Coastal Risk Reduction and Resilience: Using the Full Array of Measures

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Todd Bridges, Roselle Henn, Shawn Komlos, Debby Scerno, Ty Wamsley, and Kate White

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Coastal areas are especially vulnerable to hazards, now and in the future, posed by waves and surges associated with sea level change and coastal storms. Coastal risk reduction can be achieved through a variety of approaches, including natural or nature-based features (e.g., wetlands and dunes), nonstructural interventions (e.g., policies, building codes and emergency response such as early warning and evacuation plans), and structural interventions (e.g., seawalls and breakwaters). This paper discusses USACE's capabilities to help reduce coastal risks from and improve resilience to these hazards through an integrated approach that draws from the full array of coastal risk reduction measures.

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Preface

This report was prepared by a multidisciplinary team at the direction of the US Army Corps of Engineers (USACE) Directorate of Civil Works to clarify language used by the USACE to describe the full array of coastal risk reduction measures. This will help improve transparency and communications with our partners and stakeholders as we work together to address the increasing challenges posed by coastal storms and changing sea levels combined with aging infrastructure and a dynamic socioeconomic environment.

The Project Development Team consisted of (in alphabetical order) Dr. Todd Bridges (CEERD), Charley Chesnutt (CEIWR), Roselle Henn (CENAD), Dr. Paul Wagner (CEIWR), Candy Walters (CEPA), Dr. Ty Wamsley (CEERD), and Dr. Kate White (CEIWR).

The Author Team consisted of (in alphabetical order) Dr. Todd Bridges (CEERD), Roselle Henn (CENAD), Shawn Komlos (CEIWR), Debby Scerno (CECW), Dr. Ty Wamsley (CEERD), and Dr. Kate White (CEIWR).

Other contributors included (in alphabetical order) Randall Behm (CENWO), Lynn Bocamazo (CENAN), Kelly Burks-Copes (CEERD), Bruce Carlson (CECW), Janet Cushing (CEIWR), Gus Drum (CELRH), Jeffrey Jensen (CEIWR), Elizabeth Murray (CEERD), Stephen O'Leary (CELRH), Gene Pawlik (CEPA), Dr. Denise Reed (Chief's Environmental Advisory Board), Dr. Paul Wagner (CEIWR), and Candy Walters (CEPA).

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Executive Summary

Coastal areas in the U.S. are economic drivers for the whole country, supporting port commerce, valuable fisheries, and multiple revenue streams for state and local governments. However, coastal areas are especially vulnerable to hazards, now and in the future, posed by waves and surges associated with sea level change and coastal storms. These hazards can cause damages to human life and property as well as ecosystems. Recent hurricane events have emphasized the increasing vulnerability of coastal areas to natural disasters through the combination of changing climate, geological processes, and continued urbanization and economic investment. Improving resilience—the ability to anticipate, prepare for, respond to, and adapt to changing conditions and to withstand and recover rapidly from disruptions with minimal damage—is a key objective of reducing risk. This paper discusses USACE's capabilities to help reduce coastal risks from and improve resilience to these hazards through an integrated approach that draws from the full array of coastal risk reduction measures.

Coastal risk reduction can be achieved through a variety of approaches, including natural or nature-based features (e.g., wetlands and dunes), nonstructural interventions (e.g., policies, building codes and emergency response such as early warning and evacuation plans), and structural interventions (e.g., seawalls and breakwaters). Natural and nature-based features can attenuate waves and provide other ecosystem services (e.g., habitat, nesting grounds for fisheries). However, they also respond dynamically to processes such as storms, both negatively and positively, with temporary or permanent consequences. Nonstructural measures are most often under the jurisdiction of state and local governments (and individuals) to develop, implement, and regulate, and they cannot be imposed by the Federal government. Perhaps more well known are the structural measures that reduce coastal risks by decreasing shoreline erosion, wave damage, and flooding.

The USACE planning approach supports an integrated strategy for reducing coastal risks and increasing human and ecosystem community resilience through a combination of the full array of measures: natural, nature-based, nonstructural, and structural. This approach considers the engineering attributes of the component features and the dependencies and interactions among these features over both the short and long term. It also considers the full range of environmental and social benefits produced by the component features. Renewed interest in coastal risk reduction efforts that integrate the use of natural and nature-based features reveals the need for improved quantification of the value and performance of nature-based defenses for coastal risk reduction. The Federal, state, local, NGO, and private sector interests connected to our coastal communities possess a complementary set of authorities and capabilities for developing more integrated coastal systems. The effective implementation of an integrated approach to flood and coastal flood hazard mitigation relies on a collaborative, shared responsibility framework between Federal, state, and local agencies and the public.

Together with its partners and stakeholders, USACE can apply science, engineering, and public policy to configure an integrated approach to risk reduction by incorporating natural and nature-based features in addition to nonstructural and structural measures that also improve social, economic, and ecosystem resilience.

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Introduction

Coastal areas in the U.S. are economic drivers for the whole country, supporting port commerce, valuable fishery resources, and multiple revenue streams for states and local governments. A number of major U.S. cities are located directly on the coast, and other large population centers are within the range of tidal and coastal storm influences (Strauss et al. 2012). U.S. ports play a growing role in the increasingly globalized world economy, handling about $800B worth of goods annually and accounting for about 60,000 jobs (Jin 2008) in addition to supporting U.S. economic growth far inland through a highly interconnected transportation system. Estimates are that about 49% of the U.S. Gross Domestic Product is produced in estuarine areas, which encompass less than 13% of the area of the contiguous U.S. (Colgan 2008). The value of coastal recreation use is estimated at between $20B and $60B annually (Pendleton 2008). Coastal ecosystems in the U.S. also support a widely diverse set of species, habitats, and services. Estuaries provide nursery habitat (Beck et al. 2001) critical to the life cycles of more than 75% of the Nation's commercial catch (National Safety Council 1998).

Coastal areas of the U.S. are threatened now and in the future by erosion and damage due to storm waves, wind, and surge. Ongoing erosion, both natural and human-induced, can exacerbate periodic storm damages by diminishing natural buffers such as dunes, wetlands, and other habitats. Erosion control structures can alter the natural dynamics of coastal systems. The potential for environmental and economic damage and loss of life during storms may be further exacerbated by other factors, such as coastal development characteristics, sea level rise, and coastal subsidence. As the 2005 and 2008 hurricane seasons illustrated for the Gulf Coast, and Hurricane Sandy demonstrated for the Northeast, the potential societal, environmental, and economic consequences of coastal storms can be widespread and enduring. Public health and safety and economic stability may be at risk for developed coastlines, both directly and indirectly (e.g., water quality issues due to the failure of critical infrastructure such as wastewater treatment plants). For undeveloped coastlines, a key challenge is to ensure the continued delivery of the beneficial ecosystem services that help mitigate storm impacts. The consequences of storms can be reduced in part through improving resilience—the ability to anticipate, prepare for, respond to, and adapt to changing conditions and to withstand and recover rapidly from disruptions with minimal damage. Rising sea level and potential changes in storm frequency and severity underscore the importance of proactive approaches to reduce the risks and improve the resilience of the socioeconomic systems, ecosystems, and infrastructure.

> *Coastlines, now and even more so in the future, are especially vulnerable to threats posed by tides and coastal storms, due to geologic processes, changing climate, and ongoing development.*

Terminology

This paper uses the terms *natural, nature-based, nonstructural*, and *structural* to describe the full array of coastal risk reduction measures employed by the USACE. Some agencies and organizations have used the term *green infrastructure* to refer to the integration of natural systems and processes, or engineered systems that mimic natural systems and processes (e.g., USEPA[1], White House Conference on Green

[1] See http://water.epa.gov/infrastructure/greeninfrastructure/index.cfm#tabs-1

Infrastructure[1], Kousky et al. 2013, McDonald et al. 2005, McMahon and Benedict 2000). However, the USACE will continue to use the more descriptive terms provided here, including in the North Atlantic Coast Comprehensive Study and its associated workshops.

USACE Authorities

Several authorities and missions of the USACE support U.S. coastal risk reduction through measures that increase the resilience of coastal systems, which may include measures that avoid or decrease exposure, add redundancy, or increase robustness. Hurricane and storm risk management and related emergency preparedness, response, and recovery authorities provide direct support to state and local governments and communities threatened by coastal flood risks. Other USACE missions and operations (e.g., ecosystem restoration, navigation, dredging, regulatory, and recreation) also contribute to coastal resilience though a variety of actions taken in the public interest to contribute to economic development, improve aquatic ecosystems, encourage beneficial uses of dredged material, support shoreline erosion control, and effectively manage regional sediment resources. These USACE authorities complement other Federal agency authorities that address coastal zone management and coastal aspects of transportation, energy, and other critical infrastructure, housing and urban development, health and human services, fish and wildlife management, environmental protection, and disaster response. Since socioeconomic and ecosystem-based resources are critical to the Nation's economy and security, managing risks to their continued productivity is intrinsically a Federal responsibility, necessitating a collaborative, holistic government strategy.

Coastal Risk Reduction

Coastal systems are composed of natural and built features and their socioeconomic context (e.g., McNamara et al. 2011). Natural and nature-based features can exist due exclusively to the work of natural process, or they can be the result of human engineering and construction. The built components of the system include nature-based and other structures that support a range of objectives, including erosion control and storm risk reduction (e.g., seawalls, levees), as well as infrastructure providing economic and social functions (e.g., navigation channels, ports, harbors, residential housing). Natural coastal features take a variety of forms, including reefs (e.g., coral and oyster), barrier islands, dunes, beaches, wetlands, and maritime forests. The relationships and interactions among the natural and built features comprising the coastal system are important variables determining coastal vulnerability, reliability, risk, and resilience. Risk reduction in any given coastal area is achieved through a combination of approaches described in more detail below. Application of the full array of features in any coastal system must consider interactions among the features (e.g., the effects of seawalls on down-drift beaches) and the multiple objectives being sought for the system (e.g., erosion control, navigation, risk reduction).

