Coastal Risk Reduction and Resilience

US Army Corps of Engineers

Civil Works Directorate

US Army Corps of Engineers
BUILDING STRONG®

July 2013

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. This paper discusses USACE 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 combination of approaches, including natural or nature-based features (e.g., beaches and dunes), nonstructural interventions (e.g., policies, building codes and land use zoning, and emergency response such as early warning and evacuation plans), and structural interventions (e.g., seawalls or breakwaters). Natural and nature-based features can attenuate waves and provide other ecosystem services (e.g. habitat, nesting grounds for fisheries, etc.), 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 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 approach to reducing coastal risks and increasing human and ecosystem community resilience through a combination of natural, nature-based, non-structural and structural measures. 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 measures that integrates 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 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. 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 through the incorporation of natural and nature-based features in addition to nonstructural and structural measures that also improve social, economic, and ecosystem resilience.

Table of Contents

PDT (alphabetical order): Todd Bridges (CEERD), Charley Chesnutt (CEIWR), Roselle Henn (CENAD), Paul Wagner (CEIWR), Candy Walters (CEPA), Ty Wamsley (CEERD), Kate White (CEIWR)

Author Team (alphabetical order): Todd Bridges (CEERD), Roselle Henn (CENAD), Shawn Komlos (CEIWR), Debby Scerno (CECW), Ty Wamsley (CEERD), Kate White (CEIWR)

Contributions from (alphabetical order): Randall Behm (CENWO), 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), Paul Wagner (CEIWR), Candy Walters (CEPA)

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, our "nurseries of the sea" (USEPA 1993), provide habitat critical to the life cycle of more than 75 percent of the nation's commercial catch (National Safety Council Environmental Center, 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. The potential for environmental and economic damage and loss of life is exacerbated by many factors, including coastal development characteristics, sea level rise, coastal subsidence, and loss of environmental features, such as dunes, wetlands and other habitats that can contribute to risk reduction and coastal resilience. 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 impacts can be widespread and enduring. Rising sea level and potential changes in storm frequency and severity underscore the importance of proactive approaches to reduce the risks to coastal residents and ecosystems, and improve the resilience of the socioeconomic systems, ecosystems, and infrastructure on which they depend. The level of threat is determined in part by the degree of socio economic and ecosystem vulnerability as well as the resilience of the human and ecosystem communities absorbing these coastal impacts. Public health and safety and economic stability may be at risk for developed coastlines, including direct and indirect (e.g., water quality due to failure of critical infrastructure such as wastewater treatment plants). For undeveloped coastlines, a key challenge is ensuring continued delivery of beneficial ecosystem services that help mitigate the impacts of these changing conditions.

> *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* as modifiers to describe different types of coastal risk reduction infrastructure that the USACE considers as parts of its portfolio of risk management measures. Other terminology has and will continue to be used by our partners and stakeholders to describe the use of environmental systems to accomplish multiple purposes, including stormwater management, flood risk management, water conservation, and improved water quality as well providing other environmental benefits (e.g., USEPA[1], White House Conference on Green Infrastructure[2], Kousky et al 2013, McDonald et al 2005, McMahon and Benedict 2000).

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 States, 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 ecosystem resources, 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 include a spectrum of features, ranging from those that exist due exclusively to the work of natural process to those that are the result of human engineering and construction. The built components of the system include nature-based and engineered structures that support a range of objectives, including 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.

Natural and Nature-Based Features

Natural and nature-based features (Figure 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). Natural features are created through the action of physical, biological, geologic, and chemical processes operating in nature, whereas nature-based features are created by human design, engineering, and construction.

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

Natural and Nature-Based Infrastructure at a Glance

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

Dunes and Beaches

Benefits/Processes

Break offshore waves

Attenuate wave energy

Slow inland water transfer

Performance Factors

Berm height and width

Beach Slope

Sediment grain size and supply

Dune height, crest, width

Presence of vegetation

Vegetated Features: Salt Marshes, Wetlands, Submerged Aquatic Vegetation (SAV)

Benefits/Processes

Break offshore waves

Attenuate wave energy

Slow inland water transfer

Increase infiltration

Performance Factors

Marsh, wetland, or SAV elevation and continuity

Vegetation type and density

Oyster and Coral Reefs

Benefits/Processes

Break offshore waves

Attenuate wave energy

Slow inland water transfer

Performance Factors

Reef width, elevation and roughness

Barrier Islands

Benefits/Processes

Wave attenuation and/or dissipation

Sediment stabilization

Performance Factors

Island elevation, length, and width

Land cover

Breach susceptibility

Proximity to mainland shore

Maritime Forests/Shrub Communities

Benefits/Processes

Wave attenuation and/or dissipation

Shoreline erosion stabilization

Soil retention

Performance Factors

Vegetation height and density

Forest dimension

Sediment composition

Platform elevation

Figure 1: Natural and nature-based features at a glance. For more detailed information, see summary table in Appendix A.

For example, beaches are natural and nature-based features that provide coastal storm risk reduction (e.g., USACE 2013) 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. The dunes that may back a beach act as a physical barrier that reduces inundation and wave attack to the coast landward of the dune. Although the dune may erode during a storm, it provides a sediment source for recovery after a storm passes. Beach nourishment can be used to promote coastal risk reduction (Dean and Dalrymple 2004) by introducing additional sand into the system to reinforce the natural protection to the upland afforded by the beach, and therefore reduces risk due to wave damage and inundation. Wave damage and flood risk reduction provided by beach nourishment is enhanced when dune construction or restoration is included.

Coastal wetlands can also provide coastal storm protection services through wave attenuation and sediment stabilization. The dense vegetation and shallow water depths within wetlands can slow the advance of storm surge somewhat and slightly reduce the surge landward of the wetland or slow its arrival time slightly (Wamsley et al 2009 and 2010). Wetlands also dissipate wave energy, potentially reducing the amount of destructive wave energy propagating on top of the surge. However, each of these processes might tend to retard the storm surge propagation in one area; but in the process of slowing storm surge advance, the movement of water might be slightly redirected toward another location, potentially causing a local storm surge increase elsewhere.

Dynamic Character of Natural and Nature-Based Features

Natural and nature based features respond dynamically to processes such as storms, both negatively and positively, with temporary or permanent consequences. For wetlands, impacts might include erosion, stripped vegetation, flooding stress, salinity burn, and longer term decreases in wetland productivity; a benefit is the introduction of mineral sediments that are vital to long-term sustainability. The long-term consequences on wetland systems from hurricanes is dependent on many factors, including pre-storm landscape structure (including anthropogenic modifications), proximity of the wetland to a storm track, and the meteorological conditions that persist following a hurricane. Storms are the dominant cause of coastal change on barrier islands. Hurricane surge and waves can 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. In the case of wetlands, available evidence suggests that slow-moving storms and those with long periods of high winds (such as Hurricane Sandy) produce marsh flooding, which can reduce the storm-damage reduction benefit (Resio and Westerlink 2008). Over longer time scales, projections of sea level rise suggest that areas presently seen as "natural" may require management and intervention if their ability to provide socially desired ecosystem services is to be preserved.

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

Nonstructural Measures

The Economic and Environmental Principles and Guidelines for Water and Related Land Resources Implementation Studies (P&G, U.S. Water Resources Council, 1983) describes non-structural measures as complete or partial alternatives to structural measures, including modifications in public policy, management practices, regulatory policy and pricing policy. Nonstructural measures essentially "modify the impacts" of the flood hazard, as compared to structural measures, which "modify the flood hazard." The impacts of the flood hazard can be modified by reducing susceptibility to flood and coastal storm damage and disruption and by reducing the flood and coastal storm impact on individuals and communities. Nonstructural measures 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 (Figure 2). Nonstructural measures can be blended well with the natural and nature-based features of the coastal environment, as well as structural measures.

onstructural measures are most often under the jurisdiction of State and local governments (and individuals) to develop, implement and regulate, and cannot be 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. 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.

Non-Structural Measures at a Glance

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

Floodplain Policy & Management	Floodproofing and Impact Reduction	Floodproofing and Impact Reduction	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	Does not increase flood potential elsewhere
Improved natural coast environment	Does not increase flood potential elsewhere	Does not increase flood potential elsewhere	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			

Figure 2. Nonstructural features at a glance. For more detailed information, see summary table in Appendix A.

Structural Measures

Structural measures reduce coastal risks by decreasing shoreline erosion, wave damage and flooding. Traditional structures include levees, storm surge barrier gates, seawalls, revetments, groins, and nearshore breakwaters (Figure 3). The purpose of levees, seawalls and storm surge barrier gates is to reduce coastal flooding, while revetments, groins, and breakwaters are intended to reduce coastal erosion. All of these measures can reduce wave damage. 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 water 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. Erosion of the beach profile landward of a seawall might be stopped or at least reduced, but 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 a steeper seabed profile, which subsequently allows larger waves to reach the structure.

