

Memorandum – Coastal Engineering Review Managing Dune Systems TAR 22510

28 November 2023

INTRODUCTION AND TAR REQUEST

The National Park Service (NPS) has used various dune management strategies, including construction of high-elevation dune features, planting dune grass for stabilization, and multiple configurations of fencing. As the dunes were built, overwhelmed by storms, knocked down, and then rebuilt, it became obvious that artificial dune systems often failed to prevent significant facility and infrastructure damage. These features were also impacting barrier island geomorphic processes.

Historic knowledge from new research and NPS experience at several national seashores along the east coast indicated that building and maintaining artificial dunes was accelerating erosion of the foreshore (Godfrey and Godfrey 1976). The National Park Service also learned that the artificial dunes constructed to protect upland infrastructure could narrow the existing beach. At Assateague State Park, beach widths between the dune toe and the high tide line ranged from 6 to 25 meters between 1998 and 2005. Just north of Assateague State Park at Assateague Island National Seashore (ASIS), there are no maintained dunes, and the beach ranges from 150 to 250 meters wide. There is significantly less infrastructure in this area, resulting in less foot traffic over the dunes and allowing them to naturally roll over.

After major coastal storm events at ASIS in 1998 and 2000, ASIS decided to modify its approach to dune management and constructed an *emergency storm berm*, or high dune, to reduce the likelihood of an island breach. After several years, portions of the dunes were lowered by the National Park Service to allow natural overwash to occur to increase the natural buffering capacity of the barrier island and restore piping plover habitat. In other locations, a modified dune or berm was established at a target elevation that would prohibit overwash during normal lunar high tides and minor coastal storms but allow overwash during larger weather events. It is believed this overwash process is critical to maintaining the resiliency of the barrier island. Based on lessons learned and current research on barrier island geomorphology, new guidance is needed to better manage and preserve dune systems within NPS coastal units.

This memo provides an overview of the most current dune management strategies. It includes a brief review of variables that impact the health of a dune system and standard dune management strategies, a discussion on the use of coastal modeling to better manage dune systems, and considerations for future dune management.

To address specific concerns related to ASIS, this memo will use ASIS as an example and develop a site-specific plan.

Dune System Variables

Dunes protect the upland and low-lying backshore areas from coastal storm events by preventing or reducing flooding, breaking waves, and acting as a sand storage area (UCONN 2023). They are important coastal features, acting as a buffer between the water's edge and inland areas, as well as providing critical habitat for various flora and fauna (Broome 2015).

Typically, in coastal areas where dune systems have not been impacted by development, a healthy system will include a primary dune (also known as a foredune) and a secondary dune. An incipient foredune (also known as an embryo dune) may also be present (NSW 2001). These features are defined below.

- **Incipient foredune (or embryo dune).** These are the first dunes to form. They begin to form above the reach of the highest tide's high-water mark (also known as the spring high tide mark) due to the presence of preliminary vegetation such as beach grass, debris such as driftwood, or seaweed (Sloss et al. 2012a).
- **Primary dune (or foredune).** A continuous mound of sand that runs parallel to the shore. The primary dune is relatively stable but may be impacted by larger storms or human activity. Woody vegetation or shrubs may colonize on the landward side of the primary dune (Sloss et al. 2012a).
- **Secondary dune.** An area located landward of the primary dune where trees or coastal forests may start to form (NSW 2001). These trees or coastal forests may be referred to as "tertiary vegetation."

Figure 1 shows some of these features as they occur on Assateague Island. Sand from the shoreface is transported and caught along the preliminary vegetation or debris where the incipient foredune begins to form. These incipient foredunes grow in size until primary dunes are formed. Overwash occurs during storm events, depositing sediment landward of the dunes where tertiary vegetation forms.

Several variables can impact the health of a dune system. These variables include but are not limited to the supply and type of sediment available, sediment transport, vegetation, beach and nearshore characteristics, wind and wave characteristics, water level variations including frequency of high-water events/storms and tides, sea level rise (SLR), dune height, width, slope (dune geometry), and human activity (table 1).

Figure 1. Natural Dune System along Assateague Island (Schupp 2013, Figure 9)

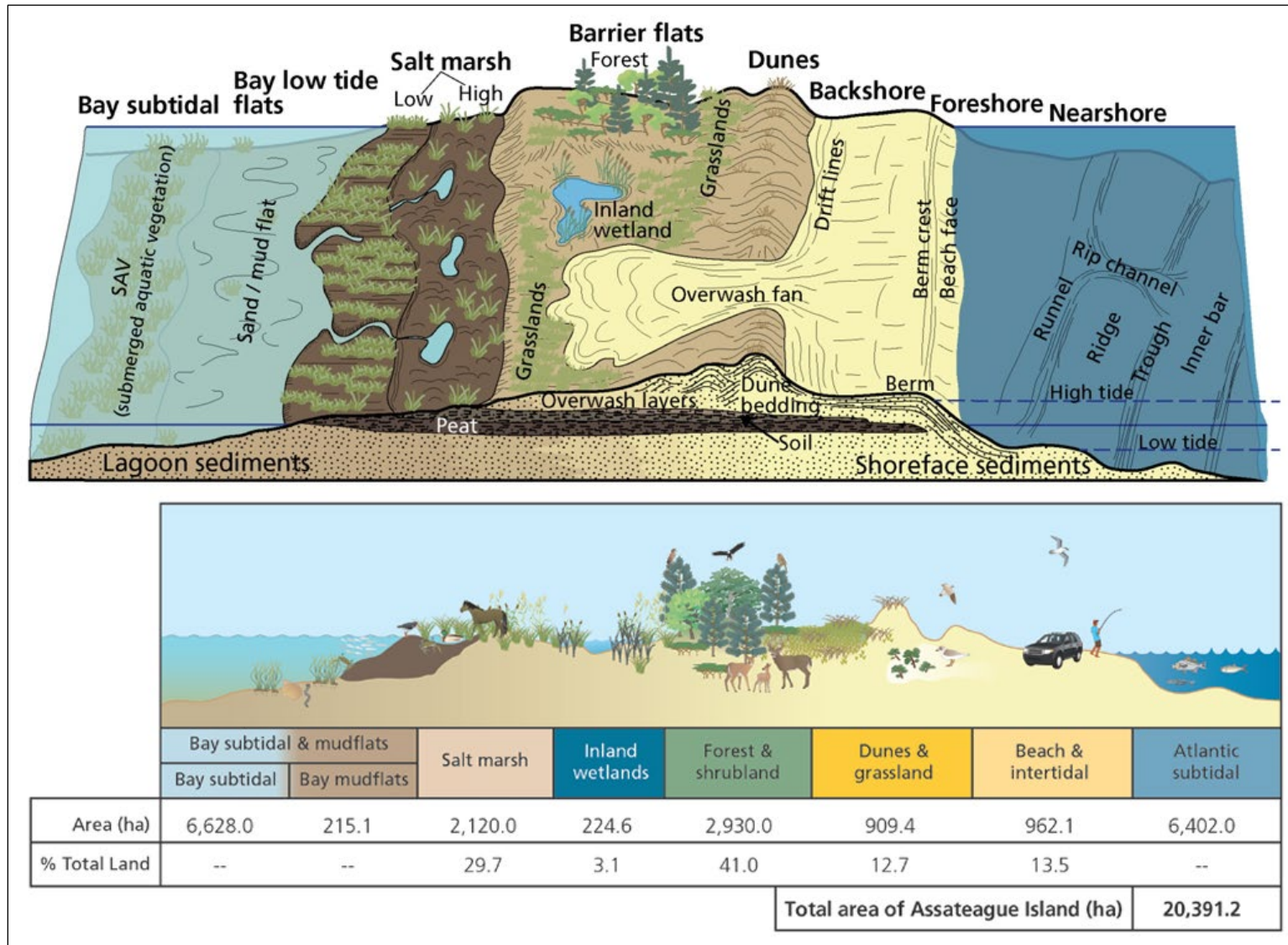


Table 1. Dune System Variables

System Variable	Subcategory	Impact(s) to Dune System
Sediment	Supply	Sediment supply from the beach to the back-beach environment is a function of sediment transport in the nearshore environment and is influenced by winds, waves, tidal range, grain size, and beach type.
Sediment	Transport	In the coastal zone, offshore sand may be transported to the beach by waves and currents. Once it reaches the beach, it may be transported landward by onshore winds until the wind speed drops and does not have enough energy to carry a given sand grain. This often occurs when it reaches an obstacle, such as vegetation or debris, and falls out of the system, forming a dune (Broome 2015). In addition, offshore bars also play a role in sediment transport to the beach face and dunes. Offshore bars will affect the sediment dynamics in the area that shape the beach and dune profiles.
Vegetation	Dune formation	Plants are the most common obstacle that can reduce wind speed and trap sand for dune formation (Sloss et al. 2012b). Without vegetation, wind blowing onshore will cause sand to continue to migrate inland and off the beach area, and wind blowing offshore would cause sand to be blown back to the intertidal area.
Vegetation	Zones	There are three main zones of dune vegetation Sloss et al. 2012a). The primary vegetation zone typically consists of beach grasses, which are tolerant to inundation by saltwater and sand blast from strong winds. Primary vegetation is typically found in the incipient dune area (figure 1). The secondary vegetation zone usually establishes itself on the primary dune and consists of shrubs or woodland plants. The tertiary vegetation zone usually consists of coastal forest plants, including stunted trees and shrubs, and usually establishes itself in the secondary dune area. In addition, on Assateague Island, salt marsh in the bayshore area plays an important role by capturing overwashed or aeolian sand.
Beach and nearshore characteristics	Bathymetry and topography	Bathymetry and topography heavily influence waves and coastal circulation and therefore determine where and how sediment is transported and dictate where vegetation grows. Nearby landforms or engineered structures may trap sediment causing some beach and dune systems to grow and others to shrink (Slovinsky 2021).

System Variable	Subcategory	Impact(s) to Dune System
Wind and wave characteristics	Seasonal transformations	Beaches and dunes are typically subject to seasonal transformations along the cross-shore profile due to changes in wind and wave characteristics. In the summertime, winds and waves are gentler. Waves tend to transport sediment on shore during summer months, and the beach develops a wide berm with taller, more established incipient dunes that ultimately develop into well-vegetated primary dunes. The length of time it takes for the well-vegetated primary dunes to develop depends on several factors, and it may happen quickly or take several seasons. Areas with wider beaches may experience less dune erosion during a coastal storm (Itzkin et al. 2021) as the beach absorbs wave energies before they impact the dune. Beginning in the fall as the weather gets stormier, wind directions change, and wave heights increase. This may cause rip currents that create scarps in the shoreline, which impacts offshore bar formation. During the fall and winter seasons, the beach berm and dunes typically erode, and sand is pulled offshore, resulting in a flatter more concave beach with more exposed dunes (Slovinsky 2021).
Wind and wave characteristics	Erosion	Short-term erosion is typically caused by storms and may impact dunes by leaving scarps, or vertical drops in the front of the dune, or by overwashing (Slovinsky 2021). Dunes may naturally recover after a short-term erosion event, but the process may take several seasons and could be compounded by multiple storm events. Long-term erosion continues over multiple years and is likely caused by multiple factors. This erosion is likely to continue without changes in ongoing processes.
Water level	Tidal fluctuations	Typical tidal fluctuations are a primary driver for coastal circulation and therefore have a high influence on sediment transport along beaches, which impact dune formation.
Water level	High-water events	High-water events include both natural disaster-type events, such as hurricanes and large nor'easters, and lesser storms. During lower water levels, waves tend to break on the beach or the berm, but under a higher water event, storm waves break further up the beach, increasing the potential for dunes to be eroded or overwashed (NSW 2001).
Water level	Sea level rise	SLR is a long-term increase in water levels that is projected to continue and likely increase in rate in the future (Sweet et al. 2022). In many areas, coasts are unable to adjust to SLR and are experiencing increased erosion. Increases in overwash due to SLR on barrier islands cause them to migrate landward, generally through the processes of shoreline retreat. It may also cause island widening, island build-up, and mainland retreat (Sloss et al. 2012a).

System Variable	Subcategory	Impact(s) to Dune System
Dune geometry	Height, width, and slope	Dune geometry is directly related to the protection level it provides. The taller the dune is and the more sand reserve in the primary dune, the more protection it will offer during storm events. Dunes can break waves and protect features landward of the dune. Dunes also provide a reserve of sand to replenish the beach. Taller dunes may prevent the natural overwash process, which may ultimately harm the barrier island. The height of the dune also has an impact on dune growth and nearshore morphology. As the dune increases in size, growth decelerates. Dune growth is restricted by sand supply (Sloss et al. 2012b).
Human activity	Infrastructure	Shoreline hardening disrupts the long-shore sediment supply, threatening dune system health and increasing their vulnerability to erosion. Construction adjacent or on top of dunes, such as walkovers or boardwalks, can also hinder dune migration.
Human activity	Foot traffic	Foot traffic on or over dunes can lead to erosion and damage dune vegetation, increasing dune vulnerability.
Human activity	Climate change	Climate change refers to long-term changes in weather patterns. Climate change impacts include but are not limited to rising temperatures, melting polar ice, increased flooding, increased storm intensity, and SLR. Increased storm intensities and SLR may lead to increases in erosion and overwash events due to higher water levels (Sloss et al. 2012a).

Standard Dune Management Strategies

Dune management will vary from site to site, and each of the dune system variables (table 1) should be considered when choosing a strategy. In addition, existing flora and fauna should be understood before developing a dune management plan. Because sand dunes are dynamic features and subject to movement, the management strategies implemented may change over time. This should be considered for all dune preservation, enhancement, and reconstruction activities.

There are a wide range of strategies that have been historically and are still currently being used for dune restoration and protection. These management strategies include monitoring and data gathering, supplementing vegetation, installing dune fencing, beach and dune nourishment, woody debris, core treatments, armoring, public education and outreach, and erosion reduction strategies. A discussion of these standard dune management strategies, the advantages and disadvantages of each strategy, and some general guidance for implementation is provided in table 2.

Table 2. Standard Dune Management Strategies and Suitable Sites for Implementation

Strategy and Description	Advantages	Disadvantages	Suitable Sites
Data gathering and dune monitoring: An essential first step for dune management is data gathering and dune monitoring. This involves collecting and documenting the environmental conditions and human factors impacting the site and health of the dune, then coming back at set intervals to monitor the health of the dune system. Collecting data on variables impacting the dune (table 1) will aid in the development of a successful dune management plan. Data gathering and dune monitoring efforts can vary in scale and size, depending on the areal extent and available resources. Cost of data gathering and monitoring will depend on size, scale, duration, and type of data collected. The cost is typically in the middle of alternatives in this table.	– Determines health of existing dune system. – Helps to determine if other management strategies should be implemented. – Helps to identify the best management strategy for a specific site and increases the chance of success. – Helps to identify when the management strategies should be adapted over time. – Needed to develop, validate, calibrate, and improve numerical models of the site that can be used to make calculations about the future of the site.	– Time consuming/requires resources to collect, maintain, and analyze. – Limited data availability/limited ability to obtain information for some sites. – May require specialized training or equipment to collect some data. – If specialized equipment is installed long term, it may require permits for installation.	– All sites. – May be done as a strategy by itself or in conjunction with most other management strategies.

Strategy and Description	Advantages	Disadvantages	Suitable Sites
Dune nourishment: Dune nourishment increases the volume of a dune by adding sediment, providing a physical buffer between the sea and inland areas. The sand buffer can naturally shift during storms, unlike hard structures, such as seawalls and bulkheads. Dune nourishment also helps support the protective capability of the entire beach system (i.e., the dune, beach, and nearshore area). As sand erodes from the dune, it will likely be transported to the surrounding beach and nearshore area where it can reduce the strength of incoming storm waves and act as an energy dissipator (NCCOS 2022). Considerations for dune nourishment include compatibility between grain size and texture and existing beach sand, time-of-year restrictions, space constraints, and permit requirements (Slovinsky 2021). This alternative is typically one of the more expensive alternatives in this table.	– May offer better protection to structures located landward of the dune. – Adds sediment to the system. – May be done in conjunction with beach nourishment.	– Sediment may travel to nearby inlets or shipping channels. – May be difficult to match existing sediment. – May adversely impact natural resources. – May cause increased wave runup, ramping, or reflection. – Risk that a storm event happens shortly after installation and erodes imported sand. – Will likely require permits and may face opposition from regulators. – Costly.	– Sites where additional protection from storm events is required and there is room to place additional sand without adverse impacts.
Dune fencing: Dune fencing includes stake-and-twine fencing, zig-zag plastic snow fencing, or a wood-stake matrix technique. Dune fences are about 2 to 4 feet high and aid in confining sands and building up dunes to provide additional protection against coastal erosion and flooding. Dune fencing may be installed perpendicular or parallel to the shore (Itzkin et al 2020). Dune fencing may be installed on the seaward or landward side of the existing dune, depending on where new dunes are desired. It is often installed with vegetation. This alternative is typically one of the less expensive alternatives in this table.	– May help sand accumulate/grow dune. – May prevent trampling of the dune. – Low cost.	– Will take time for sand to accumulate and dune to grow. – May adversely impact natural resources, such as nesting sea turtles. – May disrupt the natural deposition cycle. – May require permits.	– Sites that are generally performing well where a source of sediment exists, but the system requires additional support to stimulate dune growth. The site should also have sufficient room on the beach for the toe of the new dune to adjust, either towards or away from the water.

Strategy and Description	Advantages	Disadvantages	Suitable Sites
Vegetative measures: Dunes can be stabilized with vegetative measures, such as planting grasses and woody plants. Sand accumulation around beachgrass plants results in new root development, creating a dense mat of vegetation, which secures the dune below its surface and traps windblown sand (USDA 1992). Dune fencing may be used in conjunction with vegetation measures. This alternative is typically one of the less expensive alternatives in this table.	– May help sand accumulate/grow dune. – May help to establish habitats and biodiversity.	– Risk that a storm event happens shortly after installation and erodes vegetation before it establishes itself. – Requires monitoring. – Vegetation needs to be carefully selected. – May require permits.	– Sites where the dune has experienced loss of vegetation or newly nourished dunes and/or sites that are generally performing well where a source of sediment exists, but the system requires additional support to stimulate dune growth.
Woody debris: Placing woody debris on the surface of the dune can help stabilize the dune by adding roughness to an otherwise sandy system, helping to collect or anchor sand in the dune. This is sometimes done with discarded Christmas trees or other woody items. This alternative is typically one of the less expensive alternatives in this table.	– May help sand accumulate/grow dune.	– May adversely impact natural resources, such as nesting sea turtles. – May disrupt the natural deposition cycle. – May require permits.	– Sites that are generally performing well where a source of sediment exists, but the system requires additional support to stimulate dune growth.
Core treatment: Core treatment supplements the core of the dune to make it more resistant to erosion. This can be done with woody debris, geotubes (a tube-shaped bag made of geotextiles and filled with sand), riprap, concrete or steel bulkhead, or other structure. The cost of this alternative will vary depending on the treatment type, but it is typically in the middle to more expensive types of treatments. The more robust the treatment is, the more expensive it will be.	– Provides a line of defense if the dune is eroded. – Can be designed to withstand large storms, such as hurricanes and nor'easters.	– May adversely impact natural resources. – Will likely require permits and may be met with opposition from regulators. – Can be costly depending on core treatment. – Visitor safety concerns when foreign debris is exposed by storms.	– Sites where the dune may be subject to erosion. – For more robust core treatments: sites that require protection of critical infrastructure or resources.

Strategy and Description	Advantages	Disadvantages	Suitable Sites
Dune armoring: Armoring a dune system is the construction of a human-made structure designed to either prevent erosion or protect a structure from wave action and flooding. This may include adding concrete or load mats, bulkhead, seawall, revetment, or geotextile structure in front of or on the landward side of a dune. This practice can offer robust protection of inland resources. This alternative is typically one of the more expensive alternatives in this table.	– Protects structures located landward of the dune. – Can be designed to withstand large storms, such as hurricanes and nor'easters.	– Adversely impacts habitat covered by armoring and ecological communities dependent on the area. – Will likely require permits and may be met with opposition from regulators. – Costly.	– Sites that require protection of critical infrastructure or resources.
Public outreach, education, and visitor management: Increasing public awareness can engage visitors in protecting dunes by helping them understand the importance of dunes in the coastal system and how visitors harm dunes. Outreach can be achieved in many ways – signage, information at visitor centers, and engagement with rangers and other NPS staff. Also, structures or strategies to keep visitors off the dunes or limit the area of impact are important. This can include boardwalks over the dune, post and rope to delineate the pathway or similar methods. This alternative is typically one of the less expensive alternatives in this table.	– Engages the public to help protect the dune system. – Reduces or eliminates impacts of visitors walking on dunes, protecting vegetation, and reducing erosion. – Low cost.	– Staff time required may stress already stretched resources. – Non-compliance. – Permits needed to install post and rope or other trail delineation structures.	– Recommended for most sites.

Modeling and Design Tools for Dune Management

Forecasting the long-term evolution of beach and dune systems is becoming necessary for managers to protect established dune communities and natural habitats as climate change continues to cause more frequent and intense storms and SLR, creating new challenges for managing dune systems (Mickey et al. 2020). In the past, empirical equations and/or simplistic models were used to design dune management plans, but with computing capacity increasing exponentially (i.e., progression is not linear and modeling capabilities are far ahead of where they were even 5 years ago) and improvements in accuracy, the use of and access to state-of-the-art numerical models has increased. Additionally, models can be better validated and calibrated due to advancements in data-gathering technology.

Numerical models can inform managers about the best use of specific management strategies (table 2). The combination of data gathering, monitoring, and modeling is essential for understanding existing systems and predicting coastal dune formation now and into the future (de Groot et al. 2012). Models may help to determine the optimum elevation of a barrier island dune for a certain period in the future, SLR projections, and changes in weather patterns. Models can also provide guidance for rebuilding a deteriorated dune system to manage overwashing and prevent further deterioration of the dune system. The first step in modeling is to perform a numerical modeling assessment for the area. This will provide an existing conditions model that can be compared to a future condition, which would include the proposed management strategy, including effects of climate change (e.g., SLR, storm intensity).

In addition to advances in numerical modeling, there have been advances in design tools, which allow coastal managers to assess the potential for damage to dunes and barrier islands during storm events and predict dune system recovery. For example, FEMA 540-rule assesses if a dune should be removed or allowed to retreat based on the volume of sand above the predicted 100-year water and is easy to apply since it uses simple math (FEMA 2018). The assumption is that if the volume of sand in a dune above the 100-year stillwater level is greater than 540 square feet per foot (ft²)/ft, it will have sufficient volume to persist during the 100-year event. However, this simplistic approach is outdated and contains several deficiencies including only accounting for the 100-year event and failing to account for the position of the dune relative to the shoreline (Janssen and Miller 2022). Advances in these design tools and the ability to couple them with numerical models have further advanced dune management.

State-of-the-art models and improved design tools linked with climate projections can provide answers about how to recreate, move, armor, or allow dunes to retreat. Examples of how models and design tools are currently being used to assess dune performance are given below.

Barrier Island Management Informed by Numerical Modeling

Dauphin Island is a barrier island and dune system in Alabama. It provides coastal habitat with over 200 acres of beach, dunes, overwash fans, intertidal wetlands, maritime forest, and freshwater ponds. It was impacted by hurricanes including Ivan, Katrina, and Isaac, and needed restoration. The National Fish and Wildlife Foundation (NFWF) provided funding for an inter-agency effort between the state of Alabama, the US Army Corps of Engineers (USACE), and the US Geologic Survey (USGS) to develop the Alabama Barrier Island Restoration Study, a comprehensive plan for Dauphin Island's restoration (USGS 2017). The study began with a data collection effort including:

- Topography and bathymetric data and geophysical characterization
- Sediment characteristics and distribution
- Shoreline change

A hydrodynamic and morphologic model was then developed to forecast how the island would evolve (USGS 2017). Models used included Delft3D (D3D) and the empirical dune growth model (EDGR) to simulate the evolution of the barrier island and dune growth over time and Xbeach to simulate storm-induced erosion. The following are some of the restoration alternatives that were modeled (Mickey et al. 2020):

- Replacing a rubble mound structure with an erodible sand berm
- Various sediment nourishments
- Filling in sediment borrow pits

Various SLR project scenarios were also modeled to assess the future performance of each alternative. The study deduced that during storms, nourishment reduced dune overtopping, allowing the island to preserve height and width, whereas the no-nourishment scenario resulted in the island moving landward and decreased island height (Mickey et al. 2020).

Modeling Dune Geometry and Barrier Island Performance

Research on the ability of a dune to recover after a high-intensity/low-frequency high-water event, such as a storm, has been well documented and can be used to provide a simple measure of the short-term resiliency of barrier islands. The impacts of low-intensity/more frequent high-water events and how these events impact resiliency were not as well known. Researchers at Texas A&M University are developing a model to relate the elevation of a barrier island to water levels and, ultimately, predict whether a dune would be able to succeed on an island. Lower-frequency flood events were investigated at multiple sites across the world, and it was determined that beach and dune geometry is linked to these less frequent high-water events that occur monthly (Rinaldo et al 2020).

The data collected during this study were used to develop a model to estimate the ability of the barrier island and dune system to recover after a storm, the rate of a barrier island's migration landward, the effectiveness of the dune to act as flood protection, and the impact post-storm interventions may have on the system (Vincent et al. 2020). The goal of this model is to provide a way to determine the recommended dune geometry to protect the barrier island ecosystem and landward assets by understanding overwash events and impacts on the dune system based on statistical water levels (Conrad 2021). This model can be used to predict barrier islands' performance relative to current water levels and assess how it will function in the future with SLR.

Hydrodynamic and Sediment Transport Modeling

At Aberdeen Proving Ground (APG) in Harford County Maryland, EA and the USACE Coastal and Hydraulic Laboratory (CHL) are modeling several recommended Nature-based Solutions (NbS) to understand the impacts on the hydrodynamics and morphology during normal conditions and storm events. The ADvanced CIRCulation modeling (ADCIRC) along with the Coastal Storm Modeling System

(CSTORM-MS) will be used to evaluate storm surge and wave impacts to select recommended NbS for APG. Storm events to be modeled include historical storm events and high-frequency synthetic storms.

An Adaptive Hydraulics (AdH) model will then be developed to determine the impacts of these NbS on hydrodynamics and sediment transport in the region around APG on a finer scale than feasible in the ADCIRC model. The storm scenarios, along with a year-long timeframe scenario, will be simulated using CSTORM-MS results as boundary conditions and both the CSTORM-MS and AdH models will be used to simulate with and without project conditions for present-day sea levels along with four additional projected future SLR scenarios.

Design Tool: Fragility Curve Modeling

Fragility curves are typically used to determine the probability of exceeding a level of damage as a function of environmental change, such as those changes caused by a storm or an earthquake. They are typically used for seismic design but have more recently been applied to coastal engineering issues as a design tool.

Researchers at the Stevens Institute of Technology have been developing a fragility curve model called the Engineering Demand Parameter (EDP) to efficiently assess the likelihood of dune erosion during storm events (Janssen and Miller 2022). The EDP accounts for dune resilience parameters, such as dune volume and position relative to the shoreline, storm intensity, and duration effects. It also allows for the consideration of probabilistic estimates beyond the binary ‘survive’ or ‘fail’ models, which has been noted as a shortcoming of pre-existing design tools. The EDP also includes both storm intensity and resiliency terms, which allows for the comparison of different beach configurations in varying storm events (Janssen and Miller 2022).

Design Tool: Bayesian Modeling

A Bayesian model uses statistics to calculate the probability of an event occurring. These types of models are continually updated as more data or information are added to the model. An example of this type of model is the “Bayesian EROsion Management Network” (BERM-N), which was developed using over 50 years of data collected at over 600 locations along the Dutch coast. Information on different sand types, beach and dune geometry, and historic beach nourishments were input into BERM-N. It has been used to predict the effectiveness of beach nourishment in mitigating coastal erosion and estimate required nourishment volume (Giardino et al. 2019).

Bayesian models are effective at predicting how a beach and dune system will behave based on the data input, but models built with historic observed data may not have enough information to calculate future SLR scenarios. Numerical modeling of future scenarios can be used to import additional data into the Bayesian model so that they can better predict future events (Giardino et al. 2019).

Using Bayesian modeling as a design tool can improve the speed, flexibility, and interactive nature of assessing management needs for beaches and dunes.

Specific modeling needs of a site can be assessed during the data-gathering stage. In addition, monitoring the dune system can help to update and improve numerical models or could be used as the basis of a new model. No matter what the objective of the modeling exercise is, each model must be validated and

calibrated before the information is used for decision-making. Validating and calibrating a model involves comparing model results to observed data. It may require a significant effort as sufficient data must first be collected, then the model must be run until the results are representative of the data collected. If sufficient data are not available, the data collection process alone may take months or even years.

Dune Management Strategy at ASIS

To address specific concerns related to ASIS, a site-specific example is provided showing how the information presented in this memo can be used to develop a simplistic but site-specific framework for ASIS. This scheme can be added to and modified so that it can be implemented at other parks with adjustments to address site-specific needs.

The initial plan includes 5 iterative steps.

1. **Defining goals and identifying important criteria for the management plan.** ASIS wants a plan to manage the developed dune area from the southern boundary with Assateague Island State Park to the northern boundary of the over-sand vehicle zone that encourages overwash and other natural processes, protects infrastructure, and maintains a sizeable recreational beach width. A management strategy that balances the following criteria is required:
 - a. Natural evolution of the island, including adapting to climate change.
 - b. Safe visitor access to enjoy the park.
 - c. Minimal storm-related damage to facilities and infrastructure, such as the road and campgrounds.

Specifically, the park would like guidance on targeting the dune crest elevation and the location on the beach for dune placement.

2. **Data gathering and monitoring.** Data collection on variables impacting the dune (table 1) will aid in the development of a successful dune management plan, and continual monitoring will assess how the management plan is working. The data-gathering phase should also include:
 - a. Identifying locations, resources (natural, cultural, recreational), and infrastructure.
 - b. Identify other concerns, such as visitor safety, enjoyment, or access, and evaluate how to choose among actions for those items.
 - c. Identify existing management efforts/data/monitoring programs and document their effects in an organized manner, which will allow interested parties to draw conclusions based on their successes and failures. At ASIS, there are several management strategies already in place at various locations that have been updated and adjusted based on observations made over the years.

An example of this is the management of the North End Restoration Project that mitigates the impacts of Ocean City Inlet jetties by maintaining sand supply to northern Assateague Island at the historic pre-Ocean City Inlet rate. The jetties were originally constructed in 1934 for navigation after a storm opened the inlet in 1933. The jetties blocked the natural sediment transport, and the northern end of Assateague Island shifted west more than

1,000 feet before construction of the initial short-term sand bypassing project began in 2002 (NPS 2006a). This short-term bypassing plan included five years of monitoring. Following this initial bypassing, a long-term plan was implemented to provide a “mobile bypassing” of the sand that would have reached ASIS had the jetties not been constructed.

The data collected to evaluate the North End Restoration Project included (NPS 2006b):

- i. Geologic monitoring, including:
 - a) Shoreline surveys collected four times a year.
 - b) Cross-island profiles collected every half kilometer on the North End of the island to measure changes in the beach elevation, dune, and back barrier.
 - c) LiDAR elevation surveys collected annually.
 - d) Hydrographic surveys.
 - e) Surveys of the dredged areas.
- ii. Biologic monitoring, including piping plover reproductive success, piping plover distribution, vegetation cover, and fox distribution.
- iii. Wave, water, and current measurements.
- iv. Aerial photographs.
- v. Sediment samples.

A similar data gathering and monitoring strategy using lessons learned from this study could be developed for the area between the southern boundary of the state park to the northern boundary of the over-sand vehicle zone. Data collection can begin before the subsequent steps outlined below and should continue throughout the process so that adjustments can be made as needed.

3. **Develop and analyze alternatives.** Before developing an initial management plan, several alternatives can be developed and reviewed. At ASIS, this may include investigating various dune crest elevations and locations on the beach to determine what will be the most resilient design moving forward.

Due to the highly dynamic nature and the potential for climate change to create new conditions that have not been previously encountered, it may be prudent to investigate this with a numerical model, such as those discussed in the section above. There are a wide array of numerical models available to analyze dune and sediment movement, but a modeling effort similar to the one described in the *Barrier Island Management informed by Numerical Modeling or Hydrodynamic and Sediment Transport Modeling* subsections, would likely be best to address the specific questions related to the crest elevation and dune placement. This will allow for various SLR project scenarios and conditions to be considered and investigate how the various alternatives may respond to or impact the multiple criteria developed in Steps 1 and 2. Regulatory, cost, construction constraints, and other factors should also be considered as criteria are evaluated during this step as well.

A multi-criteria decision analysis (MCDA) or matrix that ranks the relative importance of the criteria developed in earlier steps, as well as any additional criteria developed in subsequent steps, versus the alternative's impact on those criteria, can be developed to assist with the decision-making process. A typical MCDA to evaluate alternatives typically includes the steps outlined below:

- a. Assign each criteria identified a value ranging between 0 and 100 with 0 indicating the criterion has no importance and 100 indicating the criterion is the most critical criterion for consideration.
- b. Sum the values for all criteria and calculate relative weights for each.
- c. List all the alternatives and score them for their performance against each criterion ranging from 1 to 5, 1 being the least favorable and 5 being the most favorable.
- d. Multiply the alternative scores and the criteria weights to calculate a weighted score. Sum the weighted scores to find a final weighted score for each alternative. This final weighted score for each alternative considers the alternative's scores and relative criteria weights.
- e. The highest final weighted score indicates the most desirable alternative and the lowest indicates the least desirable alternative.
- f. This process can be iterated as more information or feedback is received throughout the management plan's development.

Reviewing the alternatives in this manner allows the park to prioritize the most important design criteria and holistically consider all aspects.

4. **Develop and implement an initial management strategy.** Using the information gathered in previous steps, an initial management strategy can be developed. The plan should consider the multiple criteria developed that need to be addressed, the data collected in Step 2, and the results from any alternative analysis performed in Step 3.
5. **Review the plan and modify it, as necessary.** The plan should be reviewed at regular intervals and modified as required.

CONCLUSIONS

Many variables contribute to, and therefore impact, a coastal dune system (table 1). Because these variables change from site to site and over time, multiple management strategies may be required to maintain a healthy system. The standard dune management strategies include monitoring and data gathering, supplementing vegetation, installing dune fencing, beach and dune nourishment, woody debris, core treatments, armoring, informing the public, and erosion reduction strategies (table 2).

Managing the long-term integrity of dunes benefits coastal systems. In addition, planning for dunes to be resilient into the future will protect coastal habitats. Since dunes are dynamic, management strategies will need to be adjusted over time. Most, if not all coastal dune sites will benefit from monitoring and data gathering.

The standard management strategies can be improved or supplemented with information derived from numerical models and design tools. Recent advances in these areas have allowed more effective dune management, as well as better preparation for future conditions. These models and tools can predict finer-scale components, such as how to restore, move, armor, or retreat dunes in a specific area. They also allow for better planning, as they can help predict what management strategies will be needed as time progresses. These state-of-the-art models and improved design tools linked with climate projections can provide managers with the tools to effectively predict and plan for future management of coastal resources.

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