Natural and Nature-Based Features

Natural features are created and evolve over time through the actions of physical, biological, geologic, and chemical processes operating in nature. Nature-based features are those that may mimic characteristics of natural features but are created by human design, engineering, and construction to

[1] See http://water.epa.gov/infrastructure/greeninfrastructure/whconference.cfm

provide specific services such as coastal risk reduction. Nature-based features are acted on by the same physical, biological, geologic, and chemical processes operating in nature, and as a result, they generally must be maintained in order to reliably provide the intended level of services.

Natural and nature-based features (Table 1) can enhance the resilience of coastal areas challenged by sea level rise (Borsje et al. 2011) and coastal storms (e.g., Gedan et al. 2011, Lopez 2009). For example, beaches are natural features that can provide coastal storm risk reduction and resilience. The sloping nearshore bottom causes waves to break, dissipating wave energy over the surf zone. The breaking waves typically form an offshore bar in front of the beach that helps to dissipate the following waves. Dunes that may back a beach can act as a physical barrier that reduces inundation and wave attack on the coast landward of the dune. Although the dune may erode during a storm, in many cases it provides a sediment source for beach recovery after a storm passes.

Table 1: Natural and nature-based features at a glance. For more detailed information, see Appendix A. The vegetated features include salt marshes, wetlands, and submerged aquatic vegetation (SAV).

GENERAL COASTAL RISK REDUCTION PERFORMANCE FACTORS:
STORM INTENSITY, TRACK, AND FORWARD SPEED; SURROUNDING LOCAL BATHYMETRY AND TOPOGRAPHY





Dunes and Beaches	Vegetated Features	Oyster and Coral Reefs	Barrier Islands	Maritime Forests/Shrub Communities
Benefits/Processes	**Benefits/Processes**	**Benefits/Processes**	**Benefits/Processes**	**Benefits/Processes**
Breaking of offshore waves Attenuation of wave energy Slow inland water transfer	Breaking of offshore waves Attenuation of wave energy Slow inland water transfer Increased infiltration	Breaking of offshore waves Attenuation of wave energy Slow inland water transfer	Wave attenuation and/or dissipation Sediment stabilization	Wave attenuation and/or dissipation Shoreline erosion stabilization Soil retention
Performance Factors	**Performance Factors**	**Performance Factors**	**Performance Factors**	**Performance Factors**
Berm height and width Beach slope Sediment grain size and supply Dune height, crest, and width Presence of vegetation	Marsh, wetland, or SAV elevation and continuity Vegetation type and density	Reef width, elevation, and roughness	Island elevation, length, and width Land cover Breach susceptibility Proximity to mainland shore	Vegetation height and density Forest dimension Sediment composition Platform elevation

The functions of engineered beaches and dunes are similar to natural beaches and dunes. Engineered beaches and dunes are nature-based infrastructure specifically designed and maintained to provide coastal risk reduction services. These nature-based features often require beach nourishment to mitigate ongoing erosion and other natural processes. Introducing additional sand into the system through beach nourishment reinforces the natural protection to the upland afforded by the beach. Wave damage and flood risk reduction provided by beach nourishment is enhanced when dune construction or restoration is included.

Coastal wetlands may contribute to coastal storm protection through wave attenuation and sediment stabilization. The dense vegetation and shallow water in wetlands can slow the advance of storm surge somewhat and slightly reduce the surge landward of the wetland or slow its arrival time (Wamsley et al. 2009 and 2010). Wetlands can also dissipate wave energy, potentially reducing the amount of destructive wave energy propagating on top of the surge, though evidence suggests that slow-moving storms and those with long periods of high winds that produce marsh flooding can reduce this benefit (Resio and Westerlink 2008). The magnitude of these effects depends on the specific characteristics of the wetlands, including the type of vegetation and the wetlands' rigidity, structure, extent, and position relative to the storm track. However, while wetlands might retard the storm surge propagation in one area in the process of slowing storm surge advance, the movement of water can be redirected toward another location, potentially increasing the local storm surge elsewhere. Engineered and constructed wetlands act in the same manner as natural wetlands, though design features may be included to enhance risk reduction or account for adaptive capacity considering future conditions (e.g., by allowing for migration due to changing sea levels).

Natural & nature-based measures are capable of improving the quality and resilience of economic, ecologic, and social systems.

Dynamic Character of Natural and Nature-Based Features

Natural and nature-based features respond in many ways to storms, which are a natural part of most coastal system dynamics. Changes occurring during storms can be temporary or permanent. For wetlands, changes might include erosion, stripped vegetation, and salinity burn, which may result in longer-term decreases in wetland productivity. However, storms also introduce mineral sediments that contribute to long-term sustainability in the face of sea level rise. The long-term consequences for wetland systems from hurricanes depends on many factors, including pre-storm landscape structure (including wetland extent and relationship to other natural and built features), proximity of the wetland to a storm track, and the meteorological conditions that persist following a hurricane (e.g., salinity burn effects are reduced if high precipitation occurs during or after the storm). Storms are naturally the dominant cause of coastal change on barrier islands. Hurricane surge and waves erode barrier island beaches and, if the surge is high enough, result in overwash, breaching, or back bay flooding, which impacts the storm damage reduction potential of the islands. Over longer time scales, projections of sea level rise suggest that areas such as wetlands and barrier islands presently seen as "natural" may require management and intervention if their ability to provide socially desirable ecosystem services is to be retained.

Nonstructural Measures

Economic and Environmental Principles and Guidelines for Water and Related Land Resources Implementation Studies (U.S. Water Resources Council 1983) describes nonstructural measures as complete or partial alternatives to structural measures, including modifications in public policy, management practices, regulatory policy, and pricing policy. Nonstructural measures essentially reduce the consequences of flooding, as compared to structural measures, which may also reduce the probability of flooding. Nonstructural measures addressed by the USACE National Nonstructural Floodproofing Committee include structure acquisitions or relocations, flood proofing of structures, implementing flood warning systems, flood preparedness planning, establishment of land use regulations, development restrictions within the greatest flood hazard areas, and elevated development (Table 2)[1]. Nonstructural measures can be blended well with the natural and nature-based features of the coastal environment, as well as with structural measures.

Nonstructural measures can reduce exposure to coastal flood risks.

Table 2: Nonstructural features at a glance. For more detailed information, see Appendix A.

GENERAL COASTAL RISK REDUCTION PERFORMANCE FACTORS:
COLLABORATION AND SHARED RESPONSIBILITY FRAMEWORK, WAVE HEIGHT, WATER LEVEL, STORM DURATION




Floodplain Policy and Management	Floodproofing and Impact Reduction	Flood Warning and Preparedness	Relocation
Benefits/Processes	**Benefits/Processes**	**Benefits/Processes**	**Benefits/Processes**
Improved and controlled floodplain development	Reduced opportunity for damages	Reduced opportunity for damages	Reduced opportunity for damages
Reduced opportunity for damages	Increased community resiliency	Increased community resiliency	No increase in flood potential elsewhere
Improved natural coast environment	No increase in flood potential elsewhere	Improved public awareness and responsibility	Improved natural coast environment
Performance Factors	**Performance Factors**	**Performance Factors**	**Performance Factors**
Wave height	Wave height	Wave height	Wave height
Water level	Water level	Water level	Water level
Storm duration	Storm duration	Storm duration	Storm duration
Agency collaboration			

[1] See http://www.usace.army.mil/Missions/CivilWorks/ProjectPlanning/nfpc.aspx

Nonstructural measures are most often under the jurisdiction of state and local governments (and individuals) to develop, implement, and regulate. They can be encouraged or incentivized but not imposed by the Federal government. As a result, the effective implementation of the full range of flood and coastal flood hazard mitigation actions relies on a collaborative, shared responsibility framework between Federal, state, and local agencies and the public (e.g., Comfort et al. 2010). Additional nonstructural opportunities for coastal areas faced with significant threats from coastal storms and changing sea levels center on changes in policy and land use regulations. In addition, for developed areas with aging coastal infrastructure, the potential threats create the opportunity to reconsider infrastructure investments and the application of a broader array of nonstructural measures and nature-based features in our coastal areas to reduce risk while retaining and enhancing the natural coastal environment.

Structural Measures

Structural measures can be designed to decrease shoreline erosion or reduce coastal risks associated with wave damage and flooding. Traditional structures include levees, storm surge barrier gates, seawalls, revetments, groins, and nearshore breakwaters (Table 3). The purpose of levees, seawalls, and storm surge barrier gates is to reduce coastal flooding, while revetments, groins, and breakwaters are typically intended to reduce coastal erosion. All of these measures can reduce storm wave damage to some extent. Levees are typically onshore structures with the principal function of protecting low-lying areas against flooding. Storm surge barriers are often required within a levee system to prevent surge from propagating up navigable waterways and distributaries. In most cases the barrier consists of a series of movable gates that normally stay open to let the flow pass but will be closed when storm surges exceed a certain level. Seawalls are onshore structures built parallel to the shoreline with the principal function of reducing overtopping and consequent flooding of land and infrastructure behind due to storm surges and waves. Seawalls limit erosion of the area landward, though if the seawall is exposed to waves during part or all of the tidal cycle, erosion of the seabed immediately in front of the structure may be enhanced due to increased wave reflection caused by the seawall and isolation of the beach from the inland sediment source. This results in deeper water seaward, allowing larger waves to reach the structure. Such changes in sediment transport pathways in the vicinity of seawalls can result in enhanced erosion on the adjacent shoreline.

Structural measures reduce coastal risks by decreasing shoreline erosion, wave damage, and flooding.

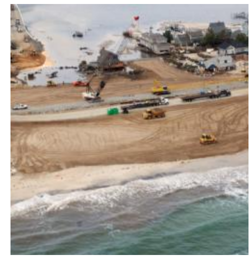
Revetments are onshore structures with the principal function of protecting the shoreline from erosion. Groins are narrow structures, usually perpendicular to the shoreline, that stabilize a beach against erosion due primarily to a net longshore loss of beach material. The effect of a groin is accretion of beach material on the updrift side and erosion on the downdrift side; both effects extend some distance from the structure. Detached breakwaters are nearshore structures built parallel to the shore just seaward of the shoreline in shallow water depths, with the principal function of reducing beach erosion by reducing wave height and thus longshore and cross-shore sediment transport. Detached breakwaters are low-crested structures that decrease wave energy and help promote a more even distribution of littoral material along the coastline. Submerged detached breakwaters are used in some cases because they do not spoil the view, but they represent a serious non-visible hazard to boats and swimmers. Like

Table 3: Structural features at a glance. For more detailed information, see Appendix A.

GENERAL COASTAL RISK REDUCTION PERFORMANCE FACTORS:
STORM SURGE AND WAVE HEIGHT/PERIOD, WATER LEVEL







Levees	Storm Surge Barriers	Seawalls and Revetments	Groins	Detached Breakwaters
Benefits/Processes	**Benefits/Processes**	**Benefits/Processes**	**Benefits/Processes**	**Benefits/Processes**
Surge and wave attenuation and/or dissipation Reduced flooding Reduced risk for vulnerable areas	Surge and wave attenuation Reduced salinity Intrusion	Reduced flooding Reduced wave overtopping Shoreline stabilization behind structure	Shoreline stabilization	Shoreline stabilization behind structure Wave attenuation
Performance Factors	**Performance Factors**	**Performance Factors**	**Performance Factors**	**Performance Factors**
Levee height, crest width, and slope Wave height and period Water level	Barrier height Wave height Wave period Water level	Wave height Wave period Water level Scour protection	Groin length, height, orientation, permeability, and spacing Depth at seaward end Wave height Water level Longshore transportation rates and distribution	Breakwater height and width Breakwater permeability, proximity to shoreline, orientation, and spacing

groins, a series of detached breakwaters can be used to control the distribution of beach material along a coastline, but just downdrift of the last breakwater in the series, there is an increased risk of shoreline erosion. Due to these effects, the placement of coastal structures for local erosion control or storm damage reduction must be considered in a systems context, and the wider implications for the adjacent natural and built environment must be evaluated with respect to both current and future sea levels and storm conditions.

Environmental and Social Benefits

Consideration of the full range of functions, services, and benefits produced by coastal projects is an important part of taking a systems approach to coastal risk reduction and resilience. These include benefits related to commercial and recreational fisheries, tourism, water supply, habitat for threatened and endangered species, and support for cultural practices. For example, breakwaters offer shoreline erosion protection by attenuating wave energy, but they can also provide recreational opportunities, valuable aquatic habitat, and carbon or nutrient sequestration. Natural features such as coastal wetlands, forests, or oyster reefs provide environmental and social benefits, but they can also contribute to coastal risk reduction or resiliency, as previously discussed. Nature-based features such as engineered beaches and dunes, or ecosystem restoration projects involving coastal wetlands, forests, or oyster reefs, provide coastal risk reduction or resiliency benefits, but they can also contribute to environmental and social benefits. Nonstructural measures may reduce social vulnerability to the impacts of changing sea levels and coastal storms, but they can also allow for wetland migration over time or support increased socio-economic benefits associated with recreation.

A more complete understanding of the ecosystem goods and services provided by the full range of coastal features, individually and in combination, will help to in formulating plans and determining benefits for risk reduction strategies. Some services are complementary, such as wetland restoration that increases habitat and wave attenuation, while others are conflicting, such as dune creation for risk reduction that competes with sightlines, raising viewshed concerns. As sea level rise and climate change influence the coastal environment, taking a comprehensive view of the services and benefits provided by interactions among natural, nature-based, nonstructural, and structural features will support decision making that could lead to improvements in the performance of the system.

Integrated Coastal Risk Reduction Approaches

USACE planning supports an integrated approach to reducing coastal risks and increasing human and ecosystem community resilience through the full array of natural, nature-based, nonstructural, and structural measures, including combinations of measures. The ability of the various types of measures to provide reliable and predictable levels of service is an important consideration in integrated risk reduction. The types of measures employed, their configuration within the network of features, and the planning and engineering approaches that are applied in developing the integrated system will depend on the geophysical setting, desired level of risk reduction, constraints, objectives, cost, reliability, and other factors.

> *USACE has long recognized the value of integrated approaches to risk reduction incorporating natural and nature-based features in addition to nonstructural and structural measures.*

For example, the Mississippi Coastal Improvement Plan (MsCIP) implemented by the USACE following Hurricane Katrina consists of natural, nature-based, nonstructural, and structural project elements that address hurricane and storm damage reduction, salt water intrusion, shoreline erosion, and fish and wildlife preservation (USACE 2009). Nature-based components such as diversion channels and floodways have long been a part of USACE flood risk management. For example, following the flood of 1927, USACE engineers recommended a plan that included floodways and natural backwater areas as well as levees (Jadwin 1928), and the system operated successfully during the flood of 2011.

An integrated systems approach to the development of coastal infrastructure considers the engineering attributes of the component features, the dependencies and interactions among these features over both the short and long term, and the ways in which those features can provide benefits across a range of objectives. Changes in one part of a system can create unintended consequences somewhere else in the system. The potential for these unintended consequences must be considered for effective coastal risk reduction. For example, hard structures may actually weaken the natural defenses provided by natural or engineered beach-dune complexes because they can induce erosion and interrupt cross-shore and alongshore littoral processes. Seawalls and revetments can work effectively with beaches and dunes when designed to be exposed to waves only during extreme events to provide an additional line of defense without interrupting non-storm coastal processes. This "lines of defense" approach (e.g., Cigler 2009, Lopez 2009) can result in combinations of measures that provide transitions to a new, less vulnerable state under different conditions.

Performance With Respect to Objectives

Knowledge about the performance of natural, nature-based, nonstructural, and structural features varies, as do the methods used to calculate and measure performance. Factors include the specified objectives, the threats under consideration (e.g., the particular range or frequency of coastal storms), and the technical information that is available for describing the relevant processes and functions. Applying a systems approach to coastal risk reduction necessitates a rigorous scientific and engineering analysis of the performance of all system components as part of planning, designing, constructing, operating, maintaining, and adaptively managing the features comprising the system.

The dynamic behavior and response of natural and nature-based systems to threats such as coastal storms and development can affect their performance with respect to system risk reduction and resiliency objectives. As a result, the coastal risk reduction and resilience services provided by these features will vary over space and time. For nature-based features such as engineered beaches and dunes, this variation can be addressed through effective planning and engineering to maintain the desired level of service. While some literature suggests that coastal features (e.g., wetlands and barrier islands) can reduce surge and waves, quantification of this performance has sometimes been based on limited data. This has resulted in widely varying characterizations of risk reduction benefits, from anecdotal to qualitative to quantitative (Wamsley 2009, Wamsley et al. 2009). For example, prior to Hurricane Katrina, the level of protection provided by wetlands had been empirically estimated with a simple "rule of thumb," assuming surge to be attenuated at a rate of X feet per Y miles of marsh. The actual situation is much more complex and depends on many details, including the storm intensity, track, and forward speed and the surrounding local bathymetry and topography. Simple rules of thumb may not take into account these complexities and changes that occur between storms (Resio and Westerlink 2008). These complexities can be addressed using more quantitative analytical methods when appropriate (Suzuki et al. 2012, Yao et al. 2012, Anderson et al. 2011, Cialone et al. 2008). Quantitative analytical methods consider the complex interactions between the storms and the natural or nature-based features, which depend on the intensity, track, and forward speed of the storm, as well as the elevation, the type, density, and height of the vegetation, and the surrounding local bathymetry and topography.

Knowledge Gaps

Federal investment in features intended to provide coastal risk reduction and resiliency should rest on solid evidence about performance. Focused research is needed to reduce the uncertainties involved in evaluating and quantifying the value and performance of natural and nature-based measures for shoreline erosion and coastal risk reduction. Federal investments supporting erosion mitigation and coastal risk reduction and resilience could benefit from more consistent integration of natural and nature-based infrastructure. Incorporating social sciences along with physical sciences and engineering (e.g., McNamara et al. 2011) can help improve understanding of measures that encompass social (technological, institutional, and behavioral) responses (Kates et al. 2012) and legal issues (e.g., Craig 2010). This would help to better inform investments in coastal systems and result in longer-term benefits for coastal risk reduction and an array of societal needs.

Collaborative Approaches

The Federal, state, and local agencies, NGOs, and private sector interests connected to our coastal communities possess a complementary set of authorities and capabilities for developing more-integrated coastal systems. Realizing this potential will involve the need for broad communication across the spectrum of interests and objectives represented with this community. USACE understands that close collaboration, both nationally and internationally, is the most effective way to develop practical, nationally consistent, and cost-effective measures to reduce potential vulnerabilities resulting from global changes (Stockton and White 2011). This approach is embodied in the Foreword to the national report issued by the Building Stronger Collaborative Relationships Initiative (USACE 2010):

> *More deliberate, comprehensive planning is needed—intergovernmental by design—and founded on an appreciation of the interconnectivity among and between natural systems and human activities. More collaborative planning, both transparent and inclusive, embracing the systems perspective of watersheds, river basins, estuaries and coastal reaches is needed to realize the promise of concerted integrated water resources management.*

Conclusions

U.S. coastlines provide social, economic, and ecosystem benefits to the Nation. Coastal areas are especially vulnerable to risks, now and in the future, posed by the combination of changing climate and geological processes and continued urbanization and economic investment. USACE, through its authorities, missions, and operations, has many capabilities to help reduce coastal risks and improve resilience through an integrated approach that draws together the full array of coastal features. Together with its partners and stakeholders, USACE can apply science and engineering to configure an integrated approach to risk reduction through the incorporation of natural and nature-based features in addition to nonstructural and structural measures that also improve social, economic, and ecosystem resilience. Attention needs to be given to the uncertainties relevant to an integrated system.

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Appendix A: Summary Table of the Benefits of Natural, Nature-Based, Nonstructural, and Structural Coastal Risk Reduction Measures

Note: This table focuses on benefits and does not provide adverse impacts or conflicts associated with resolving tradeoffs.

Coastal Storm Damage Reduction Features	Relevant Coastal Storm Damage Reduction and Resilience Processes and Functions Provided	Potentially Important Performance Factors	Potential Coastal Risk Reduction and Socioeconomic and Environmental Resilience Outcomes	Potential Additional Socioeconomic and Environmental Benefits (Direct and Indirect)
Seagrass beds	• Creation of vertical structure • Reduced current velocity at boundary • Wave attenuation • Increased biogeochemical activity and productivity • Increased sediment deposition, reduced resuspension	• Vegetation type • Vegetation density • Vegetation height • Vegetation flexibility and elasticity • Wave height • Wave period • Water level • Bed dimensions	• Coastal storm damage reduction • Shoreline erosion management • Sediment regulation • Tourism • Recreation • Education	• Water quality regulation • Fish and wildlife habitat creation and preservation • Ecosystem diversification (biodiversity) • Enhanced and diversified food production • Creation of aquatic habitat for feeding, breeding, and nurseries for food chain support • Tidal nutrient and organic carbon exchange
Coral reefs	• Wave attenuation and/or dissipation • Sediment retention	• Wave height • Wave period • Water level • Reef width • Reef elevation • Reef roughness	• Coastal storm damage reduction • Fisheries (fish and shellfish) • Tourism • Recreation • Education	• Improved biological productivity • Creation of unique and aesthetic reefscapes • Creation of suitable habitat for diverse flora and fauna • Generation of biogeochemical activity and productivity
Oyster reefs	• Wave attenuation and/or dissipation • Sediment retention	• Wave height • Wave period • Water level • Reef elevation • Reef width • Reef roughness	• Coastal storm damage reduction • Fisheries (fish and shellfish) • Tourism • Recreation • Education	• Improved biological productivity • Creation of unique and aesthetic reefscapes • Creation of suitable habitat for diverse flora and fauna • Generation of biogeochemical activity and productivity • Increased Information and knowledge • Creation of suitable reproductive habitat and nursery grounds

Coastal Storm Damage Reduction Features	Relevant Coastal Storm Damage Reduction and Resilience Processes and Functions Provided	Potentially Important Performance Factors	Potential Coastal Risk Reduction and Socioeconomic and Environmental Resilience Outcomes	Potential Additional Socioeconomic and Environmental Benefits (Direct and Indirect)
Salt Marshes	• Wave attenuation and/or dissipation • Sediment stabilization • Raw material provision (sands of particular sizes and mineral proportions)	• Wave height • Wave period • Water level • Marsh elevation • Marsh continuity • Vegetation type • Vegetation height • Vegetation density	• Coastal storm damage reduction • Shoreline erosion control • Water quality regulation • Tourism • Recreation • Education	• Ecosystem diversification (biodiversity) • Enhanced and diversified food production • Nutrient and pollution uptake and retention • Creation of aesthetic landscapes • Creation of suitable reproductive habitat and nursery grounds
Barrier Islands	• Wave attenuation and/or dissipation • Sediment stabilization	• Wave height • Water level • Island elevation • Island width • Island length • Land cover • Breach susceptibility • Proximity to mainland shore	• Coastal storm damage reduction • Shoreline erosion control • Tourism • Recreation • Education	• Creation of aesthetic landscapes • Ecosystem diversification (biodiversity) • Reduction of unwanted sediment sources • Creation of suitable habitat for diverse flora and fauna
Beaches	• Wave attenuation and/or dissipation • Nearshore sediment cycle • Raw materials (sands of particular sizes and mineral proportions) • Storage and filtration of water through sand	• Beach slope • Berm elevation • Sediment grain size • Berm width • Presence of backing dune • Sediment supply • Presence of structures • Wave height • Wave period • Water level • Storm duration	• Coastal storm damage reduction • Shoreline erosion control • Tourism • Recreation • Education	• Creation of unique and aesthetic landscapes • Flood protection • Improved water quality • Ecosystem diversification (biodiversity) • Potential beneficial use of dredged material • Biological productivity and diversity • Wildlife habitat creation and preservation

Coastal Storm Damage Reduction Features	Relevant Coastal Storm Damage Reduction and Resilience Processes and Functions Provided	Potentially Important Performance Factors	Potential Coastal Risk Reduction and Socioeconomic and Environmental Resilience Outcomes	Potential Additional Socioeconomic and Environmental Benefits (Direct and Indirect)
Dunes	• Wave attenuation and/or dissipation • Support for sediment cycle • Raw material provision (sands of particular sizes and mineral proportions) • Storage and filtration of water through sand	• Dune height • Dune crest width • Dune field width • Variability in dune height • Wave height • Wave period • Water level • Storm duration • Presence of vegetation • Berm width • Beach slope	• Coastal storm damage reduction • Shoreline erosion control • Water catchment and purification • Aquifer recharge • Tourism • Recreation • Education	• Improved water quality • Ecosystem diversification (biodiversity) • Increased recreational opportunities • Reduction of unwanted sediment sources • Increased information and knowledge • Generation of biogeochemical activity and productivity • Wildlife habitat creation and preservation • Creation of aesthetic landscapes
Freshwater wetlands	• Short- and long-term storage of overbank floodwater • Detention of surface water runoff from surrounding areas • Infiltration of flood water followed by percolation to aquifer • Sediment retention and deposition	• Vegetation type • Vegetation density • Flow velocity	• Coastal flood risk reduction • Water quality regulation • Nutrient retention and export • Tourism • Recreation • Education	• Ecosystem diversification (biodiversity) • Enhanced and diversified food production and farming • Organic matter accumulation • Nutrient and pollution uptake and retention • Generation of biogeochemical activity and productivity • Creation of habitat for macro-invertebrates, fish, reptiles, birds, and mammals, and increased landscape structural diversity • Biomass production, biomass import/export via physical and biological processes • Fish and game production (for food)

Coastal Storm Damage Reduction Features	Relevant Coastal Storm Damage Reduction and Resilience Processes and Functions Provided	Potentially Important Performance Factors	Potential Coastal Risk Reduction and Socioeconomic and Environmental Resilience Outcomes	Potential Additional Socioeconomic and Environmental Benefits (Direct and Indirect)
Maritime Forests	• Wave attenuation and/or dissipation • Shoreline erosion regulation • Soil retention via vegetation's root structures	• Wave height • Water level • Vegetation height • Vegetation density • Platform elevation • Sediment composition • Forest dimensions	• Coastal storm damage reduction • Water quality regulation • Groundwater recharge and discharge • Tourism • Recreation • Education	• Ecosystem diversification (biodiversity) • Enhanced and diversified food production and timber production • Nutrient cycling • Weathering and erosion • Air quality regulation • Creation of aesthetic landscapes • Sediment retention and deposition, including soil formation through accumulation of organics • Trace element storage and export • Fish and wildlife habitat creation and preservation
Nonstructural (e.g., elevating or relocating structures, floodproofing, land use regulation, evacuation planning, managed retreat, buyout-leaseback,)	• Reduced opportunity for damages • Increased community resiliency	• Wave height • Water level • Storm duration	• Coastal flood risk reduction • Improved community and individual preparedness • Reduced damages and repetitive losses	• Alteration of floodplain development • Sustained/improved natural coastal environment • Improved public awareness and responsibility • Support for natural floodplain • Adaptability for changing environment and societal needs • Potential for lower-cost implementation than structural measures
Levees	• Wave and surge attenuation and/or dissipation • Reduced flooding	• Levee height • Levee slope • Levee crest width • Wave height • Wave period • Water level	• Coastal flood risk reduction	• •Increased evacuation time • •Risk reduction for vulnerable populations

Coastal Storm Damage Reduction Features	Relevant Coastal Storm Damage Reduction and Resilience Processes and Functions Provided	Potentially Important Performance Factors	Potential Coastal Risk Reduction and Socioeconomic and Environmental Resilience Outcomes	Potential Additional Socioeconomic and Environmental Benefits (Direct and Indirect)
Storm Surge Barriers	• Surge and wave attenuation	• Barrier height • Wave height • Wave period • Water level	• Coastal flood risk reduction • Water quality regulation	• Reduced salinity intrusion • Harbor protection and associated economic risk reduction
Seawall/Revetment	• Reduced flooding • Reduced wave overtopping • Shoreline stabilization behind structure	• Wave height • Wave period • Water level • Scour protection	• Coastal storm damage reduction	• Possible recreational opportunities (e.g., fishing)
Groins	• Shoreline stabilization	• Longshore transport rates and distribution • Groin length • Groin height • Groin orientation • Groin permeability • Groin spacing • Depth of seaward end of groin	• Coastal erosion reduction with groin field	• Possible recreational opportunities (e.g., fishing)
Breakwaters	• Shoreline stabilization behind structure • Wave attenuation	• Wave height • Water level • Breakwater height • Breakwater width • Breakwater permeability • Breakwater proximity to the shoreline • Breakwater orientation • Breakwater spacing	• Coastal erosion reduction in lee of structure • Wave damage reduction in lee of structure	• Harbor protection and associated economic risk reduction