> *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 straight and 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 small, relatively short, nearshore structures built parallel to the shore just seaward of the shoreline in shallow water depths, with the principal function of reducing beach erosion through reducing wave height and thus, longshore and cross-shore sediment transport. Detached breakwaters are low-crested structures that decrease wave energy, are less visible, 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 do represent a serious non-visible hazard to boats and swimmers. Like 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.

Structural Measures at a Glance

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

Levees

Benefits/Processes

Surge and Wave attenuation and/or dissipation

Reduce Flooding

Risk Reduction for vulnerable areas

Performance Factors

Levee height, crest width, and slope

Wave height and period

Water level

Storm Surge Barriers

Benefits/Processes

Surge and Wave attenuation

Reduced Salinity Intrusion

Performance Factors

Barrier height

Wave height

Wave period

Water level

Seawalls and Revetments

Benefits/Processes

Reduce flooding

Reduce wave overtopping

Shoreline stabilization behind structure

Performance Factors

Wave height

Wave period

Water level

Scour protection

Groins

Benefits/Processes

Shoreline stabilization

Performance Factors

Groin length, height, orientation, permeability and spacing

Depth at seaward end

Wave height

Water level

Longshore transportation rates and distribution

Detached Breakwaters

Benefits/Processes

Shoreline stabilization behind structure

Wave attenuation

Performance Factors

Breakwater height and width.

Breakwater permeability, proximity to shoreline, orientation and spacing

Figure 3. Structural features at a glance. For more detailed information, see summary table in Appendix A.

Environmental and Social Benefits

USACE projects that integrate natural, nature-based, non-structural and structural measures to achieve coastal risk reduction goals can also produce a range of 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, provisioning of clean water, habitat for threatened and endangered species, and support for cultural practices. For example, breakwaters offer shoreline erosion protection by attenuating wave energy, but can provide additional recreational opportunities, valuable aquatic habitat, and carbon or nutrient sequestration. Ecosystem restoration features such as coastal wetlands, forests, oyster reefs, or dune and beach complexes provide intended environmental and social benefits, but may also provide coastal risk reduction or resiliency.

A more complete understanding of the ecosystem goods and services provided by the full range of coastal features will help to inform plan formulation and benefit determination for risk reduction strategies. Some services are complementary, such as wetland restoration that increases habitat and floodwater retention within those wetlands, and others are conflicting, such as dune creation for flood protection that competes with sightline or viewshed concerns (see NJ Supreme Court ruling in Borough of Harvey Cedars v. Karan, A-120-11). As sea level rise and climate change influence the coastal environment, taking a comprehensive view of the services and benefits provided by the integrated system will support adaptively managing the performance of the system.

Integrated Coastal Risk Reduction Approaches

The USACE planning approach supports an integrated approach to reducing coastal risks and increasing human and ecosystem community resilience through an optimal combination of natural, nature-based, non-structural and structural measures. The ability of the various 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 engineering approaches that are applied to developing the integrated system will depend on the geophysical setting, the desired level of risk reduction, constraints, objectives, cost, reliability, and other factors.

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 "limits the amount of flood water carried in the river to its safe capacity and sends the surplus water through lateral floodways" (Jadwin 1928), many of which operated successfully during the flood of 2011.

> *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.*

An integrated systems approach to the development of coastal infrastructure considers the engineering attributes of the component features and the dependencies and interactions among these features over both the short- and long-term. Levees and other man-made barriers are intended to reduce impacts from storm surge, but they also may cause a build-up of storm surge by obstructing the movement of water driven by hurricane-force winds, with the result that 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 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, as another line of defense. This "lines of defense" approach can incorporate other 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 to calculate and measure performance. Factors include the specified objectives, the threats under consideration (e.g., 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 performance 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 objectives. As a result, coastal risk reduction and resilience services provided by natural and nature-based features will vary over space and time. 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, which has resulted in widely varying characterizations of benefit(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" that surge is attenuated at a rate of X feet per Y miles of marsh. The actual situation is much more complex and dependant on many details including storm intensity, track, forward speed, and surrounding local bathymetry and topography. Simple rules of thumb may not take into account these complexities along a coastline or between storms (Resio and Westerlink 2008), or be able to resolve the information appropriately. 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 interaction of the storms and the natural or nature-based features, which are dependent on the intensity, track, and forward speed of the storm, as well as elevation, vegetation type, density, and height, and the surrounding local bathymetry and topography.

Knowledge Gaps

Focused research is needed to reduce the uncertainties with evaluating and quantifying the value and performance of natural and nature-based measures for coastal risk reduction. Federal investments supporting 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 2012). This would help to better inform the design of coastal risk reduction systems.

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 (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, transparent and inclusive planning, that embraces 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 (Figure 4) 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.

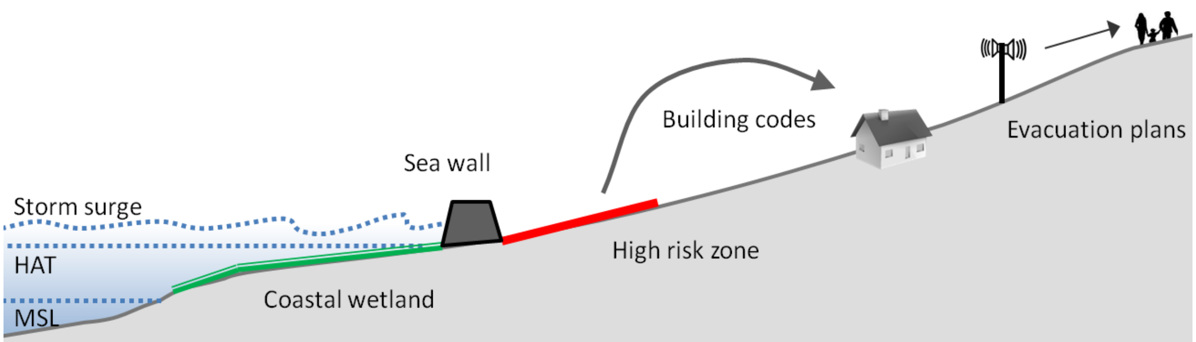

Figure 4. An integrated system can be achieved through a combination of natural, nature-based, nonstructural and structural features (from Spaulding et al, in publication).

References

Anderson, M.E., J.M. Smith, and S.K. McKay (2011) Wave Dissipation by Vegetation. Coastal and Hydraulics Engineering Technical Note ERDC/CHL CHETN-I-82. Vicksburg, MS: U.S. Army Engineer Research and Development Center. http://chl.erdc.usace.army.mil.chetn.

Borsje, B. W., B. K. van Wesenbeeck, F. Dekker, P. Paalvast, Tj. J. Bouma, M. M. van Katwijk, M.t B. de Vries (2011) How ecological engineering can serve in coastal protection, Ecological Engineering, Vol 37, No. 2, Pages 113-122.

Cialone, M.A., Brown, M.E., Smith, J.M. and Hathaway, K.K. (2008) Southeast Oahu coastal hydrodynamic modelling with ADCIRC and STWAVE. Technical Report ERDC/CHL TR-08-9, U.S. Army Corps of Engineers, Coastal and Hydraulics Laboratory, Vicksburg, MS.

Colgan, C.S. (2008) "The Value of Estuary Regions in the U.S. Economy" in *The Economic and Market Value of Coasts and Estuaries: What's At Stake?* [L.H. Pendleton, ed.] Restore America's Estuaries: Arlington VA. p. 37-64. (p 43-44).

Craig R.K. (2010) "'Stationarity is dead,' long live transformation: Five principles for climate change adaptation law." Harvard Environ Law Rev 34:9–73.

Dean, R.G. and Dalrymple, R.A. (2004) Coastal Processes with Engineering Applications. Cambridge University Press, Cambridge UK, 475 pp.

Gedan, Keryn B., Matthew L. Kirwan, Eric Wolanski, Edward B. Barbier, and Brian R. Silliman (2011) The present and future role of coastal wetland vegetation in protecting shorelines: answering recent challenges to the paradigm. Climatic Change Vol. 106, Issue 1, pp 7-29

Jadwin, E. (1928) "The Plan for Flood Control of the Mississippi River in Its Alluvial Valley. Presented to the Secretary of War and by Him to Congress." Reprinted in Annals of the American Academy of Political and Social Science , Vol. 135, Great Inland Water-Way Projects in the United States (Jan., 1928), pp. 34-44.

Jin, D. (2008) "Economic Benefits of Coastal Restoration to the Marine Transportation Sector." in *The Economic and Market Value of Coasts and Estuaries: What's At Stake?* [L.H. Pendleton, ed.] Restore America's Estuaries: Arlington VA. p. 97-115.

Kates, R.W., W.R. Travis, T.J. Wilbanks (2012) "Transformational adaptation when incremental adaptations to climate change are insufficient." *Proceedings of the National Academy of Sciences,* 109(19): 7156-7161 doi: 10.1073/pnas.1115521109

Kousky, C. , S. M. Olmstead, M. A. Walls, and M. Macauley (2013) Strategically Placing Green Infrastructure: Cost-Effective Land Conservation in the Floodplain. Environmental Science & Technology 2013 47 (8), 3563-3570

McDonald, L., Allen, W., Benedict, M., & O'Connor, K. (2005). Green infrastructure plan evaluation frameworks. Journal of Conservation Planning, 1(1), 12-43.

McMahon, E. T., & Benedict, M. A. (2000) Green infrastructure. Planning Commissioners Journal, 37(4).

McNamara, D.E., A.B. Murray, and M.D. Smith (2011) "Coastal sustainability depends on how economic and coastline responses to climate change affect each other." *Geophysical Research Letters,* Vol 38, L07401 doi:10.1029/2011GL047207

Pendleton, L.H. (2008) "The Economic Value of Coastal and Estuary Recreation." in The Economic and Market Value of Coasts and Estuaries: What's At Stake? [L.H. Pendleton, ed.] Restore America's Estuaries: Arlington VA. p. 140-165 (p. 165)

Resio,D.T.,Westerink,J.J. (2008)Modelingthephysicsofstormsurge.Physics Today 61(9),33–38

Spaulding, M, A. McIvo, M. Beck, E. Koch, I. Moller, D. Reed, P. Rubinoff, T. Spencer, T. Tolhurst, B. van Wesenbeeck, T. Wamsley, E. Wolanski, C. Woodroffe. In Publication. Coastal ecosystems: a critical element of risk reduction. Conservation Letters.

Stockton, S.L. and K.D. White (2011) "U.S. Army Corps of Engineers' Collaborative Approach to Twenty-First Century Challenges Posed by Global Change." Chapter 3 IN Global Change and Local Adaptation. p. 19-35 Springer: Netherlands.

Strauss, B.H, R. Ziemlinski, J.L. Weiss, and J.T. Overpeck (2012) "Tidally adjusted estimates of topographic vulnerability to sea level rise and flooding for the contiguous United States." *Environmental Research Letters*, 7:014033 doi:10.1088/1748-9326/7/1/014033

Suzuki, T. M. Zijlema, B. Burger, M. C. Meijer, S. Narayan (2012) Wave dissipation by vegetation with layer schematization in SWAN. Coast. Eng. 59, 64.

Sweet, W., C. Zervas, and S. Gill (2009) "Elevated East Coast sea level anomaly: June – July 2009." NOAA Technical Report NOS CO-OPS 051, National Ocean Service Center for Operational Oceanographic Products and Services: Silver Spring, MD.

USACE (2009) "Mississippi Coastal Improvement Plan (MsCIP)." Mobile: USACE Mobile District. http://www.sam.usace.army.mil/Missions/ProgramandProjectManagement/MsCIPProgram.aspx

USACE (2010) "Building Strong Collaborative Relationships for a Sustainable Water Resources Future National Report: Responding to National Water Resources Challenges." Washington DC: USACE Civil Works Directorate. http://www.building-collaboration-for-water.org/

U.S. Water Resources Council (1983) Economic and environmental principles and guidelines (P&G) for water and related land resources implementation studies: U.S. Water Resources Council, available online at http://www.usace.army.mil/cw/cecw-cp/library/Principles_Guidelines.pdf.

Wamsley, T.V. (2009) Interaction of Hurricanes and Natural Coastal Features: Implications for Storm Damage Reduction. Water Resources Engineering, Lund University. Doctoral Thesis. LUTVDG/TVVR-1049.

Wamsley, T.V., Cialone, M.A., Smith, J.M., Ebersole, B.A. (2009) Influence of landscape restoration and degradation on storm surge and waves in southern Louisiana. Journal of Natural Hazards, 51 (1), 207-224.

Wamsley, Ty V., M. A. Cialone, J.M.Smith, J. H. Atkinson, and J. D. Rosati (2010)The potential of wetlands in reducing storm surge. Ocean Engineering 37:59–68

Y. Yao, Z. Huang, S. G. Monismith, E. Y. M. Lo. (2012) 1DH Boussinesq modeling of wave transformation over fringing reefs. Ocean Eng. 47, 30.

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	• Provide vertical structure, slows current velocity at boundary • Attenuate waves, may slow velocity at boundary • Generates biogeochemical activity and productivity • Increases 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) • Enhance and diversify food production • Provide 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	• Improve biological productivity • Provide unique and aesthetic reefscapes • Provide suitable habitat for diverse flora and fauna • Generate 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	• Improve biological productivity • Provide unique and aesthetic reefscapes • Provide suitable habitat for diverse flora and fauna) • Generate biogeochemical activity and productivity • Increase Information and knowledge • Provide 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) • Enhance and diversify food production • Nutrient and pollution uptake and retention • Provide aesthetic landscapes • Provide 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	• Provide aesthetic landscapes • Ecosystem diversification (biodiversity) • Reduction of unwanted sediment sources • Provide 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) • Store and filter 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	• Provide unique and aesthetic landscapes Flood protection Improve 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 • Supports sediment cycle • Raw material provision (sands of particular sizes and mineral proportions) • Store and filter 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	• Improve water quality • Ecosystem diversification (biodiversity) • Increase recreational opportunities • Reduction of unwanted sediment sources • Increase Information and knowledge • Generate biogeochemical activity and productivity • Wildlife habitat creation and preservation • Provide 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) • Enhance and diversify food production and farming • Organic matter accumulation • Nutrient and pollution uptake and retention • Generate biogeochemical activity and productivity • Provide habitat for macro-invertebrates, fish, reptiles, birds, mammals, and 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) • Enhance and diversify food production and timber production • Nutrient cycling • Weathering and erosion • Air quality regulation • Provide 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,)	• Reduce opportunity for damages • Increase community resiliency	• Wave height • Water level • Storm duration	• Coastal flood risk reduction • Improve community and individual preparedness • Reduce damages and repetitive losses	• Alter floodplain development • Sustain/improve natural coastal environment • Improve public awareness and responsibility • Support natural floodplain • Adaptable to changing environment and societal needs • Can be lower cost implementation than structural measures
Levees	• Wave and surge attenuation and/or dissipation • Reduce flooding	• Levee height • Levee slope • Levee crest width • Wave height • Wave period • Water level	• Coastal flood risk reduction	• •Increase evacuation time • •Risk reduction for vulnerable populations
Storm Surge Barriers	• Surge and wave attenuation	• Barrier height • Wave height • Wave period • Water level	• Coastal flood risk reduction • Water quality regulation	• Reduce salinity intrusion • Harbor protection and associated economic risk reduction

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)
Seawall/Revetment	• Reduce flooding • Reduce 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

Appendix B: Talking Points

U.S. coastlines are especially vulnerable to risks, now and in the future, caused by waves and surges associated with sea level change and coastal storms that impact human and ecological resources.

As an engineering organization, the U.S. Army Corps of Engineers has long recognized the value of 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.

Coastal risk reduction can be achieved through a combination of approaches, including natural or nature-based features (e.g., beaches and dunes), nonstructural interventions (e.g., policies, building codes and land use zoning, and emergency response such as early warning and evacuation plans), and structural interventions (e.g., seawalls or breakwaters).

Natural features can support risk reduction, and also provide other ecosystem services (e.g., habitat, nesting grounds for fisheries, etc) that ultimately contribute to increased coastal resilience.

An integrated approach to reduce coastal risks and increase human and ecosystem resilience seeks an optimal combination of the available measures (natural, nature-based, non-structural and structural) in an effort to provide reliable and predictable levels of service.

The types of measures employed, their configuration within the network of features, and the engineering approaches that are applied to developing the integrated system will depend on the geophysical setting, the desired level of risk reduction, constraints, objectives, cost, reliability, and other factors.

Focused research is needed to reduce the uncertainties with evaluating and quantifying the value and performance of natural and nature-based measures for coastal risk-reduction.

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 risk and improve resilience, as embodied in our “Building Stronger Collaborative Relationships” Initiative.