, and hydrodynamic loads.

Figure 11.7. ***Salt Marsh Vegetation Establishment on Leeward Side of the Barrier Islands***

Note: The left photograph is immediately after construction, and the right photograph is approximately 1 year after construction.

Source: Courtesy of Phil Osborne, Golder Associates

On marine coasts, setting appropriate design criteria to accommodate relative sea-level change is an important consideration for any coastal engineering project but requires special considerations for island NNBF. For offshore structural measures (e.g., breakwaters) providing resilience functions, elevating the crest may be an acceptable approach to accommodating projected sea-level rise over the design life, and this could be reflected in the design criteria. However, overbuilding may not be appropriate for an island NNBF because of the requirements to facilitate some overwash at the beginning of the design life to support habitat establishment, as described in the Deltaport East Causeway example (see Deltaport East Causeway Barrier Island Features case study). Island NNBF are, therefore, more likely to involve, and are generally more amenable to, solutions incorporating adaptive management (see Chapter 7), and this should typically be reflected in the design criteria.

Particularly for islands, the regulatory and governance regime often plays an important role in establishing design criteria, because island NNBF almost always involve placement of material below the waterline, which can trigger design requirements for preventing or minimizing adverse impacts on subtidal habitats, navigation, fisheries, and other marine-based activities. Obtaining an early indication of the design implications is important to guide the design process and stakeholder engagement.

11.4.2 Site Characterization

Characterizing existing or baseline system conditions and projected future changes in the natural system encompassing a proposed island NNBF site are crucial prerequisites for developing a design that works with natural system processes (see Section 11.2.2). The open-water environment at island sites is often subject to harsher conditions and more temporal and spatial variability than comparable shore-based NNBF sites, which elevates the importance of adequately characterizing site conditions to ensure a robust design.

Adequate field data are required to support the effective design of islands to support FRM. The availability of baseline field measurements and observations to characterize key physical processes at the project site is critical for the development of concepts that are robust and sustainable, to support model verification, and to guide and inform construction operations. Data needs and sources, as well as methods and approaches for characterizing conditions at coastal and offshore sites, are provided in several established guidance documents (e.g., USACE 2002; CIRIA, CUR, and CETMEF 2002; CIRIA 2010), and may involve field measurements or modeling (numerical or physical). At a minimum, it is important to characterize the following:

- Bathymetry (and topography if applicable)
- Hydrodynamic conditions (water levels, circulation, waves—ambient and extreme)

- Sediment transport patterns (ambient and extreme) and geomorphology (sediment characteristics, lithology, sediment sources and sinks, sediment mobility, sediment budgets, longshore drift, storm-induced changes)
- Geotechnical conditions
- Environmental conditions (inundation, water quality, native habitat types, flora and fauna—abundance and diversity)

Often, the creation of island NNBF may involve re-establishing or restoring relict or degraded island features to enhance coastal resilience functions. This requires developing an understanding of historical geological conditions at the site that led to the existing state and the existing coastal resilience function provided, so that future changes can be anticipated.

Depending on regional or site-specific considerations and known hazards, it may be important to characterize the potential exposure of the site to meteorological and hydrological extremes, ice, waterborne debris (e.g., logs), crustal uplift and subsidence, tsunami, and seismic loading. For example, liquefaction of sediment during an earthquake could potentially cause settlement and subsidence of an island NNBF and loss of resilience function. If such an event were to coincide with a storm surge, flooding could occur. It should be noted that these types of considerations are not unique to island NNBF; similar considerations (i.e., the need for multihazard assessments) are relevant to the design of any FRM measures, and in line with established disaster risk reduction principles such as those identified in the United Nations Sendai Framework (United Nations 2015).

The extent of field data and levels of analysis required to adequately characterize an island site will depend on a number of considerations including project scale and location, risks and risk tolerances, criticality of the proposed NNBF within the overall FRM strategy (e.g., whether the island is part of a multiple-lines-of-defense system), overall project cost, acceptable uncertainty, and adaptive management strategies. However, system and process understanding typically supports more accurate appraisals of design alternatives, facilitates robust and cost-effective design, and reduces project risks during all stages of a project life cycle (design, construction, maintenance, and adaptive management).

11.4.3 Conceptual Design

Once design criteria have been established, the process of developing (and later evaluating) conceptual (preliminary) design options can begin. The level of effort and analysis involved in developing and evaluating options and the types of tools used for the analysis will typically depend on the size of the project, perceived project risks, and the number of potentially viable options.

Key considerations when identifying and developing island NNBF conceptual designs include the following:

- Identifying the potential role of an island NNBF within the context of broader FRM strategies (e.g., as part of a multiple-lines-of-defense approach)
- Assessing (at a conceptual level) how the island could potentially address specific project objectives and provide specific FRM functions, such as wave attenuation (see Section 11.3)
- Understanding how existing natural conditions at the site have implications for the design, as follows:
  - Meteorological (wind), hydrodynamic (waves, water levels, currents, and circulation), and geomorphological processes often place constraints on the orientation, shape, and water depths where island construction or restoration is feasible.
  - Local water depths and bathymetric features frequently limit where island construction or restoration will be economically feasible (deep waters require larger volumes of material for construction, whereas shallow waters create challenges for construction access).
  - Geotechnical conditions can affect the viability and cost of island creation or restoration (e.g., excessive settlement and consolidation, the presence of fine or soft sediments, or containment requirements may be limiters).
  - Consider availability of materials for island construction and shore stabilization, and compatibility with native materials (e.g., coarser materials may allow for steeper cross-shore profiles and, therefore, reduced island footprints, but may not be compatible with existing beach materials; different soil types may be required to support establishment of different types of vegetation and habitat). Due to the unique biogeography of island ecosystems, the use of locally sourced, ecotypic plant materials is even more important for ensuring success in the revegetation of native plants.
  - Existing uses of coastal waters may determine acceptable areas for island encroachment (such as fisheries, navigation, subsea pipelines, and utilities).
- Understanding the project footprint and impacts on the surrounding environment: The range of directions and severity of processes to which the site is exposed affect the project footprint, the extent of mainland areas where coastal resilience benefits can reliably be provided, and considerations for island and habitat stability. When analyzing design wave conditions, processes such as wave blocking and wave diffraction effects should be considered (Figure 11.8).
- Identifying natural analogues, preferably near the site or at least in similar environments, can help to provide confidence in the viability of an island NNBF solution at a particular site. However, the existence of local, natural analogues does not in itself guarantee the feasibility of island NNBF solutions. In areas where existing barrier beaches are threatened by significant erosion, relative sea-level rise, disruption of transport patterns, subsidence, or other natural processes, island NNBF may be challenging to implement and require significant adaptive management to maintain.

- Integration with other natural and human-made coastal and offshore features
- The potential to adopt hybrid solutions that incorporate structural measures to enhance coastal resilience benefits, improve island NNBF longevity, or reduce maintenance requirements
- Assessing order-of-magnitude project construction costs to provide an indication of whether cost objectives or budgetary constraints are consistent with project technical objectives, and to support with evaluation of alternatives: A first order approximation of costs developed at the conceptual design stage should typically be refined and updated throughout the course of the design process.

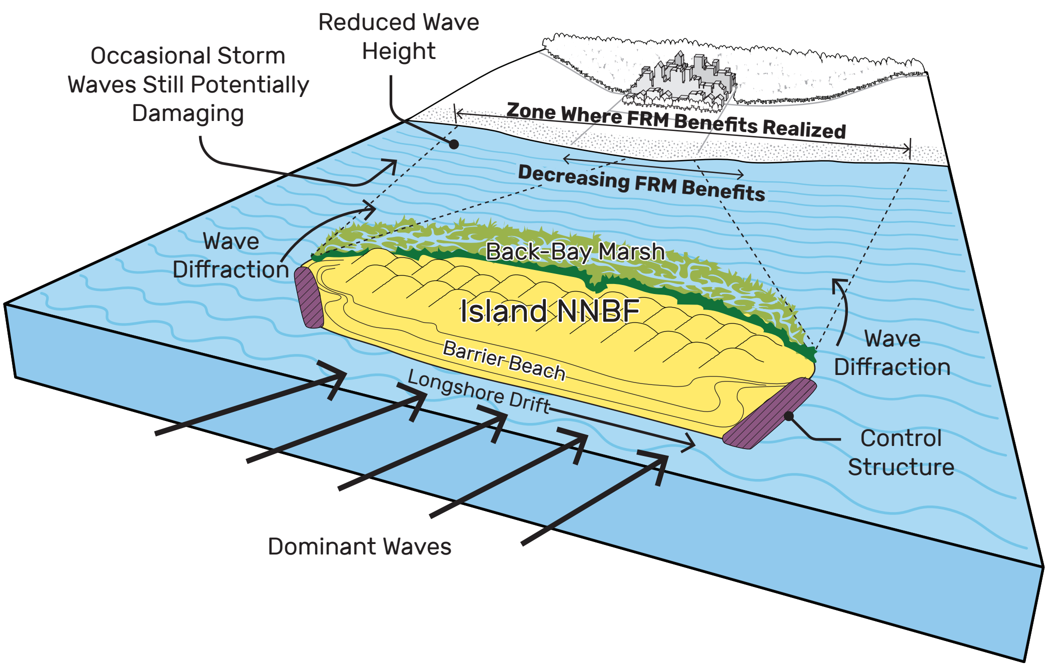
Key features of an island NNBF, and associated considerations, to be established through the design process, are listed in Table 11.2.

Table 11.2. *Island Components and Design Considerations*

Feature or component of island NNBF	Design considerations
Island plan form and layout	• Footprint and area of influence • FRM function • Stability (e.g., orientation with respect to dominant waves, response to hydrodynamic forcing, allowances for seasonal adjustments, dynamic stability, and sediment budgets) • Materials: layout affects quantities (e.g., fill) and associated project cost; local availability may constrain design options
Island profile	• Crest elevations (linked to local water level variability and desired inundation regimes for various habitat types, controls wave overtopping discharges and wave transmission into leeward areas, and affects frequency of overwash events needed to sustain back-bay habitat) • Slopes (linked to stability criteria and sediment characteristics, drainage, and vegetation) • Stability (profile response to storms) • Materials: profile affects quantities (e.g., fill) and associated project cost; local availability may constrain design options
Control structures (e.g., groins, toe berms, breakwaters, and buried seawalls)	• May help to stabilize or prolong life of NNBF, minimize maintenance, or exert additional control on island response to storms • Effectiveness of different control structures depends on dominant physical processes and local and regional conditions (e.g., groins are most effective where sediment transport processes are dominated by longshore drift; toe berms may be less effective or counterproductive in macrotidal areas) • Beyond physical effects, control structures may incorporate features to promote ecosystem function (e.g., Vertipools and textured concrete armor units)—see Chapter 14 for details on enhancing structural measures

Feature or component of island NNBF	Design considerations
Materials	• Sediment characteristics (affect stability response to wave and current action, and ability to support different vegetation or habitat types) • Compatibility with native materials (sediment, vegetation) • Vegetation tolerance to environment (salt, wave, and current exposure) • Local availability of ecotypic plant materials • Natural supply of material (sediment budgets)
Target habitats	• Inundation regime (elevation) • Sensitivity and tolerance to environmental conditions (waves, currents, wind, and salt) • Local, natural analogues

Figure 11.8. *Project Footprint and Area of Influence*



In addition to the positive impacts associated with coastal resilience and ecosystem health, the potential negative impacts of an island NNBF on the surrounding environment and downdrift coastlines is a key consideration at the conceptual design phase. The potential for an island NNBF to temporarily or permanently affect sediment transport gradients, circulation, water quality, and existing habitats in surrounding areas should be considered in light of observations and lessons learned with respect to the negative effects of island reclamation on marine environments (e.g., Smith et al. 2019). Potential adverse impacts include but are not limited to the following:

- Modification of wave and current conditions in leeward and downdrift regions, potentially leading to unwanted erosion and accretion
- Damage to sea, lake, or riverbed habitat and ecosystems at the island site and surrounding areas as a consequence of construction
- Unwanted habitat switching as a result of changes to physical and chemical system
- Impacts on water quality (e.g., impoundment of water between islands and mainland or creation of stagnant zones)
- Impacts on fisheries and navigation associated with changes in bathymetry, channel widths, currents, and wave exposure due to the presence of an island

In-depth analyses may be required or desired to better assess or constrain the risk of adverse impacts, and design modifications or adaptive management approaches may be needed to mitigate risks.

Much of the analysis performed in conceptual design will support evaluation and analysis of design alternatives (Section 11.4.4).

11.4.4 Evaluation and Analysis of Design Alternatives

Evaluation of conceptual design options should take into account technical, economic, environmental, and sociocultural criteria and can be mostly qualitative or may involve detailed multicriteria analysis and complex economic modeling (see Chapter 6). Stakeholder involvement in the evaluation is typically required (see Chapter 3). The evaluation is typically based on a comparison to a baseline “do nothing” scenario, which may include projected future system changes (e.g., climate change effects or urbanization).

When comparing and evaluating design alternatives involving island NNBF, it is important to recognize that there can be socioeconomic trade-offs in the costs and benefits of island construction and restoration. In some instances, beneficial use of dredged material from navigation channels is a cost-effective method to build and restore islands (see Swan Island Restoration Project case study in Section 11.2.2.3). Following a multicriteria analysis of seven different dredging management strategies, Bros (2007) recommended that sediment dredged from the Fraser River delta navigation channels in British Columbia, Canada, be used to provide habitat and FRM benefits on deltaic islands as the preferred strategy.

During the evaluation stage, analytical tools should be applied to refine the initial design. Analytical tools include general rules of thumb or simple equations provided in design manuals and textbooks (e.g., USACE 2002; Kamphuis 2010), as well as more sophisticated numerical modeling or physical modeling tools. In some cases, selected field experimentation can also provide valuable insight to project performance at larger scales. Selecting appropriate analytical tools to support island design applications depends on a number of considerations, which may include the characteristics of a particular site (e.g., tidal range, wave exposure, geomorphological regime, and availability of field data), the design phase (e.g., preliminary planning or detailed design), the level of project risk and stakeholder risk tolerances, the levels of uncertainty and complexity associated with the tools, and selected trade-offs or preferences for reducing design uncertainty versus adaptive management approaches.

Numerical models for storm surge and wave attenuation are one method for a priori evaluation of FRM benefits for alternative island designs. Model predictions are particularly well suited for evaluation in complex domains that typically surround island features. The following considerations for selecting and applying numerical modeling tools are specific to islands:

- **Waves.** A key effect of islands on waves is diffraction (bending) of waves into the leeward region of the island. The capability of, and need for, analytical tools (such as numerical wave models) to capture this process should be carefully assessed. For example, phase-resolving numerical wave models (such as Boussinesq wave models) tend to be better suited to capturing diffraction effects than phase-averaged (spectral) wave models (such as SWAN, MIKE21 SW). However, in cases where predicting the wave field in the lee region of the island is not a primary concern, the parametric treatment of diffraction in spectral wave models may be adequate (and computationally less expensive). Simple diffraction diagrams (Goda, Takayama, and Suzuki 1978) may even be used to characterize diffracted wave conditions in some circumstances.
- **Hydrodynamics.** Deltaic islands are often located in areas with significant water density gradients (e.g., where fresh water from a river meets the sea). The capability of hydrodynamic models to capture 3D baroclinic effects and include advection and dispersion of temperature and salinity should, therefore, be considered for these types of applications. For shallow, gently sloping sites where baroclinic effects are not significant, 2D (depth-averaged) hydrodynamic models may be adequate for capturing water circulation patterns and storm surges.
- **Storm impacts.** The capability, or lack thereof, of numerical morphological models to predict island beach and dune erosion, overwash, and breaching (i.e., the formation of a channel through a barrier island during an inundation event) is an important consideration. Even the most advanced numerical morphological modeling tools (e.g., Roelvink et al. 2009) typically require extensive field datasets to support model calibration and validation for application to shore-based settings. The design team must understand the limitations of these models, including the empirical data upon which they are based. A rigorous

evaluation of model processes and input data (which are site specific) should be performed before model application. For islands, there are many additional complicating factors. For example, storm events can induce a water level differential across barrier island features (McCall et al. 2015), which can drive groundwater flow, and impact wave overtopping and morphological response.

- **Potential for long-term morphological change or sea-level change.** For projects with a design life spanning multiple decades, longer-term morphological or sea-level change may be an important consideration. This typically requires the use of long-term historical records or hindcasts of waves and water levels in combination with sediment transport and shoreline change calculations or morphological models (e.g., 2D morphologic change models driven by coupled 2D or 3D hydrodynamic models and wave models such as DELFT-3D, MIKE ST/MT, and SISYPHE; or 1D shoreline evolution models such as LITPACK, GenCade). More recently, efforts have been made to incorporate the effects of future climate change on waves and water levels in such analyses, by forcing wave and hydrodynamic models with downscaled climate model predictions. Future projections of global sea-level change may be adapted to provide regional or local estimates of relative sea-level rise, by taking into account measured uplift or subsidence rates (e.g., James et al. 2014).

Extensive guidance and considerations for selecting and applying empirical formulae and numerical modeling tools are provided in USACE (2002), Federal Emergency Management Agency (FEMA; 2005, 2016); CIRIA, CUR, and CETMEF (2007); Barnard et al. (2014); and Resio and Westerink (2008).

Where justified by project risks and scale, laboratory physical model testing can sometimes provide a reliable option for analyzing island interactions with physical processes and FRM benefits. Particularly for offshore island sites where the costs of adaptive management and ongoing maintenance can be high compared to shore-based sites (e.g., due to the logistics and cost of mobilization), up-front investment in physical model testing can be beneficial in helping to de-risk designs and reduce project life-cycle costs. Scale physical models constructed in 2D wave flumes or 3D wave basins can be used to assess wave run-up, overtopping, transmission, and penetration into downdrift areas, wave-driven current patterns, wave-structure-beach interactions (for hybrid features), and morphological change for island NNBF (e.g., Baker et al. 2016; Knox and Rayner 2016). Care and experience are needed when designing physical model test programs to make sure the important hydrodynamic model parameters are scaled and assessed correctly, and to ensure limitations are recognized. Guidance on scale effects, model effects, and other considerations for physical model testing are provided in Hughes (1993). In some cases, selective physical model testing can be used to calibrate or validate empirical formulae and numerical models.

Following the options evaluation, one or several concepts may be brought forward for more detailed testing and analysis in subsequent design phases.

11.4.5 Developing Detailed Design for Selected Alternatives

Once the preferred conceptual design or designs are selected, the design is finalized, typically through an iterative process and leading to the development of detailed drawings, construction specifications, and cost analysis. Detailed design phase considerations are not unique to island NNBF. The level of detail and extent to which construction-related issues and methods are considered or prescribed at the detailed design phase will depend largely on the procurement and contracting approach adopted (e.g., standard, design-build, or turnkey), and the local availability of experienced contractors. The following issues and constraints may affect the detailed design development:

- Constructability
- Availability of experienced contractors
- Local availability of equipment
- Local availability and cost of suitable construction materials
- Site access (potentially including seasonal)
- Availability of locally sourced plant materials (e.g., species and seed sources)
- Restrictions on construction windows (see "Restrictions in Time Frame for Construction" in Section 11.5.2) and navigation and traffic control
- Site preparation (e.g., availability of areas for lay-down establishment, clearing, stockpiling, and control of invasive species)
- Surveying and methods of measurement (e.g., pre- and post-construction bathymetric surveys to quantify fill volumes, local benchmarks for surveying, survey tolerances, and trial sections)
- Environmental risks and management during construction (e.g., turbidity control, control of invasive species, spill prevention and emergency management, waste management, noise control, air quality, and dust control)
- Acceptable construction tolerances
- Planning for post-construction monitoring, maintenance and adaptive management (including control of invasive species)

Most island NNBF projects will require fill material to be imported and placed on the island platform to enhance, restore, or create the island and associated coastal resilience benefits. Identification and characterization of suitable sources of available fill material, and incorporation in the final design, is, therefore, a critical element of a successful island NNBF project. The fill needs to be located and characterized to understand its performance in the system. Defining characteristics may include particle size distribution (gradation curve, mean or median grain size, uniformity or sorting coefficients, percentage of fines, and maximum size), grain density (specific gravity), mineralogical composition (e.g., carbonate content), organic content, color, and other geotechnical properties. The design process will typically be iterative, considering the characteristics of available fill and the expected performance with respect to overall performance objectives. Depending on available material and priorities (e.g., FRM, habitat function, or minimizing maintenance), some trade-offs or adjustment of performance objectives and metrics may be appropriate at the detailed design phase. For example, in the Deltaport East Causeway barrier islands project (see Deltaport East Causeway Barrier Island Features case study in Section 11.4.1), material used to construct the barrier beaches (predominantly gravel with some coarse sand) was slightly coarser than grain sizes typically required for the target forage fish habitat (coarse sand to pea gravel). Using coarser material provided greater confidence that the beach would remain dynamically stable under storm wave action and maintain FRM function, with some compromise in habitat suitability.

11.5 | Implementation

After tendering is completed and a contract awarded (see Chapter 9, Section 9.6), project preparation and execution begin. Implementation of island construction differs from other previously addressed NNBF because the island is surrounded by water, and this adds an additional component to staging. This section describes the issues and processes that are unique to island features.

11.5.1 Environmental Considerations and Logistical Issues

Island NNBF typically exist in dynamic environments where forces on all sides can erode the feature. Often, the site cannot be isolated from surrounding hydrodynamic conditions (e.g., by dikes) without significant added cost. Depending on energy at the site, sediment losses may need to be factored into the implementation. Effects of multiple processes that degrade the feature may need to be evaluated, including river discharge, tidal currents, storm surge, waves, wind, and vessel wake. In addition, hydraulic conditions will change during the construction process, and the effects of these changes must be considered during the construction phase. For example, restoration of a barrier island will increase tidal currents over the island platform and around the island edges, thus eroding sediment as it is being placed. Therefore, significant room must be permitted for adaptive management during construction, monitoring, and maintenance phases. An experienced contractor is required to manage this type of project, identify change in conditions, and implement proper adaptation to achieve project goals.

Island creation and restoration include a number of construction and logistical challenges. Work often occurs in a highly dynamic and energetic environment, where an island is built from the seabed upward. Knowledge of proper and effective methods is required and includes an extensive risk assessment of the factors that might delay the project or lead to additional costs. Furthermore, relatively simple operations such as transporting land-based equipment or conducting progress surveys become more challenging when working in an unsheltered environment. Here, an understanding of the risks that might affect the planning is critical to successfully construct an island. Also, in addition to knowledge of the handling of sand, an understanding of muddy (e.g., fine or mixed) material, as well as how to create the most suitable habitat conditions, is essential to create the most optimal island that fulfills multiple benefits and truly creates additional value.

11.5.2 Managing Risks and Uncertainties

There is generally less experience with planning and construction of island features compared to other NNBF, such as beaches and dunes and wetlands. The physical and ecological environments are more diverse and variable than most land-based NNBF. This potentially poses increased uncertainty and risk.

These are the main risks and challenges during the construction phase:

1. Changing and unexpected wave, circulation, and sediment transport patterns
2. Managing impacts to ecologically sensitive habitats near the construction site
3. Changes in elevation due to sediment consolidation and compaction
4. Sediment loss due to erosion from the island platform
5. Controlling invasive species
6. Greater potential downtime because of multiple conditions that may stop or slow operations
    a. Do not work in wet season if river discharge is a potential issue.
    b. Do not work during seasons with frequent high-energy storms.
    c. Work in wintertime and cold weather may have added safety impacts and restrictions to personnel as well as impacts due to ice restricting access to the site.
    d. Predetermine environmental windows for all seasons (e.g., prevent harm to birds, fish spawning, sea turtles, and marine mammals) (see "Restrictions in Time Frame for Construction").
7. Managing delays due to greater number and interdependency of phases during island construction (compared to other NNBF)
8. Site conditions not matching initial assumptions (sediment loss rates during excavation and placement, sediment quality and availability, wave climate, and ecological evolution)

Restrictions in Time Frame for Construction

In the United States, the National Oceanic and Atmospheric Administration's National Marine Fisheries Service has issued regional biological opinions, which state that beach nourishment activities are prohibited along the southeast Atlantic coast from May 1 through October 30 to protect nesting sea turtles.

In Canada, DFO recommends timing windows that depend on regional considerations for projects in or around water as a measure to protect fish and fish habitat and to aid compliance with the Fisheries Act and Species at Risk Act.

11.5.3 Preparation and Equipment Selection

The construction of an island feature is a complex operation in which a number of aspects and risks need to be considered to successfully execute such a project. The following parameters require consideration to achieve the most cost-efficient solution:

- Equipment selection
- Availability and location of the borrow area (e.g., sediment, other building material, and other design aspects)
- Working restrictions (logistic bottlenecks)

The effort and the relative cost per unit volume of island construction are largely related to the type and amount of dredging equipment required and the distance of the borrow area (sediment source) from the island project. For example, if the building material is located near the planned island location, a cutter suction dredger might be most cost-effective—if located in relatively sheltered conditions. Alternatively, if the source of the material is located far away from the project site, a trailing suction hopper dredger would be more efficient. Furthermore, the availability and distance of suitable material will partly influence the duration of the execution time as reflected in the time that it takes a dredger to sail there and back with one load of sand. In addition, other aspects of the material source location can influence the choice of equipment (e.g., dredging in deeper or more unsheltered locations imposes another requirement on the dredging equipment).

