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Shoreline Protection Options for Humboldt Bay

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Humboldt State Environmental Management and Protection Planning Option
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Table of Contents

Figure 1: Riprap shoreline at Woodley Island Marina (photo by Rob Dumouchel)

Executive Summary

The cities, businesses, rural residences, transportation corridors, public utilities and agricultural lands that surround Humboldt Bay are currently protected by a network of natural and artificial shorelines. Many of the Bay's dikes and levees are over 100 years old and failing, and sea level rise, wave energy, and periodic storm surges are exacerbating the problem. The deterioration of this protective shoreline infrastructure is a slow moving natural hazard that will be extremely costly to this region if governments, landowners, and stakeholders don't start collaborating on innovative, practical, and affordable solutions.

The research, conducted by students in the Humboldt State University Environmental Planning Senior Practicum Spring 2016 at the request of the Humboldt Bay Harbor Commission, draws on many larger local studies, and seeks to contribute to ongoing discussions which will help planning entities make better informed decisions regarding development and use of Humboldt Bay.

This report reviews a series of non-structural, hybrid-structural, and structural armament shoreline protection methods that may be appropriate for use on Humboldt Bay. Each method is explained with technical detail, and is presented alongside site suitability requirements and the benefits and challenges associated with implementing each method. We have assembled this information in an effort to assist Humboldt Bay Harbor, Recreation, and Conservation District in guiding property owners when choosing the most appropriate methods for their site.

We have drafted a series of maps for shoreline types, wave fetch distances, wave energy, and sea level rise inundation. These maps were created to better understand and illustrate the forces impacting the Bay's shorelines which can be correlated with the wave energy site suitability sections for each option.

Regulatory constraints play a large role in the viability of implementing shoreline protection methods. The group identified agencies, laws, and permits necessary to consider when planning shoreline protection projects.

Although traditional armoring methods remain the best option in many places, there are a number of living shoreline technologies which would be appropriate for carefully selected portions of the Humboldt Bay shoreline. Making the effort to introduce non-structural and hybrid shoreline protection methods to the Bay will provide cascading ecological benefits, and will facilitate efforts to cope with the effects of sea level rise.

I. Introduction

History and Natural Processes

Humboldt Bay's shorelines, always dynamic, have been greatly modified by human agency over the last two centuries. When Europeans began to settle Humboldt Bay, they put great effort into reclaiming land for agriculture by draining wetlands and erecting extensive dike and levee systems around the Bay. This created some highly productive agricultural lands. It also contributed greatly to the loss of nearly 90% of the historical salt marshes (Laird, 2013) which used to buffer the Bay's natural shorelines from wave energy. The construction of hard structures reduced the tidal prism and resulted in the loss of salt marshes, estuaries, other ecosystems. The Bay's hardened shorelines cause the reflection of waves around the bay and prevents waves from dissipating which has changed the influence of dynamic processes of erosion, subsidence, and silt accretion that are slowly eating away many of the Bay's natural and manmade shorelines (Anderson, 2015). These processes are now amplified by climate change and sea level rise, and could be substantially sped up with a series of intense storms, an earthquake of sufficient magnitude, or a tsunami. Understanding the effects of the relatively recent attempts by humans to modify the Bay's features, in light of the procession of natural events, is key to interpreting shoreline protection options.

Existing Infrastructure Status and Habitat on Humboldt Bay

Of Humboldt Bay's entire shoreline, 75 percent is artificial, the majority built over 100 years ago. Approximately 26 miles of shoreline were considered highly vulnerable in a recent Humboldt Bay shoreline inventory (Laird, 2013) and many of these vulnerabilities are adjacent to important regional infrastructure such as the Eureka and Arcata municipal wastewater facilities, the King Salmon PG&E power plant, and Highway 101. Artificial shorelines are failing structurally because of undercutting and/or overtopping (Laird, 2013). Undercutting occurs when the lower levels of an earthen levee have been continuously stressed by tidal shifts, wave energy, and friction. Overtopping is due in part to levee or dike subsidence and Bay water level rise. Many levees and dikes are no longer tall or secure enough to prevent Bay water from flowing over or through them (Schlosser & Eicher, 2012). A legacy of inadequate maintenance has left much of the shoreline susceptible to inundation during large storm events and will have negative implications for planning for sea level rise on a landscape scale. Failure of these structures will have major impacts on the people, industries, and habitats around the Bay.

While settlers derived significant benefits from artificial shorelines, the modifications were made with a general lack of consideration for the habitat of native species altered by these structures. Dikes and levees encourage erosion behind the structure, disrupt sediment transport, provide limited wildlife habitat, and have negative impacts on estuaries that are important for the lifecycles of many aquatic species. The loss of the natural salt marshes and estuaries inhibits the shorelines from naturally securing and sustaining themselves. Natural occurring structures are some of the best solutions for coastal protection, unfortunately settlers drained these buffers before realizing the impact it would have on the futures of the communities they were establishing.

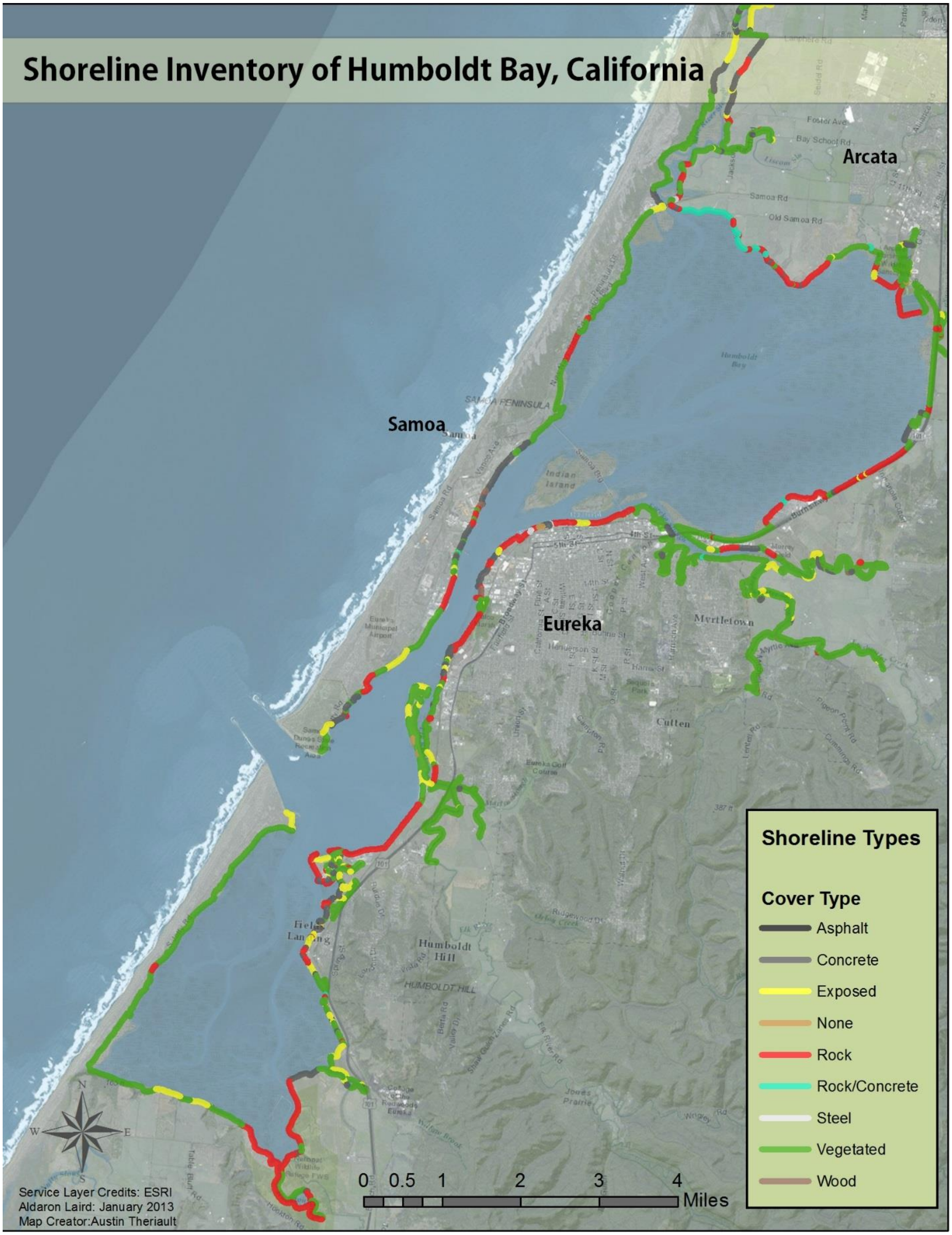

Figure 2: Inventory of shorelines along Humboldt Bay (based on GIS data created by Aldaron Laird)

Purpose

Our team was tasked by the Humboldt Bay Harbor Recreation and Conservation Commission to explore feasible options for the future of Humboldt Bay's failing artificial shorelines. Through research, interviews, and collaboration with local experts and the Humboldt Bay Harbor Recreation and Conservation District (Harbor District) we sought to identify practical, legally actionable coastal shoreline protection techniques that could increase coastal resilience while finding a balance between human needs for the safety and economic benefits provided by protective coastal infrastructure and the habitat requirements of native species.

The Harbor District included many shoreline protection related policies in the 2007 **Humboldt Bay Management Plan** (see Table 1). This report most directly addresses policy **HSM-2:** Develop an inventory of shoreline protection devices, identify potential needs for additional protection, and develop standards for new and existing Humboldt Bay shoreline protection. While reviewing shoreline protection methods we kept the policies in Table 1 in mind to ensure that the options suggested would be compatible with existing Harbor District policies.

Table 1: Shoreline protection related Harbor District policies

Policy Number	Description
HSM-2	Develop an inventory of shoreline protection devices, identify potential needs for additional protection, and develop standards for new and existing Humboldt Bay shoreline protection
HSM-3	Develop appropriate, consistent shoreline protection guidelines for commercial, industrial, and residential development around Humboldt Bay
HSM-4	Require maintenance according to the District's adopted shoreline protection standards
HSM-5	Require evidence that shoreline protection proposals protect the environment and meet District requirements
HSM-6	Require use of non-structural shoreline protection where feasible and appropriate
HSM-7	Identify needs for potential shoreline improvements necessary to accommodate bay water surface elevation changes, including potential effects of climate change
HWM-3	Re-deposition of dredged materials within Humboldt Bay may be authorized to meet plan purposes
HWM-4	Placement of fill within Humboldt Bay may be authorized to meet plan purposes
HWM-5	Potential dredged-material management options and alternative disposal methods shall be identified in a Long Term Management Strategy for Humboldt Bay
HRS-1	Develop and implement a regulatory coordination process for projects around Humboldt Bay that are consistent with adopted plans
RFA-2	Project approvals shall incorporate public access and associated services and amenities where appropriate
CAS-5	Fill placement may be used for habitat enhancement purposes
CEP-1	Impacts to streams, wetlands, estuaries, and coastal waters may be authorized for specific purposes or project types
CEP-3	Revetments, breakwaters, and other shoreline structures may be approved under specified conditions
CEP-4	Functional capacity of aquatic ecosystems must be maintained

Research Needs and Data Gathering

Innovation and experimentation with shoreline planning and implementation methods are occurring all over the globe. Our team reviewed shoreline conservation innovations seeking examples which may be applicable to Humboldt Bay.

We determined that defining feasible shoreline repair options about the Bay requires:

1. A clear understanding of the history of Humboldt Bay's shorelines and the processes of shoreline change that the Bay is currently experiencing;
2. Knowledge of the current status of shoreline infrastructure and the Bay shoreline's existing ecological conditions;
3. An assessment of successful models of shoreline conservation and infrastructure from beyond Humboldt Bay; and
4. Analysis of the regulatory and socioeconomic constraints to be accommodated, if shoreline structures of one form or another are to be built

A great deal of work has already been done by local planners to address information needs 1 and 2. Our team began to address factors 3 and 4 by building on the foundation laid by reports including **Humboldt Bay Shoreline Inventory, Mapping and Sea Level Rise Vulnerability Assessment** by Aldaron Laird of Trinity Associates (2013) and **Humboldt Bay: Sea Level Rise, Hydrodynamic Modeling, and Inundation Vulnerability Mapping** by Jeff Anderson of Northern Hydrology and Engineering (2015). Our team researched and compiled information to address tasks 3 and 4 in order to identify a range of legally feasible, and socioeconomically and environmentally desirable models of shoreline protection for Humboldt Bay.

Figure 3: The team visits the Arcata Marsh to observe its armored shoreline (photo by Rob Dumouchel)

II. Modeling the Natural Shoreline Altering Processes of Humboldt Bay

Key factors when choosing a shoreline protection method are how much wave energy the site is subjected to and how vulnerable it is to flood inundation. These factors were modeled and mapped for Humboldt Bay to assist land owners and project managers in determining what types of shoreline protection are appropriate for their locations. The following maps are for reference only and project developers should make their own observations of fetch and wave energy before designing a shoreline protection project. As is discussed below, different types of shoreline are capable of withstanding varying levels of wave energy and flood inundation. The different types of shoreline protection methods presented in this document reference the maps presented in this section.

Figure 4: Wave energy entering the mouth of Humboldt Bay (photo by Rob Dumouchel)

Fetch Distance

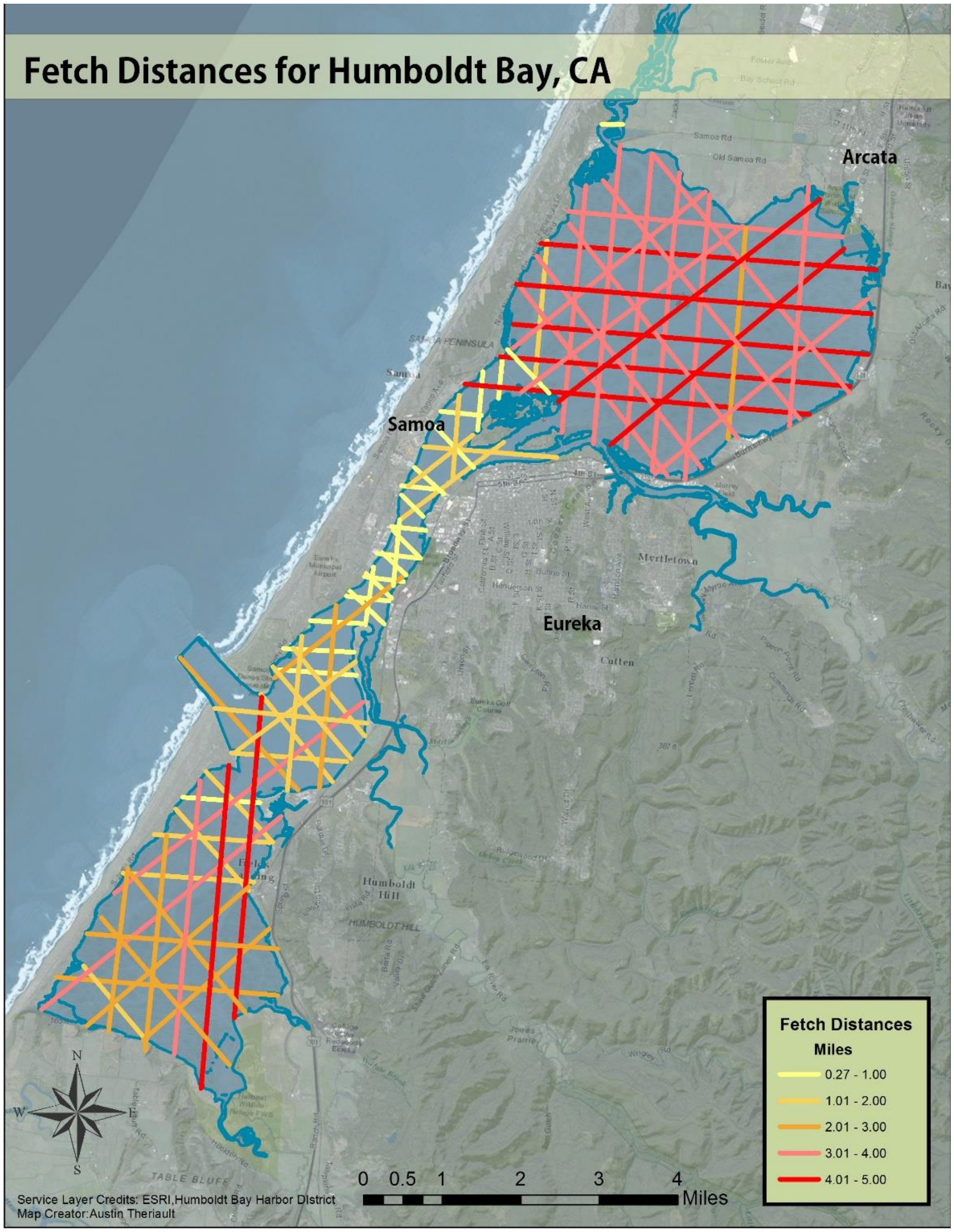

Figure 5: Fetch distance map of Humboldt Bay (Data source Jeff Anderson; Map compiled by A. Theriault)

This map shows distances of unobstructed wind flow or fetch on Humboldt Bay laid out in cardinal and inter-cardinal wind directions for true North, Northeast, East, Southeast, South, Southwest, West, and Northwest. Fetch is a key factor contributing to wave energy. This map was created by manually clipping distance lines to the border of the mean high tide level shoreline border. These data are used to calculate wave energy impacts for specific locations along the shoreline. In this report, the results can be used in correlation with the technology options which have wind fetch requirements. The highest levels of wind fetch are seen in Arcata Bay at 4 to 5 miles of fetch distance in a west to east pattern.

Wave Energy Map

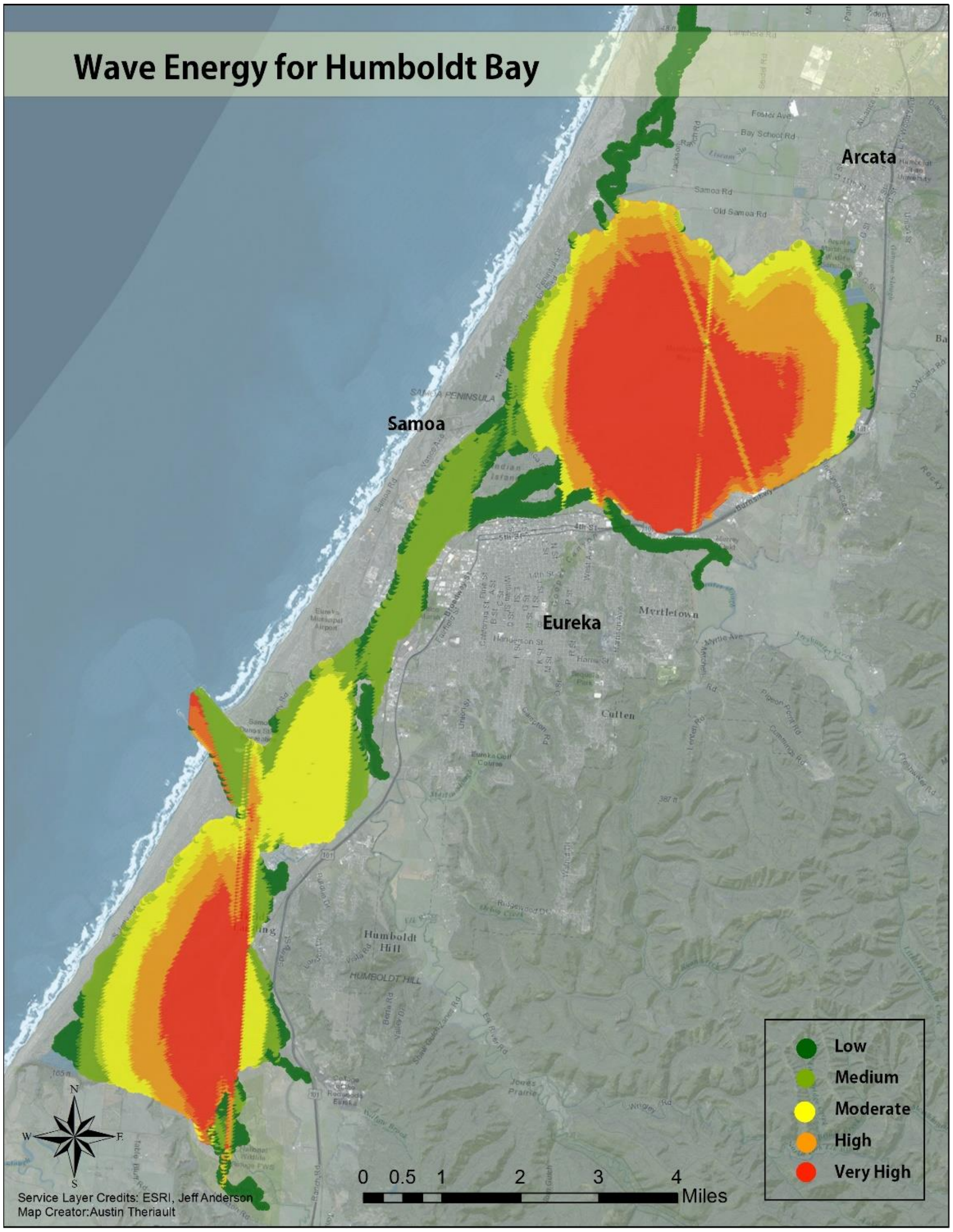

Figure 6: Wave energy map for Humboldt Bay (Data source Jeff Anderson; Map compiled by A. Theriault)

This wave energy map for Humboldt Bay shows the results of accumulated wave energy in the Bay. The data were interpolated in 1x1 meter plots for wind speed, wind direction, fetch, and average depth at mean high tide water level. This interpolation yielded data representing where wave energy and power are focused in the Bay. The data were collected and analyzed by Jeff Anderson from Northern Hydrology and Engineering. The strongest winds head north to south showing a high amount of wave energy focused on north facing shorelines. This map can be used in reference to low, medium, moderate, and high energy options in the shoreline protection methods section.

Flood Inundation

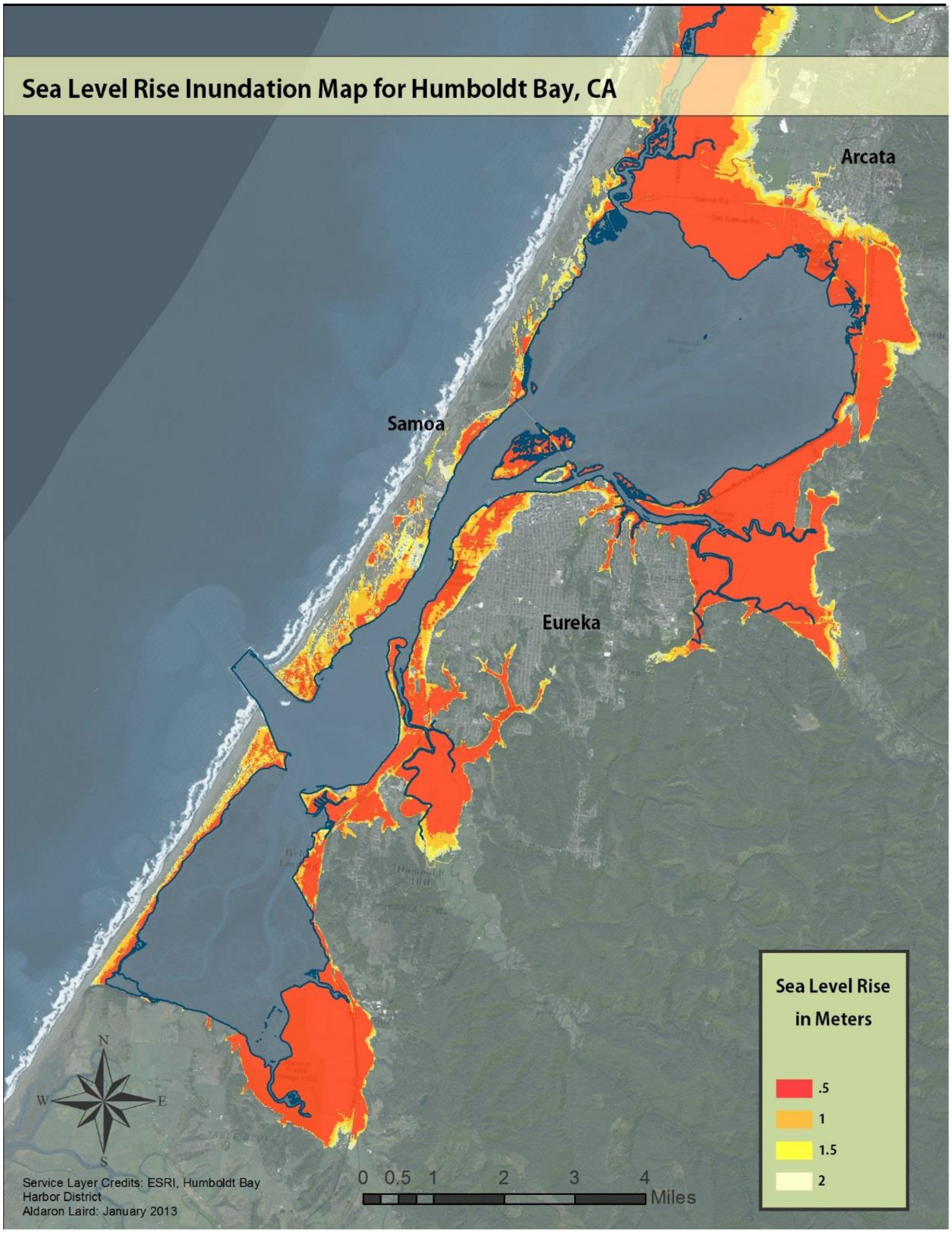

Figure 7: Sea level rise inundation map for Humboldt Bay (Data Source A. Laird; Map created by A. Theriault)

This map represents mean high water level at various sea level rise scenarios. These data represent sea level rise at .5, 1, 1.5, 2.0 meters of rise. These data were created for the **Humboldt Bay Shoreline Inventory, Mapping and Sea Level Rise Vulnerability Assessment** produced by Aldaron Laird (2013). The geospatial data can be used to see what areas are most likely to become inundated if levee repair or enhancement are not done. This map can also be used to see what infrastructure and assets are most vulnerable.

III. Shoreline Protection Methods

Introduction

With degrading dike and levee systems and now more frequent and severe storm surges and sea level rise to contend with, Humboldt Bay shorelines are under increasing threat. The Harbor District can support shoreline property owners by providing information about a range of shoreline structures which can be approved to protect their properties from inundation. In this section we outline various hard and soft engineering practices that are potentially applicable to one or more segments of Humboldt Bay's shoreline. Shoreline protection can be divided into three groups: non-structural methods (NSM), hybrid-structural methods (HM), and structural armament methods (SAM). Each method within these categories is discussed in a short profile covering site suitability, a description of how the method works, benefits of the approach, and possible challenges with applying it.

There are a wide range of shoreline protection methods available and many of them can be used in conjunction with each other. It is up to the land owners and their engineering contractors to decide which methods may be most appropriate for their section of shoreline.

Each method has been given a relative cost estimate based on past projects completed in various parts of the country. In this scale, $ = least expensive and $$$$ = most expensive. However, actual implementation costs are likely to vary wildly depending on site conditions, site accessibility, transportation, availability of labor and materials, and many other factors.

Non-Structural Shoreline Protection Methods (NSM)

Non-structural shoreline protection methods, referred to by some as living shorelines, bioengineering, or nature-based coastal adaptation, involve using natural products and processes in order to conserve, protect, and rebuild shorelines. Organic matting, fiber logs, native plants, and repurposed dredge spoils can be applied to create benefits similar to those of structural armament methods such as rock jetties and seawalls. Many non-structural methods have additional benefits such as creating a more natural shoreline aesthetic and habitat for birds and other native and migratory species. The major weakness of many non-structural methods is that the lack of hard armament elements leaves the shoreline modification vulnerable to erosion from natural forces present in the Bay. Non-structural methods can be implemented to increase public access to the shoreline and create recreational opportunities while also functioning as environmental restoration projects. Methods discussed here include: natural fiber log embankments, bank grading, planted marsh, and beach nourishment.

NSM-1: Natural Fiber Log Embankments

This method consists of a staked natural fiber embankment, woven organic matting and natural vegetation for stabilization, which can be put in place with or without dredge fill. To install natural fiber log embankments, mats composed of organic materials are laid out along eroding shorelines and then sections of coco-coir logs are laid on top of the mats. The log configuration can be customized to fit the contours of shoreline being protected. Typically, logs are placed in terraced fashion fitting the shoreline's elevation changes or are placed in single rows in areas where the elevation is level. Once placed, the logs are spiked through the mats and into the surface below to prevent low energy tidal action from lifting and floating the logs away. Once in place, the logs should accumulate natural sediments, provide a sturdy structure for vegetation to grow into, and hold sediments long enough for vegetation to take root. Some projects may benefit from being backfilled with dredged materials depending on the local sediment accumulation rate (Center for Coastal Resources Management, 2016).

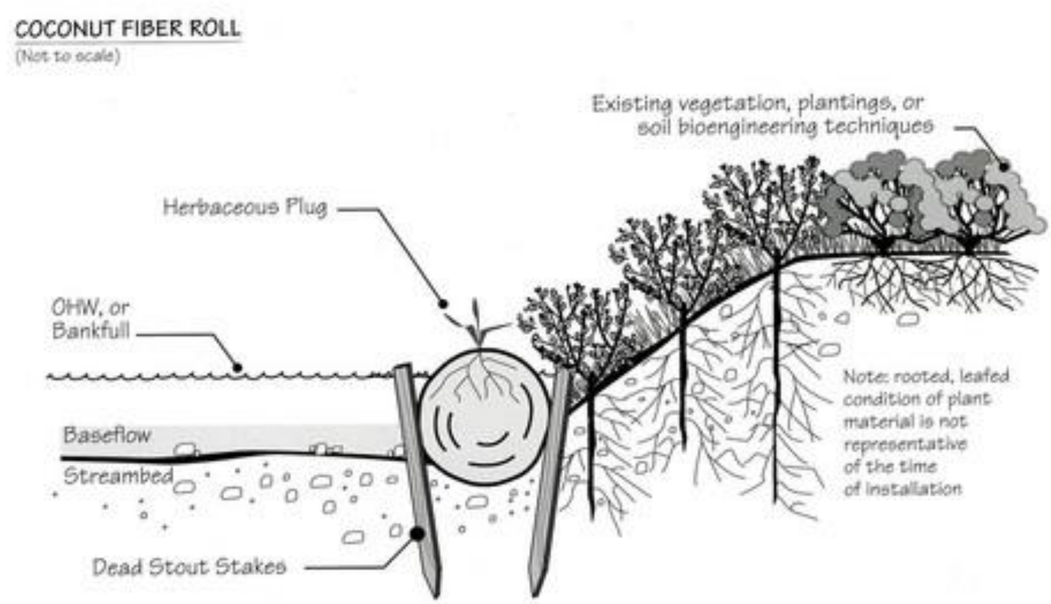

Figure 8: Diagram of fiber log embankment installation.[1]

[1] Diagram source: Indiana General Assembly – Natural Resources Commission (2012); http://www.in.gov/legislative/iac/20120404-IR-312120154NRA.xml.html

Table 2: Site suitability for natural fiber log embankment projects[2]

Site Suitability	
• Low wave energy sites • Elevations higher than mid-tide level • Very shallow tidal creeks and channels • Marsh shoreline and restoration areas • Graded or terraced banks • Minimal wave and boat wake areas	**Water Depth:** -1 foot, near shore **Wave Energy:** Low **Fetch:** .5 miles **Erosion:** 2 feet per year or less **Cost (per foot):** $

Figure 9: Before and after photos of a natural fiber log embankment project[3]

Table 3: Benefits and challenges of natural fiber log embankments[4]

Benefits	Challenges
• Relatively inexpensive and easy to implement • Matches aesthetic of natural coastlines; surrounding vegetation will readily grow into them • Effective above mid-tide level away from regular wave action • Uses no rock or other "hard" protection elements	• Ineffective against large storms, excessive wave action, and frequent tidal inundation • Not designed to reduce wave energy • Temporary unless sediment accumulates • Logs must be aggressively staked into place along both sides in order to maintain position • Requires frequent inspection, re-staking and maintenance until vegetation is well established

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[2] Table adapted from Living Shorelines for the Chesapeake Bay Watershed (Chesapeake Bay Foundation, 2007)
[3] Photos by P. Menichino for Center for Coastal Resources Management (2010); http://ccrm.vims.edu/livingshorelines/design_options/fiber_logs.html
[4] Table adapted from Living Shorelines for the Chesapeake Bay Watershed (Chesapeake Bay Foundation, 2007)

NSM-2: Beach Nourishment

Clean sand is transported and deposited onto an existing beach. Beach nourishment increases the elevation and width of an accessible beach while buffering upland areas from further erosion. Beach nourishment provides soft protection of seawalls and revetment walls by increasing the distance between upland areas and structures from storm wave events. Although a widely used restoration technique, beach nourishment is only suitable for building up pre-existing beaches (Center for Coastal Resources Management, 2016).

Figure 10: Beach nourishment in the Netherlands. Sand is brought in and dumped near shore to let natural currents refresh the sands along the coastline[5]

[5] Photo source: https://commons.wikimedia.org/wiki/File:Sand_suppletion_on_the_Dutch_coast_2.jpg (2011)

Table 4: Site suitability for beach nourishment projects[6]

Site Suitability	
• Beaches that have significant recreational or wave protection value • Beaches that have lost width	**Water Depth:** -1 foot, near shore **Wave Energy:** Low to Medium **Fetch:** .5 miles **Erosion:** 2 feet per year or less **Cost (per foot):** $$$

Figure 11: Dredged material placed on a pre-existing shoreline that experienced heavy erosion and then replanted with American beach grass along the Potomac River[7]

Table 5: Benefits and challenges of beach nourishment[8]

Benefits	Challenges
• Increases and/or retains area for recreation • Continued access to a sandy beach • Increased storm and wave buffer area • Maintains historic shoreline location	• High initial and long-term management costs (Leonard, 1990) • Impermanent, sands can easily be eroded away in a short period of time

[6] Table adapted from Living Shorelines for the Chesapeake Bay Watershed (Chesapeake Bay Foundation, 2007)
[7] Photo source: Center for Coastal Resources Management (2010); http://ccrm.vims.edu/livingshorelines/design_options/beach_nourish.html
[8] Table adapted from Living Shorelines for the Chesapeake Bay Watershed (Chesapeake Bay Foundation, 2007)

NSM-3: Planted Marsh

The planted marsh technique does double duty as shoreline protection and restoration, it focuses on replacing lost marshland vegetation in areas where elevations are still suitable or creating suitable elevations with suitable fill material and planting new vegetation. This technique should be used to expand and buffer existing tidal marshlands. In this technique, no reinforcing or armoring is used to hold the sediment in place, which can result in loss of the planted marsh in locations with high wave energy and erosion. This method is more effective when paired with containment structures such as sills or fiber logs.

Figure 12: Photo by K. Duhring. Here a recently planted marsh is being protected from grazers to ensure a successful take of the vegetation.[9]

[9] Center for Coastal Resources Management 2010

Table 6: Site suitability for planted marsh projects[10]

Site Suitability	
• 6 hours of sunlight per day • Wide intertidal areas with gradual slopes • Sandy soils, avoid excessive mulch or clay • Cleared or graded shorelines • Filled areas needing vegetation and restoration	**Water Depth:** -1 foot (or less), near shore **Water Energy:** Low **Fetch:** .5 miles or less **Erosion:** 2 feet per year or less **Cost (per foot):** $

Figure 13: Before and after a planted marsh project[11]

Table 7: Benefits and challenges of planted marsh projects[12]

Benefits	Challenges
• Cost effective • Easy to implement • Aesthetic • Habitat value extending natural areas	• Temporary until planting takes and sediment accumulates • Marsh can be lost in areas where wave energy is too strong

[10] Table adapted from Living Shorelines for the Chesapeake Bay Watershed (Chesapeake Bay Foundation, 2007)
[11] Photos by K. Duhrin for Center for Coastal Resources Management 2010
[12] Planted marsh – living shorelines, Center for Coastal Resources Management (2010); http://ccrm.vims.edu/livingshorelines/design_options/planted_marsh.html

NSM-4: Bank Grading

Bank grading aims to reduce wave energy gradually as waves break across a sloped banks which reflects wave energy and reduces erosion. Bank grading is implemented by using heavy equipment to reduce the steepness of earthen slopes along any water body. These newly created slopes are then reinforced with temporary erosion control fiber logs, mats, and blankets to stabilize the soils until planted vegetation is established. Native or suitable replacement plants appropriate for the local soil, sunlight, salt, and wind conditions are needed to enhance the odds of project success. Upland runoff should be directed away from the graded bank to prevent erosion and a return to the previous steep bank conditions. Target slope ratios will vary depending on whether bank grading is being used alone or in conjunction with other methods. The addition of planted marshes or other erosion and wave energy reducing structures can greatly increase effectiveness.

Figure 14: Example bank grading project[13]

[13] Photo by K. Duhring for Center for Coastal Resources Management (2010); http://ccrm.vims.edu/livingshorelines/design_options/bank_grading.html

Table 8: Site suitability for bank grading projects[14]

Site Suitability	
• Erosion at toe or top of earthen banks • Earthen structures that have been undercut or steep drop off into intertidal zone • High banks with falling trees and undercutting • Steep banks next to tidal marshland • Sites with no adjacent bulkheads, revetments or upland improvements • Direct sunlight for optimal vegetation growth	**Water Depth:** -1 to 5 feet, near shore **Wave Energy:** Low **Fetch:** .5 miles **Erosion:** 2 feet per year or less **Cost (per foot):** $$

Figure 15: Bank grading in progress[15]

Table 9: Benefits and challenges of bank grading[16]

Benefits	Challenges
• Dissipates wave energy within the adjacent waterbody • Reduces steepness of bank slope • Decreases erosion caused by wave action striking steep bank toes • Creates foundation for vegetation growth	• Large amount of adjacent land required to create desired slope • Heavy equipment required • Applicable permitting needed for heavy equipment use near marshlands or tidal areas • May require wetland fill permitting

[14] Table adapted from Living Shorelines for the Chesapeake Bay Watershed (Chesapeake Bay Foundation, 2007)
[15] Photo by K. Duhring for Center for Coastal Resources Management (2010); http://ccrm.vims.edu/livingshorelines/design_options/bank_grading.html
[16] Planted marsh – living shorelines, Center for Coastal Resources Management (2010); http://ccrm.vims.edu/livingshorelines/design_options/bank_grading.html

Hybrid Structural Methods (HM)

Hybrid structural methods attempt to blend hard shoreline protection methods with naturally existing features and materials. Hybrid structural methods sparingly use conventional "hard" shoreline protection methods and combine them with "softer" bioengineered solutions. The advantage of the hybrid approach is that it creates an end product that may be more attractive and provide some habitat while also being strong enough to resist the destructive forces of wind and wave energy.

Methods discussed here include:

- Toe revetment with embankment reinforcement
- Offshore oyster reef breakwaters
- Living shoreline combination options
- Vegetated rock slop protection

HM-1: Toe Revetment with Embankment Reinforcement

A small revetment wall made of rock is placed just at the toe of an eroding bank which breaks waves of moderate to medium energy and allows for sediment to accumulate behind the revetment. Erosion control mats (ECM) are used to capture and hold this sediment while providing soil stability and a substrate suitable for vegetation. Biodegradable ECMs are preferred and are available in materials such as coconut coir, wood excelsior, and mulch. Vegetation can consist of both naturally propagating plants along with the intentional planting of species like pickleweed (*Salicornia spp.*) and seashore saltgrass (*Distichlis spicata*). This solution would be appropriate in areas of moderate to medium wave energy, moderate to steep slopes, and with moderate to medium erosion. This option is similar to marsh toe revetments (SAM-3), but differs in that this method reinforces the embankment behind the revetment whereas marsh toe revetments have no major embankments behind them.

Figure 16: Toe revetment placed at the base of an eroding bank, uses established vegetation[17]

[17] Photo source: Washington Department of Ecology (2014); http://www.ecy.wa.gov/programs/sea/shorelines/stabilization/summaries.html

Table 10: Site suitability for toe revetment with embankment projects[18]

Site Suitability	
• In front of reinforced artificial shorelines, levees, dikes • Provides additional protection	**Water Depth:** -1 to -4 feet, near shore **Wave Energy:** Low **Fetch:** 2 miles or more **Erosion:** 8+ feet per year **Cost (per foot):** $$$

Table 11: Benefits and challenges of toe revetment with embankment reinforcement[19]

Benefits	Challenges
• Best of both worlds, light armament to protect shorelines while providing habitat • Requires less material, machinery, and labor than traditional armament methods • Erosion control mats provide soil stability creating an opportunity to establish vegetation • Creates an area where vegetation can take hold and be shielded from wave chop energy	• Temporary unless vegetation is established • Only works in moderate to medium wave energy zones • Fills the tidal prism, i.e. loss of volume of Humboldt Bay • Heavy equipment required

[18] Table adapted from Living Shorelines for the Chesapeake Bay Watershed (Chesapeake Bay Foundation, 2007)
[19] Marsh toe revetment with natural marsh– living shorelines, Center for Coastal Resources Management (2016); http://ccrm.vims.edu/livingshorelines/design_options/marsh_toe_revetment.html

HM-2: Offshore Oyster Reef Breakwater

Oyster reefs function as a living breakwater by absorbing wave energy before it reaches the shoreline. Oyster reefs also provide a substrate to capture sediment and upon which vegetation can be established. To create an oyster reef, recycled oyster shells are put into netted bags and positioned in the Bay. Oyster larvae will naturally attach to the shells (Cleaver, 2015). This shoreline protection method utilizes an oyster reef as a breakwater along with native vegetation which would effectively reduce levee erosion, improve water quality, and provide habitat for marine life (Choctawhatchee Basin Alliance, 2016). “Shell bags” should be anchored into place in an intertidal zone at or below mean low tide level. Oyster reefs offer a good solution to supplement other shoreline protection options or to augment existing structures by restoring ecological function and protection.

Figure 17: Artificial oyster reef in Florida[20]

[20] Photo source: Choctawhatchee Basin Alliance of Northwest Florida State College (2016); http://www.basinalliance.org/page.cfm?articleID=15

Table 12: Site suitability for offshore oyster reef breakwater projects[21]

Site Suitability	
• Evidence of existing oyster populations • Must be accessible for transportation of oyster bags • Close to shoreline near mean high tide level	**Water Depth:** 0 to 3 feet, near shore **Wave Energy:** Low **Fetch:** 1 to 3 miles **Erosion:** 2 to 4 feet per year **Cost (per foot):** $$

Figure 18: Oyster reefs at McDill Air Force Base[22]

Table 13: Benefits and Challenges of offshore oyster reef breakwaters

Benefits	Challenges
• Permanent with lasting benefits • Can supplement commercial harvest • Provides habitat • Improves water quality • Increases biodiversity • Provides a barrier to prevent erosion • Protects seagrass restoration projects	• May require filling wetland • Shell bags can be aesthetically unattractive • Side-effects on associated wildlife is not yet well studied

[21] Table adapted from Living Shorelines for the Chesapeake Bay Watershed (Chesapeake Bay Foundation, 2007)
[22] Photo Source: Reef Innovations (2013); http://reefinnovations.com/projects/us-south-east/florida/tampa-bay

HM-3: Living Shoreline Combination Option

How it works: this biotechnical option offers the most biological value as it incorporates a multitude of techniques that together create a stable and productive habitat structure. This option would be most suited for areas of the Bay experiencing medium to high erosion as it significantly dissipates wave energy. Development begins with a small revetment wall of oyster bags on the tidal run-up of the embankment. Behind this structure are staked fiber logs which will help to trap sediment while providing physical structure. The fiber logs are then backfilled with dredge spoils to decrease depth allowing for native salt marsh vegetation propagation. This layer would be covered with erosion control mats which help to hold sediment and allow for quick vegetation growth.

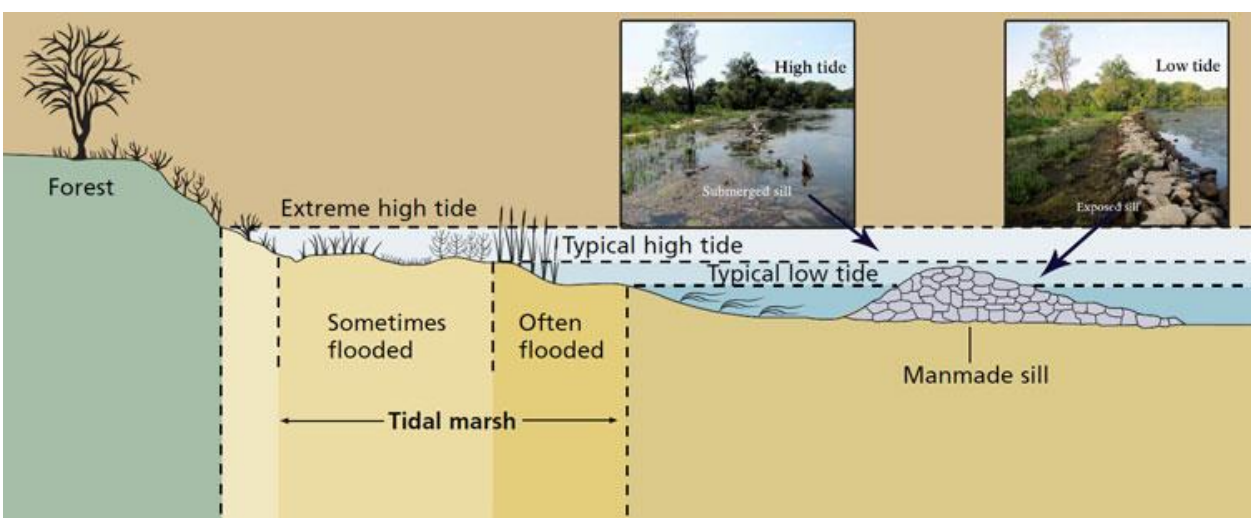

Figure 19: Living shoreline diagram[23]

[23] Alice Ferguson Foundation (2012) ; http://fergusonfoundation.org/the-farm/piscataway-park-living-shoreline-restoration/

Table 14: Site suitability for living shoreline combination projects[24]

Site Suitability	
• Areas similar to the recommended sites for the natural fiber embankment option (NSM-1) but with more wave chop and the need to reduce wave energy before reaching the fiber logs • Gradual slope run-ups to embankment • Good access for transport of needed materials • Marsh shoreline and restoration areas • Graded or terraced banks	**Water Depth:** 2 to -2 feet, near shore **Wave Energy:** Low to Medium **Fetch:** 1 to 2 miles **Erosion:** 2-8 feet per year **Cost (per foot):** $$$

Table 15: Benefits and difficulties of living shoreline combination projects

Benefits	Difficulties
• Incorporates many living shoreline techniques for maximum effectiveness of shoreline protection • Offers a high biological value through oyster habitat and native vegetation • Creates a strong buffer to wave energy, suitable in medium wave energy zones • The mixture of organic and inert materials create strong and permanent structures	• Highest cost in regards to "living shoreline" options • Requires the most effort for implementation • Requires the most materials as it includes oyster bags, rock revetment walls, fiber logs, erosion control mats, and dredge spoils • Fills the most volume of Humboldt Bay

[24] Table adapted from Living Shorelines for the Chesapeake Bay Watershed (Chesapeake Bay Foundation, 2007)

HM-4: Vegetated Rock Slope Protection

This option consists of placing rock slope protection (RSP) on slopes, backfilling with topsoil, tamping the soil, and planting suitable vegetation in the tamped topsoil. The backfill provides a base for the establishment of shallow rooted plants that provide erosion control and secure the RSP below. Once established, these plantings can create viable habitat from a barren rock slope. Depending on vegetation types, leaf litter will also produce soil further stabilizing and increasing size. This method could also be used on existing RSP or riprap structures to stabilize them if they are failing or to increase habitat and aesthetics (Caltrans, 2016).

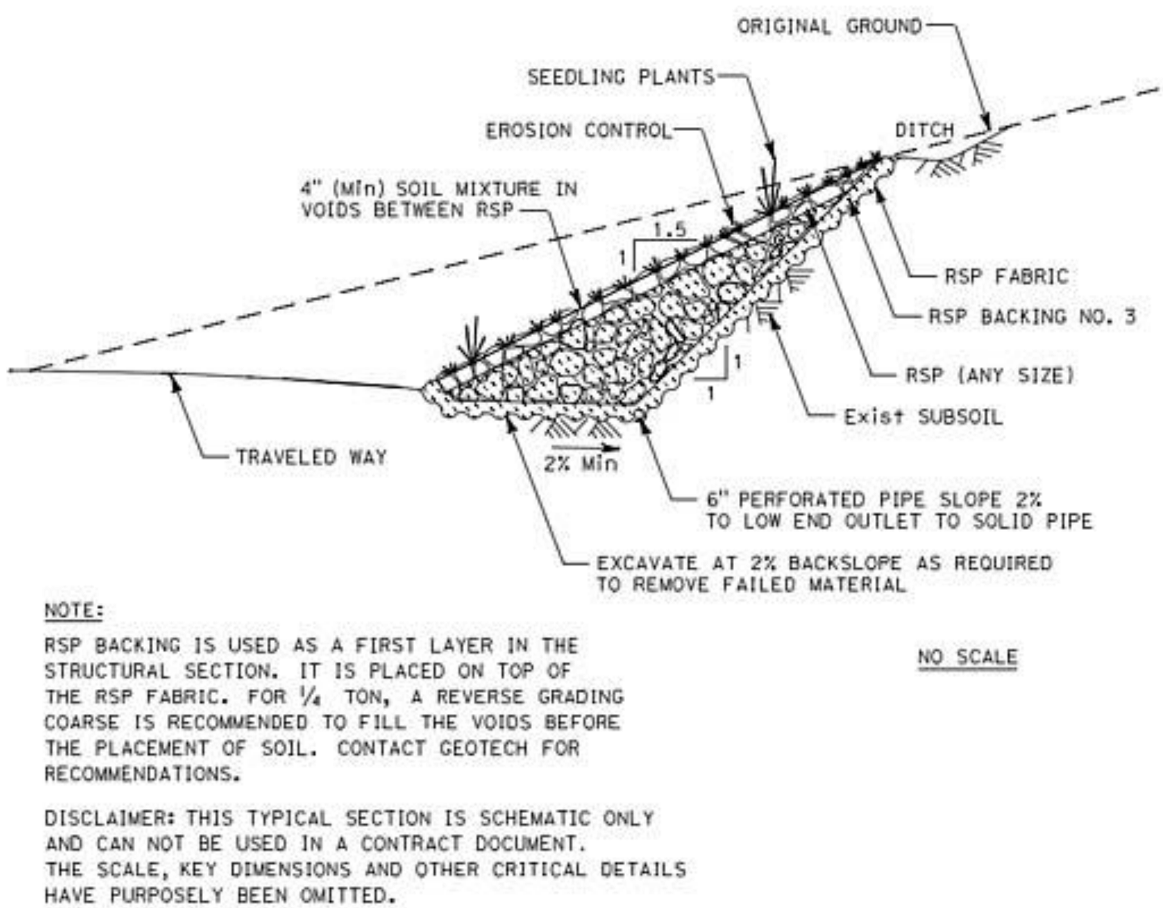

Figure 20: Caltrans diagram of RSP[25]

[25] Diagram source: Caltrans (2016); http://www.dot.ca.gov/hq/LandArch/16_la_design/guidance/ec_toolbox/steep_slopes/soil_filled_rsp.htm

Table 16: Site suitability for vegetated rock slope protection projects[26]

Site Suitability	
• RSP slopes, existing or after construction • Riprap, existing or after recent placement • Above high wave energy lines on the RSP or riprap • RSP slopes that do not receive above medium wave energy	**Water Depth:** 1 to 4 feet, near shore **Wave Energy:** Medium **Fetch:** 2 miles or more **Erosion:** 4-8 feet per year or more **Cost (per foot):** $ to $$$ depending on amount of new RSP/riprap construction

Figure 21: Caltrans backfilling soil over RSP before planting vegetation on the slope[27]

Table 17: Benefits and challenges of vegetated rock slope protection

Benefits	Challenges
• Sediment and debris accumulation • Long-term strength for taking of planted vegetation • Vegetation softens the visual impact of rock slopes • Provides habitat and cover for wildlife • Additional long-term control of erosion • Vegetation serves to strengthen and solidify the existing structure	• Placement of topsoil can only be above high wave energy lines as any soil will be washed away during high wave energy periods • Costly if constructing new RSP • Requires space for heavy equipment access • Planting of willows or other deep rooted plants requires placement of biodegradable plant tubes for their roots at the same time as the rocks are being placed • Additional effort required to establish root networks, and plants must be halophytic (salt tolerant)

[26] Table adapted from Living Shorelines for the Chesapeake Bay Watershed (Chesapeake Bay Foundation, 2007)
[27] Photo source: Caltrans (2016);
http://www.dot.ca.gov/hq/LandArch/16_la_design/guidance/ec_toolbox/steep_slopes/soil_filled_rsp.htm

Structural Armament Methods (SAM)

Many communities have used structural armament methods to harden shorelines that are most vulnerable to erosion or that have vital economic purposes. In Humboldt Bay, 77 miles of shoreline are artificial (Laird, 2013), many of them protected with rock walls. Additionally the mouth of the Bay is maintained with large rock jetties. Structural armament methods are beneficial in that they are very solid and difficult to damage. The downside is that they exacerbate erosion in front of and to the sides of the rock walls and provide minimal habitat value. In this section we discuss:

- Offshore breakwaters
- Marsh sill
- Revetment

SAM-1: Offshore Breakwaters

Offshore breakwaters protect existing beaches and shorelines by intercepting wave energy before it has a chance to erode existing shorelines. Breakwaters can both protect beaches as recreational areas as well as create calmer waters inside the breakwaters for in-water recreational activities. Strategic placement of breakwaters is necessary to limit wave reflection which is already a problem within Humboldt Bay.

Figure 22: Offshore breakwaters in Presque Isle, PA[28]

[28] Photo source, Army Corps of Engineers (n.d.); http://www2.gsu.edu/~geohab/Babaie/courses/geol2001/Hazard%20City%20application/Files/modules/shoreline/breakwaters-lake-erie-usace.jpg

Table 18: Site suitability for offshore breakwater projects[29]

Site Suitability	
• Areas with high erosion or severe undercutting due to moderate to high energy wind chop • Long shorelines with space for more than one breakwater • Areas with shallow nearshore depths and without significant submerged aquatic vegetation or shellfish habitat • Feasible access for construction equipment during installation	**Water Depth:** -4 to -15 feet **Wave Energy:** Moderate to High **Fetch:** 2 miles or more **Erosion:** 4-8 feet per year **Cost (per foot):** $$

Figure 23: Breakwater system on the York River[30]

Table 19: Benefits and challenges of offshore breakwaters

Benefits	Challenges
• Opportunities for revegetation and beach nourishment • Sand accretion and sediment stabilization • Stabilizes wetland areas • Slows inland water transfer • Decreases the upper threshold of wave run up, a significant contributor to shore term erosion events (Sorenson, 1997)	• High land costs • Aesthetically unpleasant • Ineffective against high/projected inundation levels • Requires projecting future beach shape for effective placement

[29] Table adapted from Living Shorelines for the Chesapeake Bay Watershed (Chesapeake Bay Foundation, 2007)
[30] Photo source, K. Duhring (2010); http://ccrm.vims.edu/livingshorelines/design_options/offshore_breakwater.html

SAM-2: Marsh Sill

A low-profile stone structure is used to contain sand fill to create a new marsh. Generally, sills are 6-12 inches above high water mark but can be made taller. Transplanted vegetation adds structural stability, aesthetic quality, and expands habitat. The marsh sill area is naturally enriched over time by tidal overtopping which helps with revegetation creating many ecological benefits while strengthening the shoreline. Sills are different from revetments in that they are offset further than revetments and backfilled with sand or other material to promote vegetation growth.

Figure 24: Sill placed in front of an eroding shoreline[31]

[31] Photo source, K. Duhring (2010); http://ccrm.vims.edu/livingshorelines/design_options/marsh_sill_planted.html

Table 20: Site suitability for marsh sill projects[32]

Site Suitability	
• Shallow, low wave energy sites • Needs appropriate soil and high light availability for plant growth • Must be accessible to heavy construction machinery	**Water Depth:** 2 to 4 feet, near shore **Wave Energy:** Low to Medium **Fetch:** 2 miles **Erosion:** 4-8 feet per year **Cost (per foot):** $$

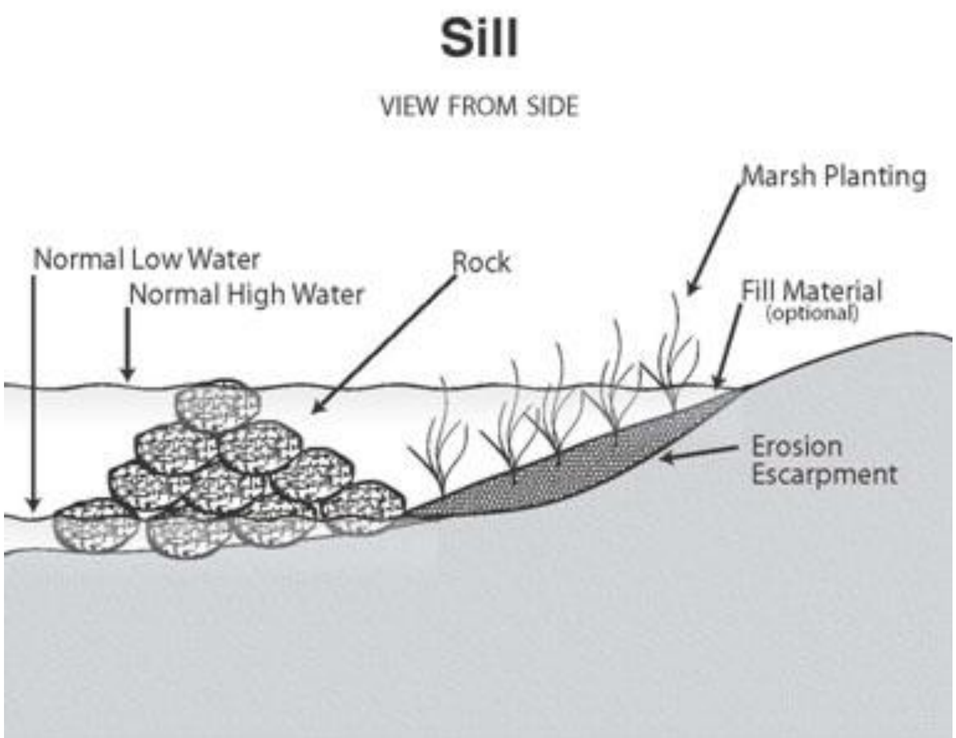

Table 21: Benefits and challenges of marsh sills

Benefits	Challenges
• Habitat for shallow-water species • Buffering of wave energy • Reduction of sediment loads • Anchor and stabilize shoreline sediments • Wider areas will receive greater natural wave attenuation and erosion control	• Plants used must be halophytic • Soil amendments may be required when replanting • Small scale implementation may not be cost effective

[32] Table adapted from Living Shorelines for the Chesapeake Bay Watershed (Chesapeake Bay Foundation, 2007)

SAM-3: Marsh Toe Revetment

Marsh toe revetments are short, freestanding, trapezoidal-shaped structures offset from the existing marsh edge near the low water elevation. Revetment heights should be near mean high water in low energy settings to allow regular wave overtopping. Height can be raised 1-2 feet above mean high water in moderate energy settings or where the marsh is less than 15 feet wide and the marsh width cannot be increased. Revetments focus on breaking wave energy at the edges of the marsh. The reduced wave chop and tidal energy during tidal events which lead to marsh loss and erