BIOENGINEERED SHORELINE STABILIZATION

Audience: The intended audience for this job aid is local, tribal, and state government representatives who do not necessarily have a technical background or experience in bioengineering. FEMA has developed this job aid to encourage planners, government officials, grant applicants, and others to consider bioengineering approaches to coastal shoreline stabilization in addition to more traditional "hard" methods.

DEFINITION

Bioengineered shoreline stabilization methods use living and nonliving plant materials together with natural and synthetic construction materials to reduce coastal erosion, establish vegetation, and stabilize shorelines. The application of bioengineering methods to stabilize shorelines is continuously evolving and often referred to as the “Living Shorelines” concept. This job aid discusses the benefits of bioengineered solutions, commonly used measures, and steps to plan and execute a successful project, including criteria to use in selecting the appropriate approach for a site. The job aid also presents successful case studies demonstrating practical applications and benefits of bioengineered shoreline stabilization methods in coastal environments subject to erosion and habitat degradation.

Bioengineered solutions use native vegetation and other suitable plant species with structural components to stabilize and reduce erosion along the shoreline. Conventional ("hard" or "grey") solutions are solely focused on and serve to provide stabilization, while bioengineered measures have added benefits discussed in this job aid. Hard or grey solutions are typically structural measures taken where absolutely inevitable (e.g. to prevent shoreline erosion in high-erosion areas), resulting in inadequate consideration for their effects on the ecosystem. These measures may be quite effective for shoreline stabilization purposes alone, but will have neutral to negative impacts on the ability of the shoreline to perform its natural ecosystem services as a habitat for plant and animal species. Applied judiciously and in limited cases (such as cases of extreme erosion rates) hard shoreline stabilization methods are an appropriate engineering intervention, but when applied uniformly over large stretches of coastline the cumulative negative effects of these interventions can be substantial and lead to degradation of coastal habitats.

Hard or grey solutions may be unavoidable in some cases, but bioengineering approaches provide a self-stabilizing, low-maintenance solution for many impaired shorelines and eroding bluffs (steeply sloped shorelines formed by loose sediment such as clay, sand, and gravel). The underlying principle requires an integrated watershed and shoreline (sediment transport) system-based approach. The approach should use sound engineering practices and ecological principles to assess, design, construct, and maintain living vegetative systems that are blended into the shoreline and the supported coastal ecosystem. The primary causes of erosion in a given watershed may be varied, but usually involve downhill sediment transportation, the process by which material (e.g., sand, silt, clay, gravel, cobbles) that makes up the shoreline moves as it interacts with wind, waves, currents, and gravity by the action of flowing water. Once sediment reaches the coast, wind, waves, and current continue to move it around. Understanding where this sediment comes from, how and why it moves as part of the coastal sediment transport system, and how it ultimately leaves the system is important for any engineering project in the coastal zone.

Bioengineering can be used on shorelines that require structural intervention to facilitate growth of natural vegetation. Once the vegetation's root system is established, it provides additional shoreline and bluff stability. Projects will likely involve an interdisciplinary effort between scientists, engineers, and landscape architects. Successful projects can help repair damage caused by erosion and slope failures; protect or enhance already healthy, functioning systems; and ensure long-term sustainability of the impaired shoreline and coastal habitat areas. Under FEMA programs, proposed bioengineering coastal stabilization project must meet program eligibility requirements, including mitigation of potential infrastructure damage.

BIOENGINEERED SHORELINE STABILIZATION

BENEFITS

TECHNICAL BENEFITS:

1. Protects against erosion while leaving the shoreline system intact (as compared with "hard" solutions which can shift the location of erosion when not installed properly or when sited inappropriately).
2. Stabilizes the shoreline and reduces current rates of shoreline erosion and storm damage. Living shorelines have been shown to experience less erosion damage than "hard" stabilization methods during storm events.
3. Enhances coastal resilience and attenuation of wave energy and storm surge.
4. Can be used to satisfy zoning and permitting requirements for waterfront development projects.
5. Creates educational opportunities to learn about natural habitats.

ECONOMIC BENEFITS:

1. Generates long-term cost savings, as native, local plants better adapt to the local climate without becoming invasive.
2. Minimizes maintenance requirements and stabilizes shorelines over time as plants, roots, and oyster reefs grow, which can be especially beneficial in remote areas.
3. Enhances natural capacity for potential adaptation to moderate amounts of sea level rise.
4. Creates opportunities for local ownership of shoreline management.
5. Increases property values.
6. Supports fisheries and other marine-based industries through maintenance of coastal habitats.

ECOLOGICAL BENEFITS:

1. Supports fish and wildlife populations through restored and enhanced habitat and ecosystem function.
2. Protects and enhances coastal wetlands.
3. Improves water quality by settling or trapping sediment (for example, once established, a marsh can filter surface water runoff, or oysters can provide coastal water filtration).
4. Increases capacity of habitat/shoreline to withstand coastal flooding, wave impact, and erosion.
5. Reduces sedimentation and nutrient loading by reducing erosion of upland sediments.

AESTHETIC BENEFITS:

1. Improves landscape in coastal and estuarine areas and allows for more natural display than traditional grey infrastructure approaches.
2. Protects cultural, historical, and archaeological resources.
3. Improves public access to waterfront through recreational activities such as fishing, boating, and birding.
4. Provides natural recreational opportunities.
5. Expands the intertidal zone, improving access.

COMMONLY USED MEASURES

Bioengineered shoreline stabilization is accomplished by making engineering interventions, commonly referred to as "living shorelines," within the coastal shoreline continuum (Figure 1). Bioengineering methods that rely more heavily on the role of native vegetation and natural materials are typically considered "greener," while those methods that rely primarily on the installation of hard structural solutions are considered to be more "grey". Almost all living shoreline

BIOENGINEERED SHORELINE STABILIZATION

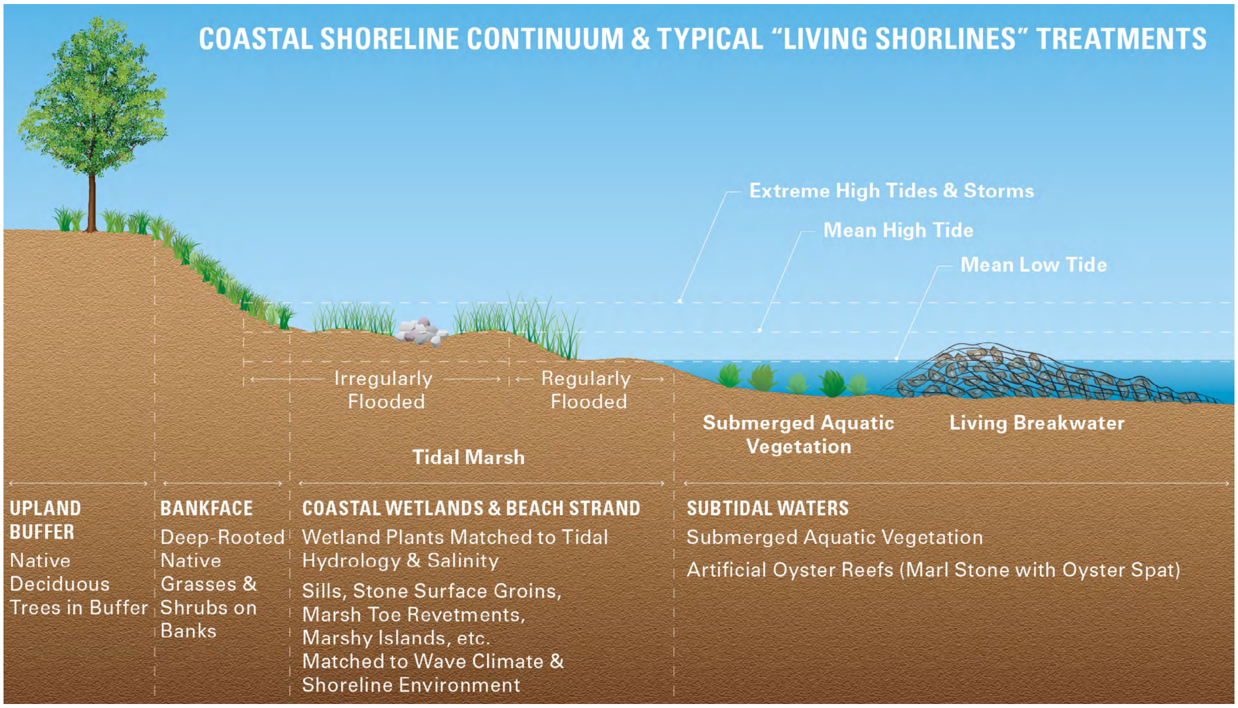


Figure 1. Bioengineering strategies for shoreline stabilization via a "Living Shorelines" approach. See Appendix for more detail on specific measures. (Source: adapted from https://www.habitatblueprint.noaa.gov/wp-content/uploads/2016/04/NOAA-Living-Shorelines-Guidance-01-300x194.png)

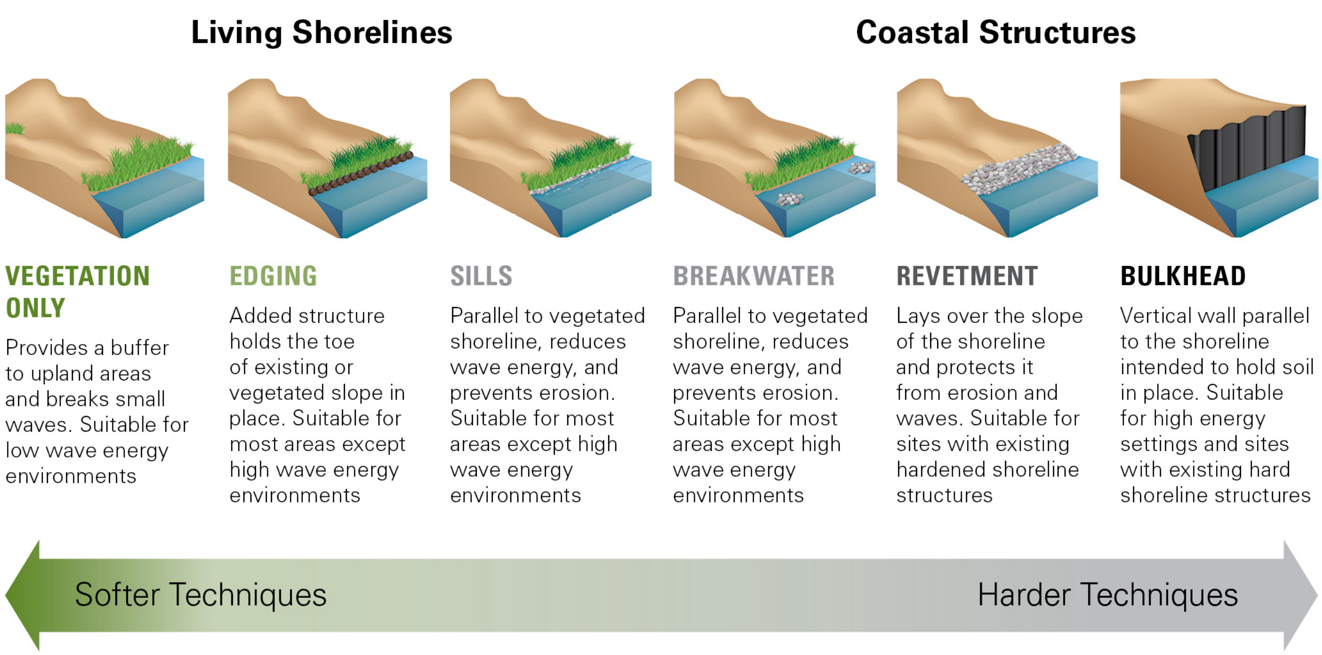


Figure 2: A continuum of green (soft) to grey (hard) shoreline stabilization techniques. (Source: This continuum is based on the more detailed continuum in the Systems Approach to Geomorphic Engineering (SAGE) Natural and Structural Measures for Shoreline Stabilization brochure (SAGE 2015)).

projects will fall somewhere in the middle of this spectrum, not fully green nor fully grey (Figure 2); however, a fully "grey" intervention would not be considered a living shoreline. Additionally, some existing "grey" structures can be made "greener" through simple alterations that incorporate native plant communities, oysters, and/or artificial habitat into the existing structure.

Commonly used bioengineered shoreline stabilization measures generally focus on reducing wave impacts, mitigating storm surge, minimizing erosion, improving slope stability, and/or creating/improving coastal habitat. Measures generally fall into one of the following categories:

- Beach/Dune Stabilization
- Bank Regrading/Stabilization
- Marsh Restoration
- Drainage
- Revetment
- Bulkhead

Table 1 in the Appendix provides more detail on some commonly used bioengineering measures applicable in coastal environments. These techniques are generally applicable to coastal stabilization projects but the specific methods chosen will vary based on project goals, site and shoreline characteristics, and habitat considerations. The types of plants used will vary based on geographic region and site characteristics; lists of native plants are generally available from state natural resources or conservation agencies.

PROJECT PLANNING AND EXECUTION – STEPS FOR SUCCESS

Planning and execution of a bioengineering shoreline stabilization project generally follows these minimum six steps:

Step 1 - Problem Definition/Objective Setting: The first step is to clearly and correctly define the problem, i.e., the extent and cause of shoreline erosion/bluff instability, and prioritizing restoration objectives as well as stakeholder needs.

Step 2 - Data Collection and Analysis: The project team should, at a minimum, collect and review data and photos to characterize the project site based on hydrodynamics, morphodynamics, sediment dynamics, anthropogenic factors, local ecology and water quality, and pertinent environmental data. Important design considerations include site accessibility, site grade and orientation, watershed flows, longshore currents, fetch (length of open water over which wind from a given direction can travel to create waves), bed material properties and sediment sources/sinks, and debris and maintenance needs.

- **Hydrodynamics** describe the movement of water at the site by processes such as waves, tides, and wind-induced currents as well as hydrological processes such as rainfall, infiltration, and runoff.
- **Morphodynamics** describe the shape and movement of the land's surface at the site over time. Site orientation, fetch, bathymetry (measurement of depth of water in oceans, seas, or lakes), and topography as well as bluff erosion and shoreline change rates are all important morphodynamic data that should be considered.
- **Sediment Dynamics** describe the movement of sediment, caused by the interaction of wind, water, and local topography with individual sediment particles. Important information includes soil composition, sediment grain size distribution, and the geotechnical properties of soil at the site.
- **Anthropogenic Factors** include all human induced impacts at the site. Examples include: existing coastal structures (e.g. bulkheads, docks), commercial (e.g. dredging and shipping), recreational (e.g. power-boating, fishing), and fisheries and agricultural (e.g. commercially harvested oyster beds and aquaculture facilities) activities.
- **Ecology** describes the naturally occurring and interdependent communities of plant, animal, and microbial species occurring at the site, and the conditions they depend on. Important information includes common species of local grasses and sea-grasses as well as listed threatened and endangered species relying on coastal habitats in the area.

Step 3 - Design Development: In order to meet all established objectives in Step 1, a combination of bioengineering techniques should be considered for a site-specific bioengineering project plan using the following selection criteria:

BIOENGINEERED SHORELINE STABILIZATION

- **Hydrology and Hydraulics:** The anticipated water surface elevations, wave and surge characteristics, prevailing currents, fetch, ice impacts, and related forces should be used to determine the most appropriate type of stabilization structure (hard, bioengineered, or a combination of the two) and the location and extent of selected measures.
- **Coastal Geomorphology:** Form and function of the shoreline and its relationship to the coast and surrounding landscape. Understanding how the actions taken at the project site will affect the adjacent properties as well as the shoreline system as a whole.
- **Geotechnical Considerations:** The type of rock and soil that make up the shoreline and surrounding area influence what measures are appropriate. Soil and geotechnical deficiencies should be evaluated to focus selection of measures that can increase soil erosion resistance and allow for the establishment of vegetation.
- **Cost Effectiveness:** Like other mitigation projects, bioengineering projects must meet cost effectiveness requirements to qualify for FEMA grant funding. Cost effectiveness is evaluated by FEMA using benefit-cost analysis; cost effective projects have a benefit-cost ratio greater than 1.0. FEMA issued supplemental guidance for incorporating environmental benefits into a BCA for stream restoration projects.

Step 4 – Permitting and Regulations: It is important to address and comply with all federal, state, and local regulations and obtain necessary permits subsequent to the completion of conceptual design. Depending on the location, impacts, measures selected, and material employed, various permits or certifications may be required before construction. In general, building and construction permits are required for a project. A list of pertinent regulations at the federal, state, and local levels is included following the case studies below.

DUPLICATION OF PROGRAM REQUIREMENTS

Bioengineered methods may be eligible activities under programs by other federal agencies, such as the U.S. Environmental Protection Agency (EPA), U.S. Army Corps of Engineers (USACE), and the Natural Resources Conservation Service. FEMA will not provide assistance for activities for which it determines the more specific authority lies with another federal agency or program. These other programs and authorities should be examined before applying for Hazard Mitigation Assistance (HMA) funding.

Step 5 – Project Implementation: Project implementation includes site preparation, construction, planting, monitoring, and aftercare. For bioengineering design to be successful, implementation should be closely supervised throughout by someone familiar with implementing bioengineering projects. Continuity of the interdisciplinary team involved in the design is highly recommended. Ideally, bioengineered measures should be installed in seasons with low storm wave induced erosion, when dormant cuttings have the highest success rate. Scheduling the sequence of work is critical to project success, such as considering endangered species' nesting seasons.

Step 6 – Post-construction Monitoring: As with any constructed project, bioengineering project plans must include maintenance and monitoring. These activities may occur more frequently while plants are establishing, but likely will be minimal after they are established. Note that maintenance costs are a local responsibility and not a FEMA-eligible cost.

Overall need for these activities depends on site conditions including climate, ongoing coastal erosion, and storm impacts.

CASE STUDIES

The following case studies discuss the selection and successful implementation of some commonly-used bioengineering measures in locations across the United States with varied site conditions and project objectives.

Case Study 1 - Virginia Institute of Marine Science (VIMS) Teaching Marsh, Gloucester, Virginia: During a bridge expansion project, six to eight feet of fill and construction debris were deposited into an existing tidal marsh. In order to restore the marsh to a functioning state, excess material was excavated and a variety of techniques were used to restore the marsh (Figure 3). These included bank grading, placing sand fill, and planting salt marsh vegetation. The project site is approximately one acre. The goals of the project were to provide a demonstration area for wetland plants, address storm water runoff, improve water quality, and create habitat for wildlife.

Figure 3. VIMS Teaching Marsh, Gloucester, VA before and after bioengineered shoreline restoration (Source: K. Duhring)

Case Study 2 - Hermitage Museum Marsh Sill, Norfolk, Virginia: In order to protect a historic wall located on the Hermitage Museum property, segmented marsh sills (low-profile stone structure containing sand fill) were installed along an eroding bank. The area behind the sills was then filled with sand and more than 5,000 native marsh plants were planted. Additionally, two other wetland areas of the property were restored using fiber logs to retain sand fill and then planted with Spartina grasses (Figure 4).

The Chesapeake Bay Foundation placed oyster reef balls near the Hermitage shoreline and along the marsh sills. Reef balls are hollow spheres of concrete with oyster larvae attached that provide a substrate for oysters to grow on.

Figure 4. Sand fill with stone sills and marsh plantings at the Hermitage Museum, Norfolk VA. The image on the left shows the site just after completion of the marsh sill project and on the right, the same location after the vegetation had begun to establish itself. (Credit: W. Priest)

Case Study 3 - Massachusetts Bank Stabilization: An exposed bank in Massachusetts was eroding at a rate of two feet per year due to seasonal wave impacts. The bank was re-graded and coir rolls were placed at the toe and up the face of the bank. Natural fiber blankets were also installed on the bank face and the site was then planted with native salt-tolerant vegetation (Figure 5). The established vegetation allowed the site to survive Hurricanes Irene and Sandy. (Source: New England Environmental)

Figure 5. Massachusetts bioengineered coastal bank restoration. On the left the pre-intervention condition is seen. In the middle image, coir logs are installed along eroding shoreline. The photo on the right shows the same site ten years after project completion. The established native vegetation has stabilized the bank face. (Source: https://climateactiontool.org/content/restore-natural-coastal-buffers-bioengineering-coastal-banks)

Case Study 4 - Stratford Point Salt Marsh and Reef Ball Shoreline Restoration, Stratford Point, Connecticut: Completed in 2014, this project consists of native salt marsh vegetation planted behind an intertidal breakwater created from reef balls (Figure 6). The first phase of this living shoreline project included a reef consisting of 64 permeable concrete reef balls along with the restoration of a salt marsh behind the reef. Due to the success of the project, an additional 327 reef balls were added in late 2016. The project was constructed on roughly 3.5 acres of intertidal zone land at Stratford Point, which is managed by the Connecticut Audubon Society. The project was the first living shoreline constructed in Connecticut, meant to serve as a test of the feasibility of living shorelines for use by other coastal communities for protection against hurricanes and storms, and for preventing erosion and other impacts of sea level rise. Since the project was completed, more than 12 inches of sediment has accumulated in the intertidal marsh, indicating that this section of shoreline has now transitioned from eroding to accreting as the marsh begins to establish itself.

Figure 6. Stratford Point, CT Bioengineered Shoreline Restoration using reefballs and native saltwater marsh plantings. On the left is the original shoreline prior to the installation of the bioengineered shoreline stabilization measures. The photo on the right shows the same site following project completion. (Source: J. H. Mattei)

BIOENGINEERED SHORELINE STABILIZATION

FEDERAL STATUTES AND REGULATIONS

National Environmental Policy Act (NEPA): The President's Council on Environmental Quality (CEQ) oversees implementation of the National Environmental Policy Act (NEPA). NEPA is the basic national charter for protection of the environment including physical, biological, social, and cultural resources. This law establishes policy, sets goals, and provides a process to review data and information to assess environmental impacts of proposed actions and consider reasonable alternatives to those actions. The NEPA regulations apply to all federally funded or authorized projects.

Coastal Barrier Resources Act (CBRA): The CBRA was enacted by Congress in 1982, and later amended in 1990 by the Coastal Barrier Improvement Act (CBIA). The legislation was implemented as part of a Department of Interior (DOI) initiative to preserve the ecological integrity of areas that buffer the U.S. mainland from storms and provide important habitats for fish and wildlife. The CBRA established the Coastal Barrier Resources System (CBRS) which protects coastal areas of designated units that serve as barriers against wind and tidal forces caused by coastal storms and as habitat for aquatic species. In addition, the CBRA limits federal financial assistance for development-related activities in designated CBRS units. The CBRA also established a category of coastal barriers within the CBRS called "Otherwise Protected Areas" (OPAs). Flood insurance is restricted in OPAs, though OPAs may receive other forms of federal assistance. Per the CBRA, FEMA HMA programs may fund projects in OPAs if they do not require flood insurance after project completion. All HMA projects located in CBRS units are ineligible except for property acquisition and structure demolition or relocation projects for open space. If a federally-funded project is in the CBRS, federal agencies must consult with the U.S. Fish and Wildlife Service (USFWS) to determine that the expenditure meets one of the CBRA's exceptions.

Coastal Zone Management Act of 1972 (CZMA): CZMA was enacted to protect, develop, and restore the natural resources of the coastal zone while balancing the need for "reasonable" growth. The CZMA outlines the National Coastal Zone Management Program. The National Coastal Zone Management Program aims to balance competing land and water issues through state and territorial coastal management programs.

National Historic Preservation Act (NHPA): Section 106 of the National Historic Preservation Act of 1966 (NHPA) requires federal agencies to take into account the effects of their undertakings on historic properties and afford the Advisory Council on Historic Preservation a reasonable opportunity to comment. Based on this regulation, if a project impacts historic or cultural resources, coordination with the State or Tribal Historic Preservation Officer may be necessary.

Executive Orders: Some Executive Orders, such as 11988 - Floodplain Management and 11990 - Protection of Wetlands apply to federally-funded projects that affect land use and development in the floodplain. FEMA completes an eight-step decision making process to evaluate projects in the floodplain.

Clean Water Act: This federal law, particularly section 404, regulates activities in wetlands. It requires permits for the discharge of dredged or fill materials into the waters of the United States, including wetlands. Primary regulatory responsibility falls to the U.S. Army Corps of Engineers (USACE) and the Environmental Protection Agency (EPA), which are responsible for permit review and enforcement. USACE regulates activities involving dredging, excavation, placement of fill, or construction of certain structures in waterways and wetlands of the United States. The following USACE permits and compliance requirements apply: Nationwide Permitting Program (NWP) 13 for pre-construction notifications and authorizations, Clean Water Act - Section 404 permit, and navigable waters Section 10 permit.

Clean Water Act Section 319 Nonpoint Source Management Program: Under Section 319 of the Clean Water Act (CWA), states, territories, and tribes receive grants to support specific nonpoint source pollution implementation projects. Bioengineering along coasts, including the shoreline of the Great Lakes, can be instrumental in local nonpoint source pollution management plan implementation while reducing natural hazards.

Endangered Species Act of 1973 (ESA): This act requires federal agencies to protect endangered and threatened species and strictly prohibit any person from harassing or harming any federally listed threatened or endangered species. The regulatory responsibility for this program rests with USFWS and the National Marine Fisheries Service (NMFS), which administer the program in cooperation with other federal agencies. Section 7 of the ESA requires all federal agencies to ensure that their actions are not likely to jeopardize the continued existence of any endangered or threatened (listed) species, or cause harm to their habitat. Under Section 7 of the Endangered Species Act, federal agencies such as FEMA must consult with FWS on any projects that might affect a federally-listed threatened or endangered plant or animal species on the project site prior to undertaking the project. If it is determined that the project could adversely impact a listed species, FEMA will work with NMFS and FWS to mitigate those effects. Other permits could be required as well.

Magnuson-Stevens Fishery Conservation and Management Act: The Magnuson-Stevens Fishery Conservation and Management Act (MSA) requires federal agencies to consult with NMFS on any action or proposed action authorized, funded, or undertaken by the agency that may adversely affect Essential Fish Habitat (EFH) identified under the MSA. When FEMA determines that a shoreline project may adversely affect EFH identified under the MSA, FEMA must consult with the National Oceanic and Atmospheric Administration (NOAA) prior to undertaking the project.

Marine Mammal Protection Act: NOAA issues permits under the Marine Mammal Protection Act (MMPA) for activities that result in a "take" of marine mammals. The MMPA was enacted in response to increasing concerns among scientists and the public that significant declines in some species of marine mammals were caused by human activities. The act prohibits, with certain exceptions, the "take" of marine mammals in U.S. waters and by U.S. citizens on the high seas. The nation's coastline provides important marine mammal habitat, including haul-outs for seals and sea lions and nearshore areas that provide important foraging opportunities.

National Marine Sanctuaries Act: The Office of National Marine Sanctuaries has a broad range of activities that fall under the living shorelines continuum, including marine debris removal from coastal, intertidal, and subtidal areas and restoration activities associated with groundings or other sanctuary injuries. If a shoreline project is located within a National Marine Sanctuary, landowners should contact the National Marine Sanctuary to discuss the project in the context of its regulations and management. The list of National Marine Sanctuaries is available online at: http://sanctuaries.noaa.gov/about/welcome.html.

STATE AND LOCAL REGULATIONS:

State and local law often runs parallel to or branches off from federal law; thus, federal, state, and local reviews are often concurrent

Water Quality Permits: Projects involving work within a stream may require a 401 Water Quality Certification from the state environmental protection agencies. Projects with the potential to affect public drinking supplies through dewatering or other construction activities must contact the state environmental agency to identify regulatory requirements that may apply. Wherever applicable, projects proposing to discharge into surface water must be in compliance with the permit requirements of the National Pollution Discharge Elimination System (NPDES).

Scenic and Historic Preservation: Permits or approvals may be required for projects that require earthmoving and/or demolition of a structure if the projects are within a certain distance from designated state wild, scenic or recreational, archaeological, prehistoric or historical sites or structures.

Tidal Wetland and Coastal Zone Permits: Special permit requirements may apply in tidal waters and ocean shorelines in some states. Permits are required for projects including engineering activity that affects dune fields, beaches or shoreline lands.

Endangered Species Regulations: Wildlife, natural resources, and fisheries departments should be consulted to ensure compliance with state threatened or endangered species regulations.

Water Rights: Each state regulates water rights within its jurisdiction. If a project diverts water or causes changes to a water course, approval or granting of water rights by the state may be required.

Floodplain Management Permits: Floodplain management permits or construction permits may be required by the local floodplain administrator for projects occurring within federally identified special hazard areas (the 1 percent annual chance floodplain).

BIOENGINEERED SHORELINE STABILIZATION

Local Stream and Wetland Ordinances: Many city or county planning departments have local ordinances pertaining to streams and wetlands. Depending on the nature of the project, several permits may be required.

Local Water Resources Permits: Local or regional irrigation and water districts are empowered to protect water resources in their jurisdiction; permits may be required for certain projects.

Other: Various agencies, utilities, and authorities should be consulted for projects that depend on specific activities and locations.

REFERENCES

Cunniff, S. and Schwartz, A. Performance of Natural Infrastructure and Nature-based Measures as Coastal Risk Reduction Features. Environmental Defense Fund, 2015.

Duhring, K. The VIMS Teaching Marsh: A Tidal Wetland Restoration and Education Project. The Virginia Wetlands Report. Winter/Spring 2001, Vol. 16, No. 1.

Federal Emergency Management Agency. Engineering with Nature Alternative Techniques to Riprap Bank Stabilization. 2007.

Florida Living Shorelines. Online: http://floridalivingshorelines.com/. 2018.

Hardaway, Jr., C. Scott, D. A. Milligan, and K. Duhring. Living Shoreline Design Guidelines for Shore Protection in Virginia's Estuarine Environments. Virginia Institute of Marine Science, 2010.

Hardaway, Jr., C. Scott, D.A. Milligan, C.H. Hobbs, III, C.A. Wilcox, K.P. O'Brien, and L. Varnell. Mathews County Shoreline Management Plan. Virginia Institute of Marine Science, 2010.

Massachusetts Office of Coastal Zone Management. StormSmart Properties Fact Sheet 1: Artificial Dunes and Dune Nourishment. 2013.

Massachusetts Office of Coastal Zone Management. StormSmart Properties Fact Sheet 2: Controlling Overland Runoff to Reduce Coastal Erosion. 2013.

Massachusetts Office of Coastal Zone Management. StormSmart Properties Fact Sheet 3: Planting Vegetation to Reduce Erosion and Storm Damage. 2014.

Massachusetts Office of Coastal Zone Management. StormSmart Properties Fact Sheet 4: Bioengineering – Coir Rolls on Coastal Banks. 2013.

Massachusetts Office of Coastal Zone Management. StormSmart Properties Fact Sheet 5: Bioengineering – Natural Fiber Blankets on Coastal Banks. 2013.

Massachusetts Office of Coastal Zone Management. StormSmart Properties Fact Sheet 6: Sand Fencing. 2013.

Massachusetts Office of Coastal Zone Management. StormSmart Properties Fact Sheet 7: Repair and Construction of Seawalls and Revetments. 2017.

Massachusetts Wildlife Climate Action Tool. Restore natural coastal buffers: Bioengineering for coastal banks. Web Resource: https://climateactiontool.org/content/restore-natural-coastal-buffers-bioengineering-coastal-banks , Accessed: December 8, 2017National Resource Conservation Service. Streambank and Shoreline Protection Manual. U.S. Department of Agriculture, 2002.

BIOENGINEERED SHORELINE STABILIZATION

Mattei, J. H., Final Report: The Stratford Point Living Shoreline. Sacred Heart University Dept. of Biology, 2017.

National Oceanic and Atmospheric Administration. Guidance for Considering the Use of Living Shorelines. 2015.

O'Donnell, J. E. D., Living Shorelines: A Review of Literature Relevant to New England Coasts. Journal of Coastal Research, 33(2), 435-451. 2017.

SAGE: Systems Approach to Geomorphic Engineering. Natural and Structural Measures for Shoreline Stabilization. 2015

Sotir, R; and Gray, D. Soil Bioengineering for Upland Slope Protection and Erosion Reduction. U.S. Department of Agriculture Natural Resources Conservation Service, 1992.

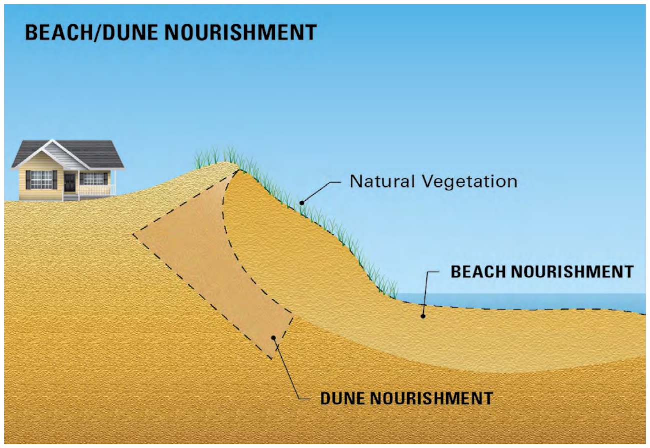
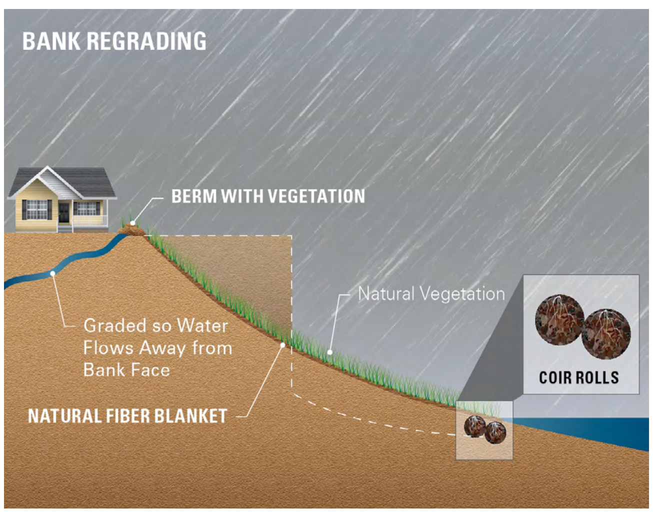
U.S. Department of Agriculture. Technical Supplement 14K Streambank Armor Protection with Stone Structures. 2007.

Woods Hole Oceanographic Institution. Stabilizing Dunes and Coastal Banks using Vegetation and Bioengineering: Proceedings of a Workshop held at the Woods Hole Oceanographic Institution, Woods Hole, MA. Edited by J. F. O'Connell, 2002.

BIOENGINEERED SHORELINE STABILIZATION

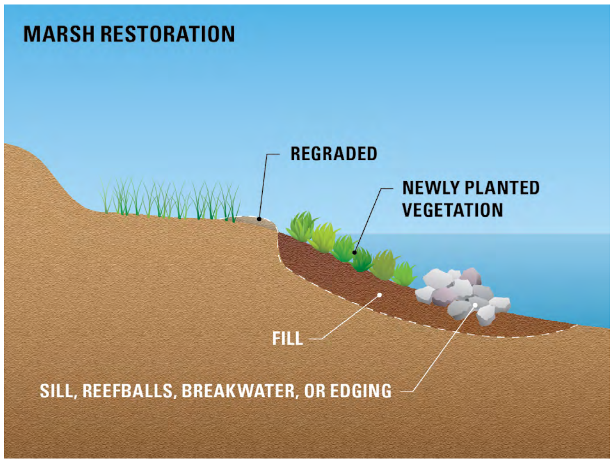
APPENDIX

Table 1. Coastal stabilization measures summary

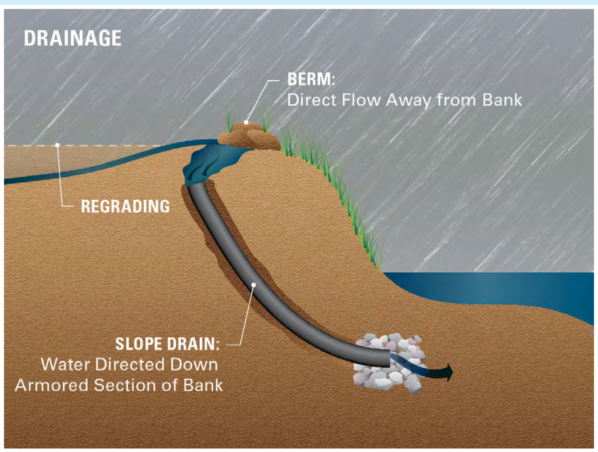
	Stabilization Measure	Description
Beach/Dune Nourishment		
	Beach nourishment	Sediment of compatible type (mean grain-size and material) is placed on the beach to widen it and add sediment to the shoreline system.
	Dune nourishment	Sediment of compatible type (mean grain-size and material) is used to reinforce eroded dune face, or in some cases to create a new dune.
	Plant beach/dune grass	Native, deep-rooted beach grasses are planted on the dune and upper beach to stabilize added sediment and trap additional sediment.
Bank Regrading/Stabilization		
	Regrade bank	Eroding bank face that is unstable and over-steepened is stabilized by reducing the slope. Placing fill at the bank toe and retreating the bank crest are two options.
	Control runoff	Surface runoff is diverted away from the eroding bank face by creating a berm at the bank crest and/or by installing drywells/French drains to encourage infiltration.
	Install coir rolls and natural fiber blankets	Blankets made of natural biodegradable fiber are rolled out onto the bank face to temporarily control erosion. Coir rolls, dense rolls anywhere from 6" to 12" in diameter and made of coconut husks, are placed parallel to the bank toe and up the toe face to provide protection from short-term erosion events like storms.
	Plant native vegetation	Native, deep-rooted, vegetation is planted through the natural fiber components into the bank face. Over time the vegetation will become established and stabilize the bank as the natural fiber components degrade.

BIOENGINEERED SHORELINE STABILIZATION

Stabilization Measure	Description
Marsh Restoration	
Regrading/fill	Unstable slopes are brought to a lower grade; sediment appropriate for supporting marsh vegetation is introduced if it does not exist.
Plant native vegetation	Appropriate native marsh vegetation is planted along the future marsh platform. In areas of very low wave energy this may be all that is needed.
Edging	In areas of slightly higher wave energy, edging in the form of coir rolls and/or oyster shell bags can be used to protect the existing vegetated toe of the marsh.
Sills	Parallel to vegetated shoreline, reduces wave energy, and prevents erosion. Suitable for most areas except high wave energy environments.
Breakwater	Offshore structures located parallel to the shore intended to break waves, reducing the force of wave action, and encourage sediment accretion. Suitable for most areas. Can be submerged or exposed. Where appropriate, can be in the form of a living reef.
Reef balls	Reef balls are complex geometric structures which can be installed to serve as an alternative to a traditional breakwater in some environments. They create habitat for shellfish, fish, and other marine animals while simultaneously providing protection to the coast by attenuating wave energy.

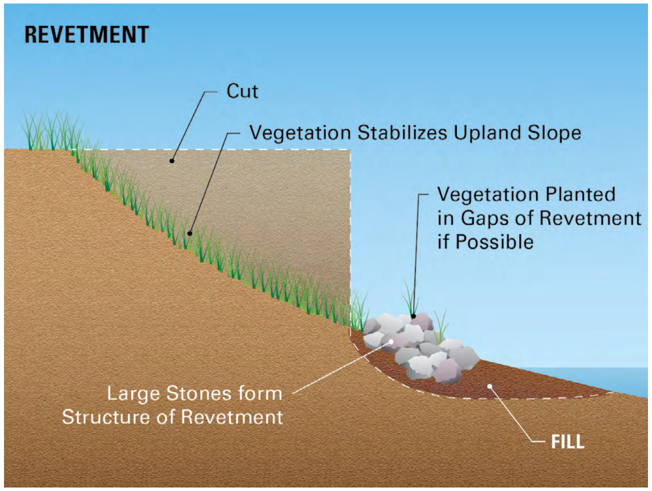


Stabilization Measure	Description
Drainage	
Chimney drain	A subsurface drainage course placed between a natural slope and an earthen buttress fill or other retaining structure
Slope drain	A drainage system used to collect and transport storm runoff down the face of a slope
Trench drain	A drain excavated parallel to and just behind the crest of a coastal bank
Berm	An earthen mound placed at the top of a coastal bank to direct runoff away from the bank face



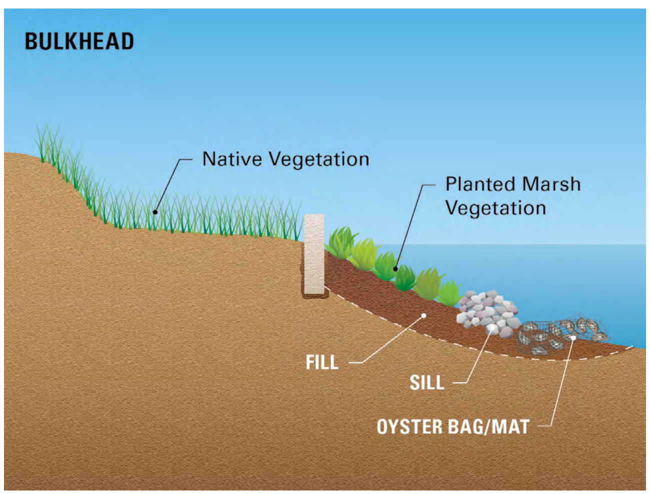
BIOENGINEERED SHORELINE STABILIZATION

Revetment



Stabilization Measure	Description
Regrade slope	Flexible, 3-D, high density polyethylene (HDPE), honeycomb-shaped earth-retaining structures; can be expanded/backfilled with a variety of materials to mechanically stabilize surfaces
Revetment	Sloped structure placed at the toe and/or face of a coastal bank to dissipate wave energy and reduce erosion; in coastal engineering these are usually made of large rocks call 'rip-rap'. Not inherently a bioengineering solution.
Plant native vegetation	Native vegetation planted on the slope above a revetment as well as within the spaces between rocks in a revetment's face can increase stability and create habitat.

Bulkhead



Stabilization Measure	Description
Bulkhead	Vertical wall parallel to the shoreline intended to hold soil in place. Suitable for high energy settings and sites with existing hard shoreline structures. Bulkheads are not a bioengineering solution, but can sometimes be combined with bioengineering methods to reduce impacts on the local ecology and shoreline system.
Artificial beach	In some cases a gravel and/or cobble beach may be constructed in front of a bulkhead to reduce direct wave impacts and reduce erosion in front of the hard structure.
Oyster bag/mat	Oyster bags/mats may be installed offshore of a bulkhead to create habitat and encourage colonization by native oysters.
Plant native vegetation	Native vegetation planted landward of a bulkhead can trap airborne sediment and reduce erosion in the case that a bulkhead is overtopped.