Compared to beach nourishments, the logistics of constructing an island are typically more complex. For example, on an island there may not be a suitable transport mechanism or lay-down area to transport and stage land-based equipment. Therefore, as shown in Figure 11.3, the first step in construction of an island is to create a body of sand, from which land-based equipment can assist in the construction process. Often, rainbowing, which is the propelling of sand in a high arc, is an efficient way of creating the first part of an island, if the legal framework permits (see Section 11.2.4). Another alternative is to use sediment dredged for navigation purposes. For example, island construction at Round Island in Mississippi, United States, exclusively used material dredged from the adjacent navigation channel, thus significantly reducing costs because excavation costs are covered by the navigation channel maintenance program. However, coordinating navigation dredging projects with NNBF construction projects adds another layer of complexity to sequencing, which may require program managers to investigate beneficial use opportunities.

11.5.4 Sediment Source Considerations

Additional considerations are the sediment volumes, sediment sources (borrow areas), types of sediments, and other materials to be used in the island construction. Placement and building with sand is a process that is reasonably well understood, and it has been applied in a number of projects. The process is more complex if the design of an island also includes the placement of muddy and silty material or rocks. Therefore, islands constructed from sand are more straightforward than those of mixed or muddy and silty material. Finer-grained material is often required for construction of back-bay marshes on islands. Because NNBF islands not only serve as a coastal resilience measure but also create specific habitats, it is essential that the requirements of the various habitats are met (e.g., sediment size and composition or inundation regimes). For example, the compaction of a silt layer after placement can lead to an undesired lowering of the elevation, which alters the inundation period, creating other habitats than expected. Insight into the main design parameters that are required to create these habitat types is essential for successful construction.

The Marker Wadden in the Netherlands is a good example of the construction of a partly muddy island (Figure 11.9) (ecoshape.org 2020). This island group is being dredged by a cutter suction dredger with material from a nearby borrow pit. First, sand-containment berms were constructed, as well as a small marina with a rock revetment. Afterward, the compartments were filled with muddy material until a desired height. The islands are constructed in a freshwater lake environment for the purpose of creating swamp and marsh habitat, functioning as a foraging area for a number of (migratory) bird species.

Figure 11.9. *Marker Wadden*

Source: Courtesy of Natuurmonumenten (Dutch Nature Conservancy)

11.5.5 Sequencing Considerations

Depending on the design requirements and the hydrodynamic conditions, additional protective measures may need to be implemented to prevent erosion during (and after) the construction phase. However, the ability to contain the site during construction may be limited due to significant hydraulic forces that can damage containment structures. In addition, any containment will influence stability of surrounding features and associated habitats.

The placement of material in a high-energy environment can create an obstruction of the flow, which promotes erosion (Figures 11.10 and 11.11, Table 11.3), and standard mitigation tools, such as silt curtains, may not be applicable in high-energy systems. This may lead to erosion of the island under construction or change the erosion sedimentation patterns in the vicinity. Additional mitigation efforts to manage this risk, such as temporary structures or permanent but buried hard structures, may be employed to balance sediment loss with rate of infilling. Numerical modeling can be used to quantify the effect prior to construction (e.g., hydraulic conditions and wave climate).

Figure 11.10. ***Example Construction Phasing***

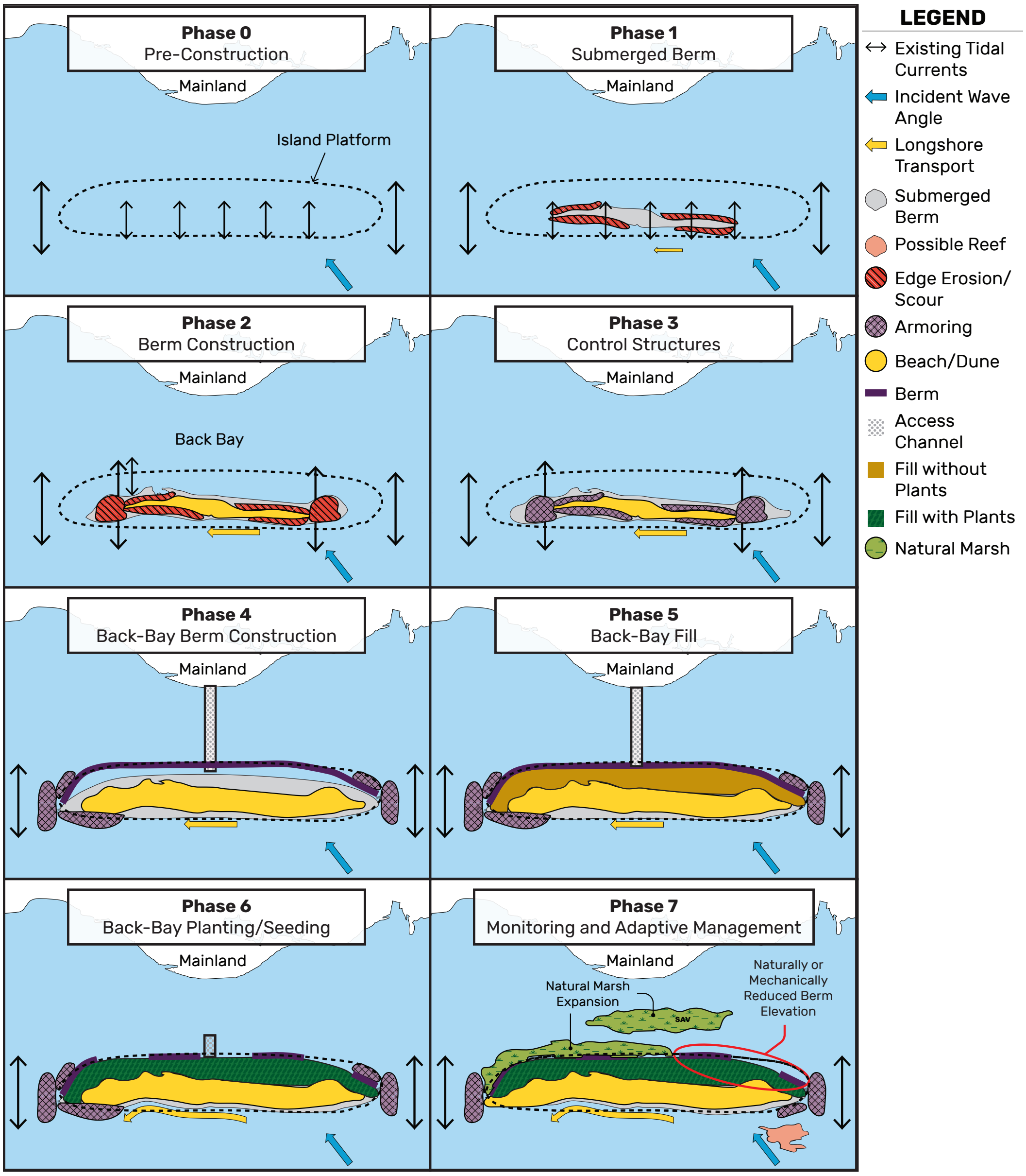
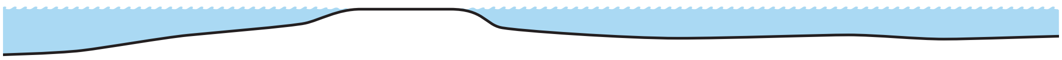


Table 11.3. *Description of Example Construction Phasing in Figure 11.10*

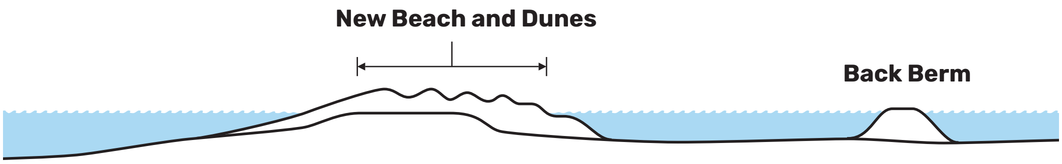
Phase	Action
Phase 0: **Pre-construction**	• Baseline monitoring (e.g., waves, bathymetry, circulation) • Baseline habitat evaluation
Phase 1: **Submerged berm**	• Initial underwater sediment placement on the existing shoal • Monitor hydrodynamic changes • Quantify sediment loss • Monitor surrounding habitat
Phase 2: **Berm (foreshore) construction**	• Construction of foreshore berm • Create back-bay sheltered environment • Monitor hydrodynamic changes • Monitor sediment transport patterns
Phase 3: **Control structures**	• Based on sediment loss, evaluate alternatives for temporary control measures to stabilize the site during construction
Phase 4: **Back-bay berm construction**	• Retention structures to hold fine-grained sediment during back-bay infilling • Create back-bay access, if needed
Phase 5: **Back-bay fill**	• Deliver mixed sand, silt, and clay to back bay • Monitor consolidation • Meet consolidation requirements • Grade for high marsh, low marsh, etc. • Breach berm to permit tidal exchange
Phase 6: **Planting**	• Evaluate water and sediment quality • Assess benefits of planting versus natural colonization • Establish and monitor wetland, upland, and dune plant communities • Evaluate need for protective measures such as wind fence
Phase 7: **Monitoring and adaptive management**	• Based on sediment loss, evaluate alternatives for sustained control measures to stabilize erosion-prone parts of the island • Monitor to develop adaptive management plan focusing on morphology, sustainability, and habitat

Figure 11.11. *Construction Sequence Example: Cross Section*

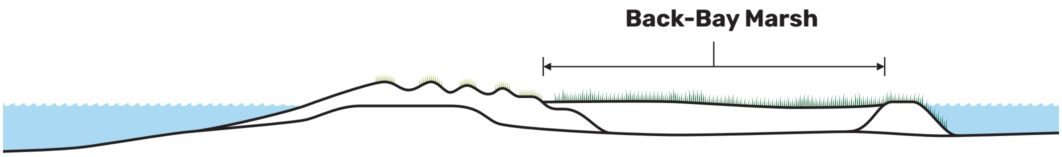
Restoring Barrier Islands



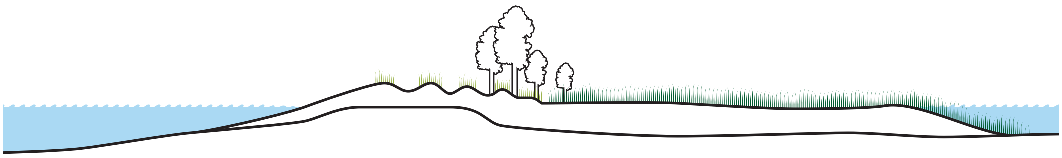
The natural barrier island has eroded away into the form of a sandbar. The protective dunes have disappeared and lack vegetation.



A new beach and dunes are created by placing sand on top of the eroded barrier island. A temporary back berm is installed to contain the back-bay marsh.



The back-bay marsh is created by placing muddy sediment between the barrier island and the back berm. Marsh vegetation and SAV are planted to stabilize the soil.



Mature dunes and mature vegetation stabilize the new barrier island ecosystem, which attracts flora and fauna. The back berm is either removed or erodes naturally.

The occurrence of large storm events can also cause severe damage to the island under construction, leading to project delays and additional costs. A wave climate analysis during the design phase can reduce this risk. Planning critical construction activities during seasons with less storm activity can further reduce the risk of erosion. Also, placing relatively coarse sandy material in the areas where erosion is expected to be most severe is a way to reduce or prevent erosion from occurring. The placement of hard structures is another way of preventing erosion from occurring during and after the construction phase. However, the exact definition of the requirements with respect to the stability of the island is the main driver in determining the mitigation measures to prevent erosion. For example, allowing for a dynamic or gradual erosion of the island may be part of the project design objectives. In this case, less effort is needed to mitigate the risk.

If construction occurs in a sensitive environment, an outward berm can be constructed first to contain or reduce the spreading of fine sediment into the environment, as has been done in the tidal flat construction at the Galgeplaat, the Netherlands (see Figure 11.12) (publicwiki.deltares.nl, n.d.).

Figure 11.12. *Construction at the Galgeplaat (the Netherlands)*

Source: Courtesy of EcoShape/Van Oord

11.5.6 Construction Monitoring and Adaptive Management

Uncertainties associated with island construction are typically greater than those associated with other NNBF because of the numerous, interdependent variables that influence processes in these exposed, high-energy environments. Therefore, monitoring and adaptive management during construction are generally required to ensure that the island is constructed according to design, meets the specifications, and maintains future functionality. Two of the most significant uncertainties during island construction that may require adaptive management are loss of (noncohesive) sediment and the behavior and consolidation of cohesive sediments. A third source of uncertainty that must be addressed in adaptive management but is beyond the scope of these guidelines is construction safety in dynamic open-water locations. Typically, experienced contractors can manage risks to workers and equipment.

A comprehensive monitoring plan should be developed that addresses these and other risks and uncertainties during construction. Bathymetric and elevation surveys can be used to identify the magnitude and location of sediment losses. Current and wave data can identify potential areas of scour. Surveying compaction and consolidation of cohesive sediment can be used during construction to evaluate if the sediment behaves as expected, and if adjustments to design and execution are necessary. For example, if compaction and consolidation are greater than expected, elevations and inundation regimes will be different than design criteria, complicating establishment of vegetation. Additional sediment may be required to ensure the elevation meets design specifications. Similarly, sediment loss due to erosion around the island perimeter during construction may be greater than expected. In both these situations, potential mitigation efforts should be identified a priori in the design phase to ensure rapid response to any unexpected changes. For example, sources for additional sediment or materials for temporary control structures should be identified. As part of the design and contracting processes, responsibilities associated with potential increased costs and schedule changes should also be identified.

Circulation and wave climate will change gradually in response to construction, and these changes may require modifications to subsequent construction phases. Although robust hydrodynamic models may be used as a screening-level approach to support construction planning and sequencing for large projects, model fidelity is often insufficient to quantify changes during construction. Therefore, monitoring data are required to quantify actual conditions and identify any unacceptable sediment losses, risk to ecosystem, or risk to construction staff or equipment. For these conditions, mitigation measures should be undertaken in the field using an iterative monitoring and adaptive management approach.

Islands are particularly vulnerable to erosion after sediment placement but before vegetation is established. Island features are exposed to wind, waves, and currents, which can rapidly move or undermine sediment. One factor that reduces loss of sediment is successful establishment of vegetation as part of the final construction phase. However, issues related to sediment loss from lack of vegetation is an uncertainty that is generally managed post-construction (see Section 11.6).

Monitoring of the island profile elevations and vegetation development should continue before, during, and after planting. Adaptive measures may be required to reduce sediment transport from the island platform. These measures may include fencing or ground cover to reduce eolian transport. Similarly, submerged structural measures may be required to reduce platform sediment loss until SAV or reefs are established.

Construction monitoring and adaptive management are key components to ensure timely and cost-effective completion. In addition, the surrounding environment should be monitored. If sensitive habitats are located near the construction site, turbidity, hydrodynamic conditions, and ecosystem health are typically monitored to manage risks. Protective measures (such as berms to minimize turbidity in back-bay marsh or SAV) can be implemented as part of an adaptive management approach.

11.6 | Monitoring, Maintenance, and Adaptive Management after Construction

Monitoring the island after construction is required to verify performance and develop post-construction adaptive management strategies (see Chapter 7) to maintain ecological and FRM functions. Ongoing monitoring allows iterative modifications to the adaptive management plan to optimize performance. By evaluating and addressing uncertainties, iterative adjustments can be made to the island NNBF to evaluate intended outcomes and inform future island projects.

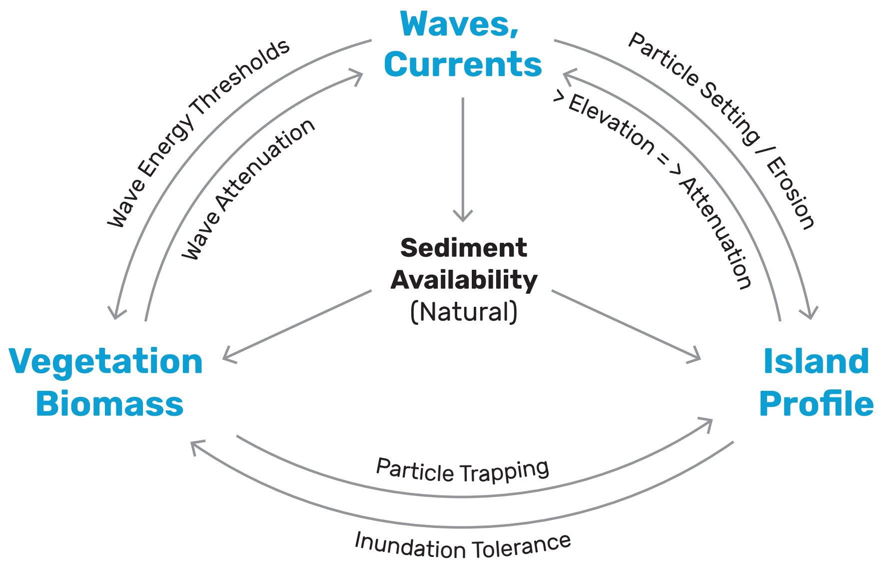
Monitoring and management strategies will be site specific and depend on environmental conditions, objectives, and resources. Depending on monitoring budget, the challenges of monitoring island sites (which may be remote), project objectives, and performance metrics, managers may have to develop monitoring priorities. For example, to evaluate coastal resilience function of an island, a suite of hydrodynamic, ecological, and topographic parameters may be required (see Figure 11.13 in "Simplified Resilience Conceptual Model for Swan Island Restoration Project"). Monitoring for other objectives, such as island benefits for migratory birds and other wildlife, will require information about the variety and density of flora and fauna.

As another example, if the island is eroding at an unacceptable rate, additional monitoring may be required to identify the root causes. Once the causes are identified, alternative solutions can be identified and evaluated. For example, armoring or temporary hard structures may be implemented (Figure 11.10 and Table 11.3). The Deltaport East Causeway (see Deltaport East Causeway Barrier Island Features case study in Section 11.4.1) also demonstrates adaptive solutions that are based on site monitoring. Similar monitoring and adaptive management approaches are applied to evaluate and maintain ecosystem function. For example, elevations change over time, and unwanted vegetation may be introduced because inundation or other processes are not properly balanced. Therefore, regrading and replanting may be required. Experimental approaches (such as pilot studies) may be beneficial to determining proper long-term habitat maintenance strategies. Finally, adaptive management and maintenance requires responsible parties to be identified up front in contracts or other planning documents (e.g., monitoring and adaptive management plans).

Simplified Resilience Conceptual Model for Swan Island Restoration Project (Maryland, United States)

To evaluate the coastal resilience performance of Swan Island in Chesapeake Bay, an understanding of the hydrodynamic processes, sediment movement processes, and ecological responses are required. Through a series of iterative group-mediated workshops, the project team identified a simplified conceptual model that represents the required parameters to understand and quantify island resilience performance. Called the *simplified resilience conceptual model*, these parameters and the relationships between them are shown in Figure 11.13. Water movement (waves and currents), plant biomass, elevation (island profile and nearshore bathymetry), and sediment supply represent the measured system parameters collected by the project team (Davis et al., forthcoming; Herman et al. 2020). Further, a monitoring and adaptive management plan developed to track progress will ensure project goals are met. This living document serves as a blueprint for the project team and codifies all aspects of the monitoring approach (what, how, and how often data are collected), reporting and data management, roles and responsibilities, performance metrics, and decision thresholds for adaptive management action (Herman et al., forthcoming).

Figure 11.13. *Simplified Resilience Conceptual Model for Swan Island Restoration Project*



Note: This model was developed to capture important system-level components that drive the response to restoration and will capture the overall resilience of the system.

Source: Adapted from Herman et al. 2020

11.7 | Gaps and Future Directions

The following gaps and corresponding proposed future directions would support broader application of island NNBF:

- **Use of multiple habitat types.** Research on the potential combined, complementary effect of multiple habitat types from offshore to onshore in terms of both short-term and long-term protective benefits (Lopez 2009; Guannel et al. 2016; Arkema et al. 2017) is required to justify larger NNBF projects such as islands. This would emphasize a systems approach to implementing NNBF, rather than a single-habitat approach.
- **Island area of influence.** Quantitative studies on island areas of influence are required to address habitat switching issues and potential impacts of island restoration. Short-term impacts should be balanced against long-term outcomes and consider a systems approach. This issue is presently one of the primary regulatory hurdles to NNBF implementation.

- **Innovation.** Innovative practices and field experimentation (learning by doing) should be encouraged. Risks can be managed to assure that experiments will not cause irreparable damage. Therefore, innovative practices can be tested and demonstrated. Successful practices can then be broadly applied at other sites. The concept of living laboratories (de Groot and van Duin 2013; van Eekelen et al. 2017) provides an ideal means to improve understanding of island systems while pushing innovation and implementation that improve coastal resilience and ecosystem diversity.
- **Regional case studies to inform island feasibility.** Although the basic dynamics of island evolution are understood, the highly variable conditions in which island NNBF can provide coastal resilience benefits require more regional case studies in a variety of environmental conditions (e.g., circulation, climate, waves, tidal range, sediment type, geomorphology, dimensions, native habitats). With a broad range of case studies, design teams can select relevant analogues for their site. These case studies will illustrate when island features are feasible and support optimization of design, implementation, and maintenance approaches.

11.8 | References

Arkema, K. K., G. Guannel, G. Verutes, S. A. Wood, A. Guerry, M. Ruckelshaus, P. Kareiva, M. Lacayo, and J. M. Silver. 2013. “Coastal Habitats Shield People and Property from Sea-Level Rise and Storms.” *Nature Climate Change* 3 (10): 913–918.

Arkema, K., R. Griffin, S. Maldonado, J. Silver, J. Suckale, and A. D. Guerry. 2017. “Linking Social, Ecological, and Physical Science to Advance Natural and Nature-Based Protection for Coastal Communities.” *Annals of the New York Academy of Sciences* 1399 (1): 5–26. doi:10.1111/nyas.13322.

Baker, S., M. Sturm, B. Pinchin, and A. Cornett. 2016. “Physical Modelling of the Lakeview Waterfront Connection Project.” Paper presented at 6th International Conference on the Application of Physical Modelling in Coastal and Port Engineering and Science, Ottawa, ON, May 2016.

Barnard, P. L., M. van Ormondt, L. H. Erikson, J. Eshleman, C. Hapke, P. Ruggiero, P. N. Adams, and A. C. Foxgrover. 2014. “Development of the Coastal Storm Modeling System (CoSMoS) for Predicting the Impact of Storms on High-Energy, Active-Margin Coasts.” *Natural Hazards* 74 (2): 1095–1125.

Blama, R. N. 2012. *Barren Island Dredged Material Placement for Regional Sediment Management*. ERDC/CHL CHETN-XIV-21. Vicksburg, MS: U.S. Army Corp of Engineers.

Brantley, S. T., S. N. Bissett, D. R. Young, C. W. Wolner, and L. J. Moore. 2014. “Barrier Island Morphology and Sediment Characteristics Affect the Recovery of Dune Building Grasses Following Storm-Induced Overwash.” *PLOS ONE* 9 (8): e104747.

Bridges, T. S., K. A. Burks-Copes, M. E. Bates, Z. A. Collier, J. C. Fischenich, C. D. Piercy, E. J. Russo, et al. 2015. *Use of Natural and Nature-Based Features (NNBF) for Coastal Resilience*. ERDC SR-15-1. Vicksburg, MS: U.S. Army Engineer Research and Development Center, Environmental Laboratory, Coastal and Hydraulics Laboratory. http://hdl.handle.net/11681/19336.

Bros, W. 2007. "Sustainable Dredging Program on the Lower Fraser River." MBA thesis, Simon Fraser University.

Carter, R. W. G., D. L. Forbes, S. C. Jennings, J. D. Orford, J. Shaw, and R. B. Taylor. 1989. "Barrier and Lagoon Coast Evolution under Differing Relative Sea-Level Regimes: Examples from Ireland and Nova Scotia." *Marine Geology* 88 (3–4): 221–242.

CECI (Coastal Engineering Consultants Inc.). 2013. *NRDA Caillou Lake Headlands Beach and Dune Restoration (TE-100) Final Design Report*. Prepared for Coastal Protection and Restoration Authority of Louisiana. Baton Rouge, LA: Coastal Engineering Consultants.

CIRIA (Construction Industry Research and Information Association). 2010. *Beach Management Manual*. Second Edition. London: Construction Industry Research and Information Association.

CIRIA, CUR, and CETMEF (Construction Industry Research and Information Association, CUR, and CETMEF). 2007. *The Rock Manual: The Use of Rock in Hydraulic Engineering*. Second Edition. Report C683. London: CIRIA.

Costanza, R., O. Pe´rez-Maqueo, M. L. Martinez, P. Sutton, S. J Anderson, K. Mulder, 2008. "The Value of Coastal Wetlands for Hurricane Protection." *AMBIO: A Journal of the Human Environment* 37 (4): 241–248.

CPRA (Coastal Protection and Restoration Authority). 2007. *Integrated Ecosystem Restoration and Hurricane Protection: Louisiana's Comprehensive Master Plan for a Sustainable Coast*. Baton Rouge, LA: Coastal Protection and Restoration Authority.

Davis, J., P. Whitfield, D. Szimanski, B. R. Golden, M. Whitbeck, J. Gailani, B. Herman, A. Tritinger, S. C. Dillion, and J. King. Forthcoming. "A Framework for Evaluating Island Restoration Performance: A Case Study from the Chesapeake Bay." In *Integrated Environmental Assessment and Management*. Special Series: Incorporating Nature-Based Solutions to the Built Environment. https://doi.org/10.1002/ieam.4437.

de Groot, A. V., and W. E. van Duin. 2013. *Best Practices for Creating New Salt Marshes in a Saline Estuarine Setting, a Literature Review*. IMARES Report No. C145/12. Wageningen: IMARES. https://edepot.wur.nl/248715.

Deltares and Delft Hydraulics. 2008. *Dredging and Land Reclamation Technical Manual*. Prepared for Strategic Projects Directorate, Ministry of Works, Kingdom of Bahrain. Delft, NL: Deltares.

Duck, R. W., and J. F. da Silva. 2012. "Coastal Lagoons and Their Evolution: A Hydromorphological Perspective." *Estuarine, Coastal and Shelf Science* 110: 2–14.

ecoshape.org. 2020. Marker Wadden KIMA. *EcoShape*. https://www.ecoshape.org/en/projects/marker-wadden/.

Elliott, M., J. W. Day, R. Ramachandran, and E. Wolanski. 2019. "A Synthesis: What Is the Future for Coasts, Estuaries, Deltas and Other Transitional Habitats in 2050 and Beyond?" *Coasts and Estuaries: The Future*. Edited by E. Wolanski, J. Day, M. Elliott, and R. Ramesh. Cambridge: Elsevier.

Erwin, M. E., D. F. Brinker, B. D. Watts, G. R. Costanzo, and D. D. Morton. 2011. "Islands at Bay: Rising Seas, Eroding Islands, and Waterbird Habitat Loss in Chesapeake Bay (USA)." *Journal of Coastal Conservation* 15: 51–60. https://doi.org/10.1007/s11852-010-0119-y.

FEMA (Federal Emergency Management Agency). 2005. *Final Draft Guidelines for Coastal Flood Hazard Analysis and Mapping for the Pacific Coast of the United States*. A Joint Project by FEMA Region IX, FEMA Region X, FEMA Headquarters. West Sacramento, CA: Northwest Hydraulic Consultants.

FEMA. 2016. *Guidance for Flood Risk Analysis and Mapping: Coastal General Study Considerations*. Washington, DC: Federal Emergency Management Agency.

Forbes, D., G. Parkes, G. Manson, and L. Ketch. 2004. "Storms and Shoreline Retreat in the Southern Gulf of St. Lawrence." *Marine Geology* 210 (1-4): 169–204.

Fullarton, M., R. B. Nairn, C. J. Petykowski, J. P. Selegean, and L. T. Barber. 2006. "Cat Island Restoration, Green Bay." Paper presented at Coastal Engineering 2006 – Proceedings of the 30th International Conference, San Diego, CA, September 2006.

Garrison, J. R., J. Williams, S. P. Miller, E. T. Weber, G. McMechan, and X. Zeng. 2010. "Ground-Penetrating Radar Study of North Padre Island: Implications for Barrier Island Internal Architecture, Model for Growth of Progradational Microtidal Barrier Islands, and Gulf of Mexico Sea-Level Cyclicity." *Journal of Sedimentary Research* 80 (4): 303–319.

Gilmore, G. R. 1995. "Environmental and Biogeographic Factors Influencing Ichthyofaunal Diversity: Indian River Lagoon." *Bulletin of Marine Science* 57(1):153–170.

Goda, Y., T. Takayama, and T. Suzuki. 1978. "Diffraction Diagrams for Directional Random Waves." *Coastal Engineering Proceedings* 1 (16): 35.

Grouthes, T. M., and K. W. Able. 2016. *Assessment of Dredge Material Island Shorelines as Habitat for Juvenile Summer Flounder and Other Fishes*. Final Report to the U.S. Army Corp of Engineers Navigation Section, Baltimore District. Baltimore: U.S. Army Corps of Engineers.

Grzegorzewski, A. S., M. A. Cialone, and T. V. Wamsley. 2011. "Interaction of Barrier Islands and Storms: Implications for Flood Risk Reduction in Louisiana and Mississippi." *Journal of Coastal Research* 59 (59): 156–164.

Guannel, G., K. Arkema, P. Ruggiero, and G. Verutes. 2016. "The Power of Three: Coral Reefs, Seagrasses and Mangroves Protect Coastal Regions and Increase Their Resilience." *PLOS ONE* 11 (7): e0158094. https://doi.org/10.1371/journal.pone.0158094.

Hequette, A., and M. Ruz. 1991. “Spit and Barrier Island Migration in the Southeastern Canadian Beaufort Sea.” *Journal of Coastal Research* 7 (3): 677–698.

Herman, B., P.E. Whitfield, J. Davis, D. Szimanski, R. Raves Golden, A. Tritinger, J. Gailani, T. M. Swannack, and J. K. King. Forthcoming. *Swan Island Ecosystem Restoration Monitoring and Adaptive Management Plan*.

Herman, B., T. M. Swannack, J. K. King, P. E. Whitfield, J. Davis, D. Szimanski, D. Bryant, and J. Gailani. 2020. “Ecological Habitat Modeling Workshop.” ERDC/EL SR-20-1. Paper presented at the Proceedings from the U.S. Army Corps of Engineers and the National Oceanic and Atmospheric Administration – National Ocean Service, Cambridge, MD, April 2019.

Hughes, S. A. 1993. *Physical Models and Laboratory Techniques in Coastal Engineering*. Advanced Series on Ocean Engineering: Volume 7. Singapore: World Scientific. https://doi.org/10.1142/2154.

James, T. S., J. A. Henton, L. J. Leonard, A. Darlington, D. L. Forbes, and M. Craymer. 2014. *Relative Sea-Level Projections in Canada and the Adjacent Mainland United States*. Geological Survey of Canada Open File 7737. Ottawa, ON: Natural Resources Canada.

Jones, R. R., and D. A. Garza. 1998. “Co-Management of the Razor Clam (*Siliqua patula*) Fishery at Haida Gwaii, British Columbia, Canada.” In *Proceedings of the North Pacific Symposium on Invertebrate Stock Assessment and Management*. Edited by G. S. Jamieson and A. Campbell. *Canadian Special Publication of Fisheries and Aquatic Sciences* 125: 385–391.

Kamphuis, J. W. 2010. *Introduction to Coastal Engineering and Management*. Second Edition. Advanced Series on Ocean Engineering: Volume 30. Singapore: World Scientific.

Kirwan, M. L., D. C. Walters, W. G. Reay, and J. A. Carr. 2016. “Sea Level Driven Marsh Expansion in a Coupled Model of Marsh Erosion and Migration.” *Journal of Geophysical Research* 43 (9): 4366–4373.

Knox, P., and A. Rayner. 2016. *3D Physical Model Study of a Shoreline Improvement Scheme for Euclid, Ohio, USA*. Technical Report OCRE-TR-2016-012. Ottawa, ON: National Research Council Canada.

Leatherman, S. P. 1976. “Barrier Island Dynamics: Overwash Processes and Eolian Transport.” Paper presented at the 15th International Conference on Coastal Engineering, Honolulu, HI, July 1976.

Lewis, D. A., J. A. G. Cooper, and O. H. Pilkey. 2005. “Fetch Limited Barrier Islands of Chesapeake Bay and Delaware Bay.” *Southeastern Geology* 44 (1): 1–17.

Lopez, J. A. 2009. “The Multiple Lines of Defense Strategy to Sustain Coastal Louisiana.” *Journal of Coastal Research* 54 (10054): 186–197. https://doi.org/10.2112/SI54-020.1.

McCall, R., G. Masselink, T. Poate, J. Roelvink, and L. Almeida. 2015. “Modelling the Morphodynamics of Gravel Beaches During Storms with XBeach-G.” *Coastal Engineering* 103: 52–66.

Narayan, S., M. W. Beck, P. Wilson, C. J. Thomas, A. Guerrero, C. C. Shepard, B. G. Reguero, G. Franco. J. C. Ingram, and D. Trespalacios. 2017. “The Value of Coastal Wetlands for Flood Damage Reduction in the Northeastern USA.” *Scientific Reports* 7(1):9463. https://doi.org/10.1038/s41598-017-09269-z.

Narayan, S., M. W. Beck, B. G. Reguero, I. J. Losada, B. van Wesenbeeck, N. Pontee, J. N. Sanchirico, J. C. Ingram, G. M. Lange, and K. A. Burkes-Copes. 2016. “Effectiveness, Costs and Coastal Protection Benefits of Natural and Nature-Based Defences.” *PLOS ONE* 11 (5): e0154735. https://doi.org/10.1371/journal.pone.0154735.

Oertel, G. F. 1985. “The Barrier Island System.” *Marine Geology* 63: 1–18.

Pilkey, O. H., J. A. G. Cooper, and D. A. Lewis. 2009. “Global Distribution and Geomorphology of Fetch-Limited Barrier Islands.” *Journal of Coastal Research* 25 (4): 819–837.

publicwiki.deltares.nl. n.d. Tidal Flat Nourishment – Galgeplatt, NL. *Building with Nature Guideline*. https://publicwiki.deltares.nl/display/BTG/Tidal+flat+nourishment+-+Galgeplaat%2C+NL.

Reguero, B. G., M. W. Beck, D. N. Bresch, J. Calil, and I. Meliane. 2018. “Comparing the Cost Effectiveness of Nature Based and Coastal Adaptation: A Case Study from the Gulf Coast of the United States.” *PLOS ONE* 13 (4): e0192132. https://doi.org/10.1371/journal.pone.0192132.

Resio, D. T., and J. J. Westerink. 2008. Modeling the Physics of Storm Surges.” *Physics Today* 61 (9): 33.

Ricklefs, R. E., and I. J. Lovette. 1999. “The Roles of Island Area *per se* and Habitat Diversity in the Species–Area Relationships of Four Lesser Antillean Faunal Groups.” *Journal of Animal Ecology* 68 (6): 1142–1160.

Riggs, S. R., S. J. Culver, D. V. Ames, D. J. Mallison, D. R. Corbett, and J. P. Walsh. 2008. *North Carolina’s Coasts in Crisis: A Vision for the Future*. A White Paper by the Members of the North Carolina Coastal Geology Cooperative Research Program. Greenville, NC: East Carolina University.

Roelvink, D., A. Reniers, A. P. Van Dongeren, J. V. T. de Vries, R. McCall, and J. Lescinski. 2009. “Modelling Storm Impacts on Beaches, Dunes and Barrier Islands.” *Coastal Engineering* 56 (11-12): 1133–1152.

Rupprecht, F., I. Möller, M. Paul, M. Kudella, T. Spencer, B. K. Van Wesenbeeck, G. Wolters, et al. 2017. “Vegetation-Wave Interactions in Salt Marshes under Storm Surge Conditions.” *Ecological Engineering* 100: 301–315.

Schupp, C. A., N. T. Winn, T. L. Pearl, J. P. Kumer, T. J. Carruthers, and C. S. Zimmerman. 2013. “Restoration of Overwash Processes Creates Piping Plover (*Charadrius melodus*) habitat on a barrier island (Assateague Island, Maryland).” *Estuarine, Coastal and Shelf Science* 116: 11–20.

Smith, L., P. Cornillon, D. Rudnickas, and C. B. Mouw. 2019. "Evidence of Environmental Changes Caused by Chinese Island-Building." *Scientific Reports* 9 (1): 5295. https://doi.org/10.1038/s41598-019-41659-3.

Stallins, J. A. 2005. "Stability Domains in Barrier Island Dune Systems." *Ecological Complexity* 2 (4): 410–430. https://doi.org/10.1016/j.ecocom.2005.04.011.

Stutz, M. L., and O. H. Pilkey. 2002. "Global Distribution and Morphology of Deltaic Barrier Island Systems." *Journal of Coastal Research* 36 (10036): 694–707. https://doi.org/10.2112/1551-5036-36.sp1.694.

Stutz, M. L., and O. H. Pilkey. 2011. ""Open-Ocean Barrier Islands: Global Influence of Climatic Oceanographic and Depositional Settings." *Journal of Coastal Research* 27 (2): 207–222. https://doi.org/10.2112/09-1190.1.

United Nations. 2015. *Sendai Index for Disaster Risk Reduction 2015–2030*. Geneva: The United Nations for Disaster Risk Reduction.

USACE (U.S. Army Corps of Engineers). 2002. *Coastal Engineering Manual*. EM 1110-2-1100. Vicksburg, MS: U.S. Army Corps of Engineers, Engineer Research and Development Center.

van Eekelen, E. M. M., L. Sittoni, F. van der Goot, H. E. Nieboer, M. J. Baptist, J. Boer, and F. H. Tonneijck. 2017. "The Living Lab for Mud: Integrated Sediment Management based on Building with Nature Concepts." Paper presented at Central Dredging Association (CEDA) Dredging Days, Rotterdam, NL, November 2017. https://www.ecoshape.org/app/uploads/sites/2/2017/11/Ceda-2017-paper-Van-Eekelen-Sittoni-et-al-THE-LIVING-LAB-FOR-MUD-INTEGRATED-SEDIMENT-MANAGEMENT-BASED-ON-BUILDING-WITH-NATURE-CONCEPTS.pdf.

Walters, D., L. J. Moore, O. D. Vinent, S. Fagherazzi, and G. Mariotti. 2014. "Interactions between Barrier Islands and Backbarrier Marshes Affect Island System Response to Sea Level Rise: Insights from a Coupled Model." *Journal of Geophysical Research: Earth Surface* 119 (9): 2013–2031.

Wamsley, T. V., M. A. Cialone, J. M. Smith, B. Z. Ebersole, and A. S. Grzegorzewski. 2009. "Influence of Landscape Restoration and Degradation on Storm Surge and Waves in Southern Louisiana." *Natural Hazards* 51: 207–224.

Well, J. T., and J. M. Coleman. 1985. *Deltaic Morphology and Sedimentology with Special Reference to the Indus River Delta*. Technical Report Number 424. Baton Rouge, LA: Coastal Studies Institute, Louisiana State University.

Wray, R. D., S. P. Leatherman, and R. J. Nicholls. 1995. "Historic and Future Land Loss for Upland and Marsh Islands in the Chesapeake Bay, Maryland, USA." *Journal of Coastal Research* 11 (4): 1195–1203.

Works Consulted

Adams, M. A., and I. W. Whyte. 1990. *Fish Habitat Enhancement: A Manual for Freshwater, Estuarine, and Marine Habitats*. Department of Fisheries and Oceans, Canada and Envirowest Environmental Consultants. Vancouver, BC: Minister of Supply and Services.

Barbosa, S. M., and M. E. Silva. 2009. "Low-Frequency Sea-Level Change in Chesapeake Bay: Changing Seasonality and Long-Term Trends." *Estuarine, Coastal Shelf Science* 83 (1): 30–38.

Caro, R. A. 1974. *The Power Broker: Robert Moses and the Fall of New York*. New York: Knopf.

Environmental Assessment Maintenance Dredging Sinepuxent Bay and Isle of Wight Bay Federal Navigation Channel Project. January 2014. Ocean City, Worcestor County MD.

Environmental Assessment Maintenance Dredging Susquehanna River Federal Navigation Channel Project. January 2013, Havre de Grace, Harford County, MD.

Environmental Assessment Maintenance Dredging Twitch Cove and Big Thorofare Federal Navigation Channel Project. December 2015. Somerset County, MD.

EWN (Engineering with Nature). 2018. *Strategic Plan 2018–2023: Expanding Implementation*. Vicksburg, MS: U.S. Army Corps of Engineers.

Farley, P. 1923. "Coney Island Public Beach and Boardwalk Improvements." Paper 136. *The Municipal Engineers Journal* 9 (4).

Grossman, D. H. 1998. *International Classification of Ecological Communities: Terrestrial Vegetation of the United States*. Arlington, VA: Nature Conservancy.

Kearney, M. S., and J. C. Stevenson. 1991. "Island Land Loss and Marsh Vertical Accretion Rate Evidence for Historical Sea-Level Changes in Chesapeake Bay." *Journal of Coastal Research* 7 (2): 403–415.

Kraus, N. C., and K. Hayashi. 2004. "Numerical Morphologic Model of Barrier Island Breaching." Paper presented at Coastal Engineering 2004 – Proceedings of the 29th International Conference, National Civil Engineering Laboratory, Lisbon, PT, September 2004.

Laczo, T. D., M. L. Gomez, and R. N. Blama. 2013. *Regional Sediment Management for Atlantic Coast of Maryland and Assateague Island Seashore (Assateague By-Pass Project)*. ERDC/CHL CHETN-XIV-35. Vicksburg, MS: U.S. Army Corps of Engineers.

Mangor, K., I. Broker, and D. Haslov. 2008. "Waterfront Developments in Harmony with Nature." *Terra et Aqua* 111: 21–30.

MDE (Maryland Department of the Environment). 2017. *Innovative Reuse and Beneficial Use of Dredged Material Guidance Document*. Baltimore: MDE.

National Research Council. 1995. *Beach Nourishment and Design*. Washington, DC: National Academy of Sciences.

Shepard, F. P. 1937. “Revised Classification of Marine Shorelines.” *The Journal of Geology* 45 (6): 602–624.

Shepard, F. P. 1948. *Submarine Geology*. New York: Harper.

Shepard, F. P. 1973. *Submarine Geology*. New York: Harper.

Simpson, D., M. Wray, J. Houghton, and J. Klekotka. 2007. “Mixed Sand and Gravel Beach Design and Construction for Habitat Restoration.” Paper presented at the Coastal Sediments 2007 Conference, New Orleans, LA, May 2007.

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