Techniques and Application of Living Shorelines in Delaware

Guidance on how to visualize and design living shorelines using selected elements and materials to meet site-specific goals.

Delaware Living Shoreline Committee

Standards of Practice Sub-Committee

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1.0 Introduction

The term “living shoreline” describes an array of management techniques that rely on natural and nature-based features (NNBF) to achieve both shoreline stabilization and ecological goals that maintain or restore the natural ecological connectivity across the land-water interface. A suite of guidelines and other technical sources are available to assess sites for living shoreline suitability, design, and implementation, and to evaluate how well projects succeed in meeting their goals and objectives. This document addresses design elements and common building materials associated with different types of living shorelines.

The term “living shoreline” is not used to describe standalone structural shoreline protection techniques such as rip-rap armoring, bulkheads, groins, sills, jetties, breakwaters, and/or beach nourishment projects, where ecological function is typically absent or limited. However, these structural techniques can be combined with NNBF to provide measurable (net) increases in ecological function; the “living” portion of the living shoreline (DE LS Monitoring Framework). Typical living shoreline components utilized in Delaware and other Mid-Atlantic states include coir logs, oyster shell bags, vegetation, and substrate (soils and sediments). Although living shorelines predominantly utilize natural materials, the energy regime at a particular site will inform material choice and configuration to meet project-specific goals and site conditions. For example, sites with exposure to high wave energy, such as the Atlantic Ocean or Delaware Bay coastlines, are not good candidates for “softer” living shoreline techniques using only these natural materials, as the conditions present in these environments typically require the incorporation of materials with greater stability/durability such as rock or modular, concrete-based structures. These elements dampen or attenuate wave energy and protect less stable elements of the living shoreline. Conversely, living shorelines located in lower energy regimes do not typically require such robust structural components. While sometimes tempting, over-engineering living shorelines can increase project cost and potentially lead to negative environmental consequences (e.g., shorelines disconnected from tidal flow, habitat fragmentation, attraction of invasive species).

The following guidance is intended to aid individuals and groups pursuing application of living shoreline techniques to conceptualize and design site-specific living shoreline projects through the thoughtful selection and configuration of construction materials to achieve project goals and objectives. If the user is consulting this document for help designing a living shoreline project for a specific site, it is recommended they have already consulted the *Site Evaluation for Living Shoreline Projects in Delaware: Guidance and Worksheet* document and the Living Shorelines Feasibility Model to better understand whether conditions at their project site impose design constraints or require other special consideration. If the user of this document desires to further understand what is meant by, and included in, the term “living shoreline” in the state of Delaware, it is recommended they consult the *Developing Monitoring Plans for Living Shoreline Projects in Delaware: A Goal-based Framework* document, which provides additional insight into the theory and rationale behind goal-based project design and evaluation. Importantly, if you are designing and plan to construct a living shoreline project, recognize that you must obtain necessary approvals (permits) from the Department of Natural Resources and Environmental Control (DNREC) and the U.S. Army Corps of Engineers (USACE). More information on permitting requirements for DNREC can be found here

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(https://dnrec.delaware.gov/water/wetlands-subaqueous/permits/), and more requirements for the USACE here (https://saw-reg.usace.army.mil/NWP2021/NWP-54.pdf). To evaluate whether your project qualifies for an abbreviated permit processing procedure under DNREC's Living Shoreline Stabilization Statewide Activity Approval (SAA), follow this link (https://documents.dnrec.delaware.gov/wr/Documents/2020-Living-Shoreline-Stabilization-Statewide-Activity-Approval.pdf).

1.1 Document Goal

The overall goal of this document is to guide the reader through a three-step process to facilitate the development of an appropriate and successful living shoreline project:

1. **Define Project Goals ->**
2. **Select Design Elements to Meet Goals ->**
3. **Select Materials for Design Elements**

In most cases, site-specific hydrodynamic forces such as waves (including boat wakes), currents, and tides will influence living shoreline design and materials selection. For the purposes of this document, energetic regimes associated with such forces have been categorized as low, medium, and high on a relative scale without quantitative definitions. It should be noted that most sites experience multiple regimes that can vary temporally (e.g., seasonally), spatially (e.g., site facing multiple directions with varying fetch and wind), or due to specific acute events (e.g., storms). The *Site Evaluation for Living Shoreline Projects in Delaware: Guidance and Worksheet* document and the Living Shorelines Feasibility Model can help users identify the "typical" energy regime, but users should also consider periodic events such as storms, as well as longer-term considerations like sea level rise when categorizing their site.

Throughout this document there are recommendations and general guidance regarding the ability of various design elements and construction materials to withstand forces across a range of energy environments. These are general guidance recommendations, not absolutes, and do not apply universally. Your site-specific conditions, constraints, and data may call for different approaches. For site-specific energy evaluations beyond what is provided in aforementioned documents, it is advisable to contact a restoration or engineering professional with living shorelines experience. Additionally, Section 4 of this document provides a series of living shoreline case studies to exemplify how the various design elements and their materials can work together to meet project specific goals under a variety of energetic conditions.

1.2 Delaware Definition of a Living Shoreline

The State of Delaware SAA states that a living shoreline encompasses a variety of techniques that provide shoreline stabilization/resilience through the use of predominantly natural materials, systems, habitats and/or processes exclusively or in combination with a structural component to preserve, enhance and/or restore ecological functions and connections between upland and aquatic areas. There are two listed living shoreline classifications:

1. **Conventional Living Shoreline:** techniques composed entirely of nature-based materials constructed in lower energy systems (e.g., planted marsh with grading or minimal clean fill necessary to support vegetation, natural coir fiber log toe protection, and oyster shell bags toe protection).

2. **Hybrid Living Shoreline:** techniques used for conventional living shorelines but with an increased use of structural components necessary to withstand and dissipate wave generated forces in moderate to higher energy systems (e.g., intertidal oyster/mussel reef structures with a planted marsh, marsh toe revetment with an existing marsh and marsh toe sills with a planted marsh).

1.3 Living Shoreline Goals

Successful living shoreline designs are the result of addressing well-defined goals developed through an understanding of a site and the primary drivers creating the need for intervention. Goals need to address shoreline stabilization but also the desired ecological outcomes. Goal formulation has been described in detail in the Developing Monitoring Plans for Living Shoreline Projects in Delaware: A Goal-based Framework and includes the following considerations:

1. **Shoreline Position (Horizontal/Vertical)** One of the most common reasons that living shorelines are constructed is to slow rates of erosion (i.e., landward retreat) along the leading (waterward) edge of beaches, coastal wetlands, and developed shorelines. These edges are under pressure from natural erosional forces including waves, storm surge, tides, and upland drainage, in concert with sea level rise, and possible human-induced forces such as boat wakes. Projects with a primary goal of stabilizing shoreline position are designed to reduce the horizontal landward migration of the shoreline, vertical shoreline scour, and/or facilitate vertical sediment accretion.

2. **Habitat** Delaware's shoreline includes important feeding, roosting, and nursery habitat for a variety of fish and wildlife species of concern, including those commercially valuable, important to recreation, or are threatened or endangered. Living shorelines can halt loss or degradation of, or effectually increase and enhance, these habitats. For example, living shoreline projects can protect sensitive coastal wetland habitats situated just inland behind them, create conditions for the expansion of such wetlands, and/or improve the habitat quality of the coastline itself such as through the creation of reefs and accretion of beaches.

3. **Water Quality** One of the most important ecosystem services of Delaware's coastal habitats is that of improving water quality through the processes of ecological filtration and material sequestration that takes place in coastal wetlands or is performed by shellfish that rely on coastal habitats. Heavily altered and degraded shorelines are less capable of providing this service effectively. Therefore, some living shoreline projects may be implemented primarily to maintain or improve water quality by reducing concentrations

of nutrients, contaminants, and/or suspended solids that can negatively impact ecosystems, fish and wildlife, and human health.

Stakeholders may have additional reasons for choosing to implement a living shoreline such as resource protection (e.g., archeological sites), improve ecosystem services, increase coastal aesthetics, protect public investments, etc. But for the intervention to be a living shoreline, it should address one or more of the three stated goals above.

2.0 Common Living Shoreline Design Elements

Living shorelines consist of material components, or ***design elements***, configured to address physical and ecological vulnerabilities and direct change towards a defined goal(s). This configuration must accommodate site-specific characteristics such as: elevation relative to sea level, grade, footprint, topographic complexity, soil porosity, neighboring shorelines, exposure to sunshine, salinity, neighboring land uses, wave and wind-borne energy, and tides.

Design elements are selected and combined to help a living shoreline reach its intended goal(s). Some elements are commonly used to meet specific goals, for example:

1. Structural elements, such as toes and sills, and biological elements, such as vegetation and shellfish beds can address **shoreline position goals** by promoting either horizontal stability or providing a range in horizontal extent for a shoreline to fluctuate between.

2. Structural elements, such as sills and terraces that control the shoreline profile, can achieve and maintain specific vertical and horizontal positions to address **habitat goals**. Biological elements, such as vegetation, can directly serve as habitat. Other elements, such as drainage channels and grading, can support and maintain the many different biogeochemical and inundation regimes needed for habitats.

3. Design elements such as vegetation and shellfish, can address **water quality goals** by physically removing a variety of pollutants through feeding, growth, and sediment trapping and retention.

Design elements can be composed of a variety of standard or novel materials. The appropriate materials selection is determined by evaluating how each potential material choice will facilitate the ecological or physical progress of the design element towards the goals. The selected materials are then configured into the design elements that provide a specific function, such as energy attenuation while retaining ecological connectivity. Material options are discussed in more detail in Section 3, but are noted for each design element in the sections 2.1-2.8.

Some common design elements are described below (2.1-2.8). For each element, the following information is provided:

- Uses: General intended effects of application.
- Common Materials: Commonly utilized materials to construct the design element.
- Goal Alignment: Reasonably expected results of appropriate application.
- Ecological Opportunities: Potential ecological outcomes of appropriate application.
- Limitations/Considerations: Potential drawbacks, inappropriate applications, or negative consequences associated with the design element. These constraints may involve ecological, regulatory, or logistical issues and may not apply to all projects.

2.1 Offshore Energy Attenuation Structures

Definition: Off-shore intertidal or subtidal structures placed approximately parallel to shore or in patterns positioned to intercept wave energy vectors for the purposes of protecting shoreline features (e.g., marshes, beaches, marinas, properties, etc.). The mechanisms of protection include forming a barrier to wave energy, attenuating wave energy, or a combination of both. Deployment of these structures can reduce or eliminate erosion and often promotes enhancement and expansions of natural features through the gradual accumulation of additional sediment, a process known as accretion. Depending on the configuration of the structure (i.e., length, height, width, and material type), deployment positioning and patterns, certain structures may still allow a significant amount of cross-shore and long-shore movement of sediment and fauna (e.g., horseshoe crabs).

Uses:

- Attenuate or block wave energy in moderate to high energy environments.
- Accrete sediment shoreward if the structure is appropriate.

Common Materials:

- Rock sized to the energy conditions
- Contained rock and shell (e.g., HESCO® baskets)
- Proprietary inorganic fabrications (WADs®, Reef Balls®, Oyster Castles®, etc.)
- Wood (e.g., logs, root wads)
- Underlayment such as rock, geotextile/geofabric, geogrid matting, rock mattresses, etc.

Goal Alignment:

- Certain offshore structures can maintain shoreline position or enhance it by mimicking the benefits of established oyster reefs. For example, low relief breakwaters can intercept incoming waves, causing them to break before reaching the shoreline, which reduces or eliminates further shoreline erosion. In some cases, sediment accretion can rebuild eroded shorelines over time.

- In some subtidal areas, depending on factors such as wave energy, salinity, and recruitment, breakwaters can develop into functioning oyster reefs that provide shoreline protection and habitat. Selection of materials with plentiful interstitial space or rough surfaces for shellfish attachment, can further enhance habitat value to fish and shellfish (Figure 1). This secondary benefit is often overlooked during the design process, yet it is ecologically significant.

Figure 1. Wave Attenuation Devices® (WADs®) dissipating wave energy while also providing interstitial space for habitat (Photo Credit: Chris Pfeifer).

Ecological Opportunities

- Provide interstitial space for oysters and ribbed/blue mussels in areas with brackish to full salinities.
- Enhance and stabilize substrate in their lee for benthic invertebrates and foraging opportunities (e.g., shorebirds). The reduced energy in the lee also benefits mussels and/or submerged aquatic vegetation. Naturally accreted sediment deposits may eventually support colonization by intertidal wetland vegetation.
- Maintain and/or direct faunal passage between water and shore through strategic breaks in arrays designed with overlapping patterns or through passageways in proprietary concrete structures.
- Allow for layered approaches to maximize habitat value such as boulder cores surrounded by smaller rock, or rock-filled HESCO® baskets clad in an outer layer of recycled shell.

- Allow flexibility to tailor designs with curved or irregular edges, varied slopes and heights, and size of material to help meet specific goals to capture and retain sediment for benthic stability for plants and infauna (i.e., both vertical and horizontal structural variability).
- Provide for energy reductions landward of the offshore feature to enhance SAV establishment and "safe havens" for nekton and nesting habitats.

Limitations/Considerations:

- Although a natural material, rock is not endemic to many Delaware shorelines. Its use in living shorelines can create habitat for species once more common to oyster reefs but also potentially unwanted species such as Asian shore crabs. Although sometimes necessary, alternatives to rock should be considered.
- May extend vertically into the upper portion of the tidal range (e.g., visible above water at certain tide stages) and be perceived as an eyesore. Height of structure is dictated by the topography/bathymetry of the site and the level and duration of wave energy protection desired.
- Interstitial void space (e.g., gaps) between materials may have the potential to entrap (impinge) wildlife (e.g., horseshoe crabs, terrapins) depending on size. Consideration should be given to limit impingement risk.
- Could reflect wave energy if not designed correctly and create scour on both the subject and/or neighboring properties.
- Can create navigation hazards, due to limited visibility of fully or partially submerged structures or dislodged structures due to poor anchoring or damage following extreme weather events.

2.2 Toes: Base-Stabilization

Definition: "Toe" describes a low-profile configuration of material intended to protect and stabilize the waterward edge of a living shoreline structure or a natural feature such as an eroding marsh scarp in front of which it is constructed. In either case, the toe intercepts and attenuates incident wave energy to promote non-erosive conditions in areas located immediately landward (Figure 2).

Figure 2. Oyster Shell bag base-stabilization (Photo Credit: Partnership for the Delaware Estuary).

Uses:

- Stabilize other design features (e.g., fill), acting as a low-relief, armored slope and retaining structure.
- Stabilize a natural feature, such as a low-relief terrace, decayed peat edge, or vegetated area.

Common Materials:

- Rock
- Shell loose/bags/baskets
- Coir logs
- Hardwood logs

Goal Alignment:

- Toe protection usually helps designs meet the Shoreline Position goal, providing structural stability to the land-water interface.
- If the material is appropriate for shellfish colonization or vegetative grow-through, toes can promote habitat development and water quality uplift.

Ecological Opportunities:

- Provide interstitial space for oysters and ribbed/blue mussels in areas with brackish to full salinities.

- Can stabilize sediment to develop as unvegetated mud flat terrace post-transgression of vegetation (e.g., a toe placed along a vegetated marsh edge may reinforce and add resilience to a marsh edge or can remain after future loss of the vegetation and therefore allow the area to transition to a stable mudflat).

Limitations/Considerations:

- Spaces between materials, if present, may entrap wildlife (e.g., horseshoe crabs, terrapins) depending on size.
- If continuous along a shoreline, toe materials can reduce or increase foraging opportunities (e.g., along a natural marsh edge) or disrupt or attract intertidal faunal movements.
- Could reflect wave energy if not designed correctly and create scour.
- May stabilize areas that are better suited to maintaining more of their naturally dynamic character.
- Longevity: natural materials, such as coir logs, will biodegrade over time after which they may no longer provide the intended function. This may be acceptable if vegetation has established in the meantime and is ultimately able to withstand wave energy without erosion. If energy climate dictates the need for more permanent toe protection, materials with greater durability such as wooden logs or rock may be needed.

2.3 Sills: Low-profile Vertical Positioning

Definition: Sills are linear structures placed parallel to the existing shoreline, behind which silt or sand is usually placed to develop habitat (Figure 3). Although sometimes confused with the living shoreline itself, sills can be a component of a living shoreline if their application facilitates an ecological goal (uplift). Crest elevations of sills are typically set relative to a tidal datum such as mid-tide or mean high water. Sills can be designed with breaks or gaps if applied along extended stretches of shoreline to allow for hydrologic exchange, drainage, and faunal movement.

Uses:

- Wave attenuation
- Physical armoring/toe protection
- Retention of landward fill

Common Materials

- Rock
- Shell
- Proprietary concrete fabrications (reef balls, oyster castles, etc.)

Figure 3. Oyster bag still with natural sedimentation behind (Photo credit: DNREC Wetland Monitoring and Assessment Program).

Goal Alignment:

- Sills usually help designs meet the Shoreline Position goal, providing structural stability to the leading (waterward) edge of living shorelines making first contact with incident wave energy.
- Sills can be used to meet habitat goals (e.g., fill placed behind sill to provide specific vegetated habitat).
- If the material is appropriate for shellfish colonization or vegetative grow-through, sills can also promote habitat development and water quality uplift.

Ecological Opportunities:

- Provide interstitial space for oysters and ribbed/blue mussels in areas with brackish to full salinities.
- Create a stable marsh edge for vegetation, ribbed mussels, other invertebrates, and foraging fish and wildlife.
- Maximize faunal passage between water and shore (e.g., over top of sill at higher tide stages, through designed breaks/gaps at lower tide stages).

Limitations/Considerations:

- Often entirely rock, a non-endemic element along many Delaware shorelines, that can create habitat for species once more common to oyster reefs but also potentially unwanted species such as Asian shore crabs.

- Gaps between materials (e.g., spaces between rock) if present may entrap wildlife (e.g., horseshoe crabs, terrapins) depending on size.
- If continuous along a shoreline, sills can create a uniform abrupt transition from water to marsh and reduce foraging opportunities or disrupt natural intertidal faunal movements.
- Could reflect wave energy if not designed correctly and create scour.
- May stabilize areas that are better suited to maintaining more of their naturally dynamic character.
- Can create navigation hazards.
- Often shell must be contained to maintain structural stability. Materials used to contain shell (mesh bags) may degrade over time. Colonization by encrusting organisms will encapsulate mesh bags and maintain structural stability. Without colonization, loose shells will no longer provide protection once mesh bags degrade. Mesh bags may also pose a wildlife entrapment hazard and contribute to marine micro-plastics pollution.
- Rock must be sized appropriately for wave energy environment.

2.4 Groins and Jetties: Internal and External Sediment Trapping/Control

Definition: Structures built perpendicular to the shoreline used to interrupt longshore transport and retain sediment/sand at key positions along a shoreline.

Uses:
- Sediment retention/capture
- Can be deployed externally or internally to a living shoreline design, depending on where sediment capture/retention is desired (Figure 4).

Figure 4. Oyster Castle® groin placed inside and along the front of a living shoreline (Photo Credit: Partnership for the Delaware Estuary).

Common Materials:

- Rock
- Bagged Shell
- Wood
- Prefabricated materials (e.g., Oyster Castles®)

Goal Alignment:

- Groins can help meet the Shoreline Position goal, facilitating sediment retention on the up-drift margin of the structure.
- Although groins are primarily a structural device, choices regarding materials and integration with other more traditional habitat enhancement elements, can allow groins a place in ecological restoration.
- If the material is appropriate for shellfish colonization or vegetative grow-through, groins can also promote habitat development and water quality uplift.

Ecological Opportunities:

- Provide interstitial space or benthic substrate for shellfish or vegetation.
- Can stabilize sediment to develop as supratidal, intertidal, or subtidal vegetated or unvegetated habitats (e.g., mud flat) for foraging fish and wildlife.
- Can create diverse topography, higher flats on one side and deeper pools or troughs on the other side.

Limitations/Considerations:

- Groins typically promote accretion only on the up-drift side and at the potential cost of further erosion on the down-drift side due to sediment starvation. Therefore, their design must address any threat they represent to areas down-drift.
- Often entirely rock, an unnatural element along most Delaware shores, that can create habitat for species once more common to oyster reefs but also potentially unwanted species such as Asian shore crabs.
- May extend above mean low water and be perceived as an eyesore or navigation hazard depending on distance offshore.
- Void space between materials, if present, may entrap wildlife (e.g., horseshoe crabs, terrapins) depending on size.

2.5 Internal Compartmentalization

Definition: Internal compartmentalization is the process of partitioning or subdividing a living shoreline into smaller, spatially discrete units.

Uses:

- Limit/localize the extent of potential failure. For example, if a retaining structure is breached resulting in the loss of sediment, the impacts may be localized and minimal if the shoreline is divided into multiple sub-compartments.
- Accelerate passive accretion and promote even distribution of deposited sediment. For projects utilizing natural accretion, establishing multiple internal compartments can help increase the rate and uniformity of sediment deposition throughout a project area.
- Retain sediment within project area. Internal compartments can also help retain naturally deposited sediment and imported fill by reducing wave energy and limiting sediment transport within and out of a living shoreline project area.
- Enhance structural stability. Internal compartmentalization can help distribute lateral forces exerted by the weight of other living shoreline components, namely soil or sediment upgradient of retaining structures.

Common Materials:

- Coir fiber logs
- Bagged or loose shell

- Wooden logs

Goal Alignment:

- Compartmentalization can help meet the Shoreline Position goal by isolating failure and promoting redundancy and resilience.
- When living shoreline projects incorporate research aspects, compartmentalization may be used to isolate treatments/replicates within an experimental design. (e.g., plant community health, biochar, and nutrient sequestration research).

Ecological Opportunities:

- Coir logs are a good, non-persistent material that will help accelerate accretion and promote more uniform sediment deposition in newly constructed projects before logs eventually degrade.
- When used to define compartments, coir logs allow for root penetration leading to stable bands of vegetation.

Limitations/Considerations:

- Bagged or loose shell can be used to define internal compartments. However, shell does not provide many of its potential ecological services (e.g., habitat) if buried, in which case alternative material may be preferred.
- Compartmental boundaries constructed too tightly without appropriate drainage, can retain water prohibiting vegetation growth.

2.6 Terraces: Topographic Complexity and Niche Development

Definition: Terracing is a specific application of internal compartmentalization used for achieving vertical grade changes between adjoining compartments. Materials are positioned at different elevations within spatially distinct zones (e.g., compartments) to create "steps", platforms, or ridges (Figure 5). Grade changes are usually oriented in the cross-shore direction progressing from higher to lower elevation moving offshore. Elevation can also vary in the longshore direction (parallel to the shoreline). Terraces differ from grading and filling (See 2.8) in that sharp vertical transitions occur between terrace "lifts", as opposed to a smooth graded bank with uniform slope. Terrace borders can be stabilized using toes and sills (See 2.2).

Figure 5. Newly installed coir fiber log terraces awaiting natural sedimentation (Photo credit: DNREC Wetland Monitoring and Assessment Program).

Uses:

- Terraces add topographic complexity to a living shoreline by creating distinct habitat zones with different hydrologic regimes (frequency and depth of flooding). This mimics natural coastal features and supports different wetland plant communities (e.g., high and low salt marsh) (Figure 6).
- Terracing can be used in habitat mosaics to provide stable transitions/boundaries between multiple vertically distinct habitat zones (e.g., vegetated intertidal->unvegetated intertidal->unvegetated subtidal mudflat->oyster reef).
- Terraces can help maintain a stable shoreline profile during shoreline transgression due to sea level rise; however, the hydrology within each zone will change as water depth increases through time.

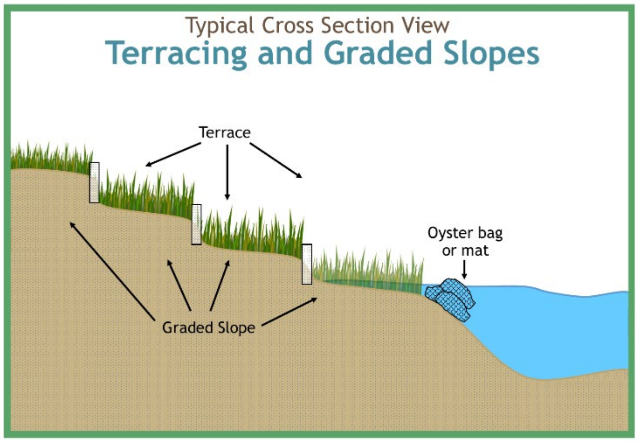

Figure 6. Graphic of a typical cross section view of a living shoreline using terrace(s) and graded slopes.

Common Materials

- Coir logs
- Hardwood logs
- Shell loose/bags/baskets
- Rock
- Imported fill placed in discrete lifts and/or naturally accreted sediment deposited within appropriately constructed containment structures

Goal Alignment:

- Terracing is commonly used to meet Habitat goals by providing the appropriate vertical position (and thereby hydrology) for desired habitat types and plant communities in a living shoreline.
- Terracing can help meet the Shoreline Position goal by maintaining a stable shoreline profile with discrete depth zones during sea level rise-induced shoreline transgression.

Ecological Opportunities:

- Terracing can enhance habitat complexity if designed to facilitate the development and persistence of multiple habitat types or plant communities within different hydrologic zones.
- Terracing can enhance shoreline resilience by helping maintain stable profiles during coastal transgression in response to rising sea level.

Limitations/Considerations:

- While sloping shorelines naturally promote drainage, terraces that are constructed too tightly and without proper drainage pathways can retain too much water, which can inhibit vegetation growth or cause structural failure.
    - Gentle (1-2 percent) shore-normal sloping across terraces will facilitate positive drainage and help avoid ponding.
    - Including openings or areas with slightly lower elevation (e.g., inverts) within containment structures will lower the chances of drainage-related erosion as tide waters recede.
    - Careful design and placement of openings (Figure 7) can create and maintain connections between terrace compartments that facilitate movement of living resources and hydrologic exchange.
    - It is important to consider how the connections between compartments can be protected to prevent scour or sediment loss. Designs with staggered, overlapping gaps and/or curved ends can help prevent loss and scour (Matt's Landing project).
- Vertical uniformity within terrace lifts increases the chances of failure in the event structures settle or subside evenly. As most habitats span a range of elevations, microtopographic variability within individual terrace lifts can provide different niches to allow options to biological components under changing conditions.
- Designs that include vertical space for continued elevation building or pathways for inland vegetation migration may be less vulnerable to vegetation die-off because of shoreline transgression from sea level rise.

Figure 7. Oyster shell bags placed in a curved overlapping formation allowing living resources and hydrologic exchange (Photo Credit: DNREC Wetland Monitoring and Assessment Program).

2.7 Drainage Pathways: Natural Tidal Flow and Upland Drainage

Definition: Drainage pathways mimic the function of creeks allowing for water to enter and exit a living shoreline project. Drainage pathways also facilitate the maintenance or development of internal habitat complexity. The most common need for drainage pathways is to ensure tidal exchange between the living shoreline and the adjacent waterbody. Unless the crest elevation of containment structures exceeds the high tide elevation and there are no gaps, which would prevent water from entering the living shoreline, water exchange is truly focused on drainage. In this case, the goal is to ensure that water that enters the project area at high tide can sufficiently drain at low tide, otherwise ponding may occur causing a variety of problems as stated below. The second situation where drainage is required is when significant intertidal features are located inland of a living shoreline project. In such cases, the living shoreline must be designed to allow for passage of such water as it drains not only from the living shoreline itself but also from intertidal areas landward of the project. Otherwise, the living shoreline may cause water to be impounded farther inland even though drainage within the living shoreline project itself is okay.

Uses:

- Maintain tidal influence shoreward of a living shoreline or other designed or natural feature while also maintaining tidal egress during a falling tide and allowing surface sheet flow and channel flow from adjacent uplands.

- Incorporating drainage pathways into living shoreline design ensures nutrient, sediment, and faunal movement while preventing ponding that can result in loss of vegetation and resilience of a living shoreline.

Common Materials:

- Maintenance or redirection of existing intertidal rivulets or incorporating breaks or lower elevation areas (e.g., weirs/spillways) in shoreline structures
- Planting configurations
- Contained shell
- Coir fiber logs in lower energy areas

Goal Alignment:

- Properly positioned and sized drainage pathways support proper tidal flushing and nutrient and sediment transport with the targeted area.
- Drainage pathways can help designs meet the Shoreline Position goal by providing proper hydrologic connectivity of each component (if a habitat mosaic design) and allowing for water passage rather than interception along the waterward margin.
- Drainage pathways can be used to meet habitat goals by maintaining the proper conditions for vegetation persistence, as well as providing access to fauna (e.g., fish, crabs) to use for foraging or nursery areas.
- If the material along the borders is appropriate for shellfish colonization or vegetative grow-through, drainage pathways can also promote shellfish habitat development and water quality uplift.

Ecological Opportunities:

- Drainage pathways can provide the interconnectivity that is characteristic of shorelines across the mosaic of habitats and relied on by fish, invertebrates, shellfish, etc. to access foraging, shelter, and nursery habitat.
- Drainage pathways can prevent hyper-saturation (i.e., waterlogging) of sediments within a living shoreline due to ponding, which can prevent vegetation from becoming established or loss of existing vegetation and destabilization of a shoreline.

Limitations/Considerations:

- Although drainage can be implemented by retaining (i.e., not blocking) existing natural drainage pathways during living shoreline implementation, to correctly develop appropriate drainage for specific volumes of water in larger projects, expert advice should be sought.

- Boundaries for drainage pathways can be reinforced to maintain their position, but caution should be taken regarding what materials are used. Non-porous/impermeable materials (e.g., line of oyster castles) may disconnect the pathway edge from the adjacent marsh and/or increase the velocity of incoming/outflowing water.
- Reestablishment of historic drainage footprint may facilitate drainage stability.
- Excessive drainage features may damage the desired habitat.

2.8 Graded Slopes

Definition: While some shorelines in natural coastal systems of Delaware may exhibit variable and dynamic elevations, most stable shorelines are characterized by sloping morphology with progressively increasing elevations moving shoreward. Sloping shorelines dissipate wave energy through a hydrodynamic process known as wave run-up. Shoreline vegetation increases frictional resistance, which helps to further dissipate wave energy and maintain stable shorelines. The frequency, depth, and duration of inundation varies across sloping shorelines providing hydrologic conditions that support a variety of wetland plant species and other aquatic resources. Shorelines, especially those that are more severely eroded, may require grading as part of initial project installation to (re)establish a more gradually sloping profile. Grading may involve cutting back upland soils landward of an eroding shoreline and/or placing fill in front of (waterward) of eroding shorelines. In either case, the goal is to create a shoreline profile having a generally uniform slope that transitions smoothly from upland/supratidal to intertidal or subtidal elevations.

Uses:

- Create slopes that dissipate wave energy without causing erosion and prevent wave reflection and undercutting where eroded marsh edges and beach scarps occur.
- Stabilize initial installations where existing substrate is inadequate for habitat or planting vegetation (e.g., sand or mud flat).
- Jump start creating a more desirable profile where low sediment supplies in the water column would prolong slope establishment if natural accretion alone were used.

Materials:

- Sediment (e.g., dredged material, on-site soil, or mined and trucked sand)

Goal alignment:

- Graded slopes can help designs meet the Shoreline Position goal by creating a stable shoreline morphology that naturally dissipates wave energy. Sloped shorelines also facilitate vegetation development, which helps to further stabilize the substrate and attenuate wave energy.
- Graded slopes can be used to meet habitat goals by maintaining the proper conditions for different vegetation communities and faunal movement.
- Graded slopes can be an effective means to transition between terraces.

Ecological Opportunities:

- Graded slopes can help increase vegetation diversity allowing for greater uplift and resilience.
- Graded slopes allow for a gradual transition of microhabitats and easy faunal movement perpendicular to the shore with each tidal cycle. Gradual transitions also facilitate landward migration of plant communities due to sea level rise.

Limitations/Considerations:

- Relatively higher cost of material, transportation, and grading.
- Establishment of an ideal slope may come at the cost of lost upland, riparian zone/buffer areas, and/or nearshore areas depend on where excavation or filling occurs.
- Environmental impacts associated with mined and transported material.
- It may be possible to balance cut and fill using on-site material to avoid the cost and environmental impacts associated with importing fill from off-site.
- Natural or targeted steepness and extent of slope varies between different types of shorelines (e.g., Atlantic coastal shoreline versus bayshore coastlines).

3.0 Common Materials Used for Design Elements

The design elements presented above, if properly selected and configured, can help a living shoreline meet its intended goals. Selecting appropriate construction materials is also critical to achieving project goals, and many of the design elements can be constructed using a variety of materials. The appropriate choice of materials will ultimately depend on each project’s goals and design, which is formulated based on site-specific energetic, ecologic, geomorphic, and other considerations - often a balance must be developed. For example, more stable or durable materials will likely be required in high energy and/or exposed shorelines, sometimes at the expense of materials having greater alignment with local geology or ecological goals. In those instances, additional internal ecological features should be considered to balance the external, protective requirements. Softer, more ecologically beneficial materials may be appropriate for a greater proportion of the design at lower energy, sheltered sites.

In this section, a variety of common material options are presented and discussed. To inform their relationship to various design elements and to minimize redundancy, materials are described relative to their capabilities and performance for the following objectives:

- Energy Attenuation: The ability of material to withstand or intercept energy;
- Horizontal/Vertical Positioning: The ability of material to either facilitate or maintain a particular three-dimensional position;
- Drainage: The ability of materials to facilitate movement of water across the living shoreline; and
- Habitat: The value of the material to provide a growth medium, refuge, or attachment substrate for living organisms.

The appropriateness of each material for various design elements is visually summarized in a color-coded, four-cell table in each material's respective section:

Energy Attenuation	**Horizontal/ Vertical Positioning**	**Drainage**	**Habitat**

The color coding should be interpreted as follows:

- Red: The material is unlikely to be appropriate for a design element intended to serve the purpose in the cell.

- Yellow: The material is possibly appropriate for a design element intended to serve the purpose in the cell but can either vary based on site-specific conditions or there is little information available on this use. It is recommended that the user seek additional information or professional input.

- Green: The material is likely to be appropriate for a design element intended to serve the purpose in the cell.

Anchoring: Finally, anchoring systems are briefly discussed throughout this section. As anchoring requires professional input, this section is intended as an introduction to the topic, rather than a guide for self-implementation. Anchoring of materials can serve many purposes, include holding vertical and horizontal position, preventing material from slumping or sinking, and prolonging the structural integrity of the material. Anchoring should be sufficient to meet the intended purpose(s) but should not be over-designed to outlast the material being anchored or the time period the anchoring is required to be necessary. There are a variety of ways to anchor design elements, and different types may benefit from different approaches. All anchoring strategies require regulatory approval, as with material choice and design element configuration and placement, so appropriate techniques may vary by location.

3.1 Sediment

Sediment typically consists of natural earthen material comprised of varying amounts of small-grain mineral (e.g., sand, slit, clay) and organic particulate matter. These materials may be moved either by natural processes like erosion and deposition in which case they are usually called “sediment” or through deliberate human actions (often mechanized) in which case they are typically called “fill”. As part of living shoreline design, fill is typically placed to alter the site dimensions, most commonly to increase the elevation of the land surface (including subaqueous lands). Fill is often placed at the water’s edge to increase the land area of the site waterward often to achieve a sloping or terraced shoreline profile. Target elevations, achieved through filling and/or excavation, are frequently specified to achieve specific hydrologic conditions, which are dictated by the relative elevation of the land and water surface. Since water surface elevations cannot be changed, living shoreline designs commonly manipulate land elevations to achieve the desired hydrologic conditions. Sites can be filled with material excavated on-site, or mined sand or dredged material obtained off-site. Alternatively, designs can be implemented to encourage deposition of suspended sediment in the water column; a process known as natural accretion. In both cases, placed or deposited material raises the land elevation. These approaches vary in the time needed to achieve elevation changes and the degree of control/precision of outcomes. Sediment is foundational for establishing vegetation that then becomes a key component in a stable shoreline and one that provides habitat to a variety of resident and/or transitory species and improves water quality.

Outside of beaches (which are not considered living shorelines), sediment is typically unable to withstand erosive energy on its own as the sole material component of a living shoreline. Fill used to build a shoreline out (horizontal) or up (vertical) is usually contained or placed behind other materials that will attenuate wave energy or retain material. Similarly, sediment in drainage pathways on its own may be unable to withstand erosive energy and is at risk of eroding without the use of other stabilizing materials.

Sediment Relationship to Design Elements

Energy Attenuation	**Horizontal/ Vertical Positioning**	**Drainage**	**Habitat**

3.2 Vegetation

Plants installed at proper elevations in the form of seeds, plug/container specimens, or salvage material (vegetation near the site that has broken free from the marsh and will drown if not moved to a higher elevation) can be used as a primary or secondary component of projects from the dune face to subtidal water depending on the species, location, and conditions. Common examples include smooth cordgrass (*Sporobolus alterniflora*) for low to medium energy intertidal salt marsh areas and American beachgrass (*Ammophila breviligulata*) and coastal panicgrass (*Panicum amarum*) for dunes. Subtidal species known collectively as submerged aquatic vegetation (SAV) are not characteristic of Delaware Bay and are very rare elsewhere in Delaware but can have significant benefits to shorelines if they can be reestablished in appropriate areas. Plant species should carefully be selected to survive in existing flooding and salinity conditions onsite. Understanding hydrologic conditions including the frequency, depth, and duration of inundation within a site based on the relative elevations of land and surface water is essential to developing planting plans for living shoreline projects.

Vegetation is capable of intercepting and reducing incoming energy, although it should not be relied upon to provide the primary energy attenuation services anywhere but at the lowest energy sites. At sites with higher energy, vegetation should be used systematically in tandem with other energy attenuation materials to provide greater structural stability. Vegetation can slow water and allow sediment particles to settle, promoting accretion and improving water quality. The vegetation also enhances water quality through the removal of nutrients such as nitrogen along brackish shorelines and phosphorus and nitrogen in freshwater. Additionally, the root structures of plants can help hold soils together promoting horizontal position and helping to maintain the morphology of drainage pathways. Root/rhizome growth is also the primary means of gaining vertical elevation along shorelines with little natural sediment supply. Like energy attenuation, in highly erosive drainage areas, vegetation should be used in tandem with other structural materials to reduce erosion along drainage pathways. Finally, vegetation serves as habitat to a variety of resident and transitory species in all types of wetlands. Decaying plant matter known as detritus is important for energy transfer across trophic levels and supports food webs both within and beyond living shoreline project areas.

Vegetation Relationship to Design Elements

Energy Attenuation	**Horizontal/ Vertical Positioning**	**Drainage**	**Habitat**

3.3 Coir Fiber Materials

Coir is a natural fiber material produced from the outer husk of coconuts. Coir typically comes as matting or in log form. Coir materials are typically anchored with wooden stakes and twine. Coir is expected to degrade and decompose over the course of years, depending on site conditions and depth of placement. Vegetation and shellfish (e.g., ribbed mussels) can be planted directly into coir materials or will likely colonize them if site conditions allow.

Coir logs come in various diameters and densities and can be configured in a wide variety of orientations and patterns and usually easily placed by hand. Coir logs are commonly used to retain fill. Depending on their arrangement, coir logs can be used for vertical transitions between successive lifts on terraced living shorelines or to reinforce the toe of a fill slope along its waterward edge in low energy environments. Coir logs are also frequently used to subdivide larger areas for internal compartmentalization. Logs must be placed in ways to avoid disrupting drainage patterns or intertidal movement of fauna. Coir matting is often laid down ahead of placing fill material as an underlayment to increase bearing capacity and reduce subsidence on sites with soft substrates. Coir matting is sometimes installed on top of fill to aid soil retention while vegetation becomes established.

Anchoring systems for coir logs are typically comprised of wood stakes and natural twine materials (Figure 8). These materials, like the logs themselves, should be comprised of organic materials that can biodegrade over time as the coir materials become colonized with vegetation or are buried within the shoreline soil matrix.

Figure 8. Wood stakes and twine installed to anchor coir logs (Photo credit: DNREC Wetland Monitoring and Assessment Program).

Coir logs can be aligned to capture natural sediment accretion or retain fill material on low to moderate energy sites. Depending on the hydrology of the site, ponding can occur behind coir logs and needs to be addressed in the site design. Little initial habitat is created with coir materials, but if used properly in the appropriate energy regime coir can provide refuge for plant communities to develop and provide habitat. Additionally, plants can be directly installed in coir logs or through coir matting. In the absence of other structural components, coir logs in and of themselves are not resilient to moderate to higher coastal energies.

Coir Fiber Materials Relationship to Design Elements

Energy Attenuation	Horizontal/ Vertical Positioning	Drainage	Habitat

3.4 Shell: Oyster, Clam, Whelk

Shell is a common material used in living shoreline projects. In addition to providing an ideal attachment substrate for oysters and ribbed/blue mussels, the space within and between shells can provide habitat for many other types of invertebrates including snails, tunicates, amphipods, and other fauna that provide food for fish and other wildlife. Shell is often obtained through recycling programs with restaurants or shucking houses, reducing waste, and returning this valuable material to the water bodies in which it belongs. Shell is typically deployed in a variety of containers. Mesh bags are the most common containment method, but they are usually made of plastic, which raises concerns regarding microplastics pollution. Other containers include steel gabions and various bags made of cotton, cellulose, and starch. The alternate bag materials are currently uncommon due to the associated cost and limited durability in marine and even low energy environments. Shell can be contained within the confines of other material, such as coir logs, oyster castles, etc.

Containers of shell can easily be configured into diverse shapes, installed by hand due to the typically low weight (container-dependent), and have shown great stability in retaining shape and positions (even low-weight shell bags when stacked in groups) (Figure 9). By creating a design element out of a material that directly provides habitat, shell is a material that will inherently add ecological uplift to a living shoreline project. However, the structural stability of shell is highly dependent on the durability and longevity of the containment material and whether the shell eventually becomes colonized by oysters, mussels, or other encrusting organisms. Without such colonization, structural functions of shell will be limited to the lifespan of the original containment material.

Figure 9. Oyster shell bags tightly stacked forming a toe (Photo Credit: Douglas Janiec).

The manner of stacking, or other forms of deployment, anchoring, and positioning are critical when using shell bags. Anchoring of the bags can be accomplished with wooden stakes and twine if needed.

Shell Relationship to Design Elements

Energy Attenuation	Horizontal/ Vertical Positioning	Drainage	Habitat

3.5 Prefabricated Structures (e.g., WADs®, Oyster Castles®, Reef Balls®)

These structures are typically molded concrete that provide standardized predictable sizes allowing exact grid or stacked placement to design specifications. The structures also typically provide some adaptive value being movable or reusable. Other than smaller fabrication (e.g., oyster castles®), most of these materials require placement by barge-mounted cranes or similar heavy equipment.

The structures provide alternatives to rock for energy attenuation in moderate to high energy environments. They provide added value because they are often molded with large hollow spaces making them able to attenuate wave energy instead of reflecting wave energy as with rock but also still allow significant passage of water, sediment, and fish. The large spaces also provide shelter to fish mimicking the function of reefs. The concrete provides a suitable surface for shellfish and the concrete texture can be amended for some of the structures to further enhance shellfish colonization.

Proprietary Concrete Fabrications Relationship to Design Elements

Energy Attenuation	Horizontal/Vertical Positioning	Drainage	Habitat

3.6 Wood

Wood can consist of timber logs, dimensional lumber, or a variety of sizes of coarse woody material and debris. Wood can have the added value of its natural texture and appearance, local availability, durability, ice tolerance, and low cost. However, wood has drawbacks in its buoyancy when not saturated. Different species of wood have significantly different properties. Of particular interest is density, buoyancy, strength, and rigidity. In general, hardwood species have many of the desired properties for living shoreline projects. Conversely, softwood species do not. Other factors when dealing with wood are extent of knotting in the wood, types of treatments wood may have been exposed to, and handling of wood (transport, equipment, safety).

Wood provides a degree of flexibility in design and construction and can be placed in a variety of configurations parallel or perpendicular and at the toe or further away from the shore. Configurations of wood can allow significant passage of water, sediment, and fish as needed. Wood also has potential suitability for low through moderate energy environments. Secondary benefits of wood installations within living shorelines can be their use as perching or basking locations for organisms or subtidal habitat for fish, particularly if root ball systems remain. All wood placement typically needs to be anchored in some fashion. Typical anchoring mechanisms include duckbill cable anchors, burial under existing sediment or imported fill, attachment to other ballast materials (e.g., stone boulders) using chain or cable or larger more robust staking (e.g., small pilings). When considering anchoring requirements for woody materials, uplift forces resulting from material buoyancy, ice, and consistent interaction with waves and tidal action must be considered.

Wood Relationship to Design Elements

Energy Attenuation	Horizontal/ Vertical Positioning	Drainage	Habitat

3.7 Rock

Rock generally consists of quarry stone of various size (e.g., rip-rap) but can also include natural stone (e.g., unfractured cobble). Sizes can vary greatly based on project need from pieces of less than 50 lbs. to boulders of greater than 3,000 lbs. or more. Rock sizes can be mixed as needed. Placement can be done by hand for some projects but often design will require barge or land-based heavy equipment to deliver and place the rock. Rock has the benefit of being a natural material but is not endemic to most Delaware shorelines and not a locally sourced material throughout most of the state. Rock structures must be designed properly for local conditions to reduce potential vulnerability to scour and movement.

Rock structures can significantly reduce wave energy but the manner in which they do and how that affects sediment transport and deposition varies greatly by site and design (Figure 10). The rough surfaces of rock structures not only attenuate wave energy, but also can concentrate and reflect, refract, and diffract significant wave energy with potential unwanted consequences. Rock can provide some limited habitat, such as for oyster recruitment and juvenile fish refuge depending on cavity size, but the design of rock structures are not a primary shellfish substrate and should avoid creation of cavities of a size likely to entrap fish and wildlife (e.g., terrapin or horseshoe crab). Rock structures provide porosity for water but limited passage of sediment or fish. As such, rock structures retain fill; however, designs using rock should include gaps for faunal movement and drainage. Rock is among the most durable materials used in living shoreline construction and is expected to persist provided it is appropriately sized based on site-specific wave energy.

Figure 10. Rock toe sill reducing wave energy (Photo Credit: Chris Pfeifer).

Rock Relationship to Design Elements

Energy Attenuation	Horizontal/ Vertical Positioning	Drainage	Habitat

4.0 Case Studies/Examples

Case Study projects listed below highlight the use of various design elements and common materials to meet site specific goals. General project details, monitoring efforts, adaptive management, and several photos are provided for each living shoreline.

Name	Goal	Energy Level	Design Elements	Common Materials
Lewes	Shoreline Position	Low/Moderate	Salt Marsh Terrace Internal Compartmentalization	Coir Logs Vegetation Natural Sedimentation

Delaware Botanic Gardens	Habitat	Low	Toe	Wood Vegetation
Read Avenue Dewey Beach	Water Quality	Moderate	Offshore Energy Attenuation Structures: Breakwater	Oyster Shell Bags Hesco Barrier Vegetation Rock
Sassafras Landing	Shoreline Position	Moderate	Gapped Toe Sill Graded Slope	Quarry Stone Sand (Imported) Oyster Shell Bags Vegetation
Mispillion Harbor	Habitat Water Quality	Moderate	Breakwaters Salt Marsh Toe Salt Marsh Terrace Internal Compartmentalization	Oyster Shell Bags Oyster Castles Coir Logs
Delaware City Refinery	Shoreline Position	High	Offshore Energy Attenuation Structures	Prefabricated Structures
Seagrass Plantation	Shoreline Position	High	Offshore Energy Attenuation Devices Shell Toe	Prefabricated Structures Oyster Shell Bags Vegetation Oyster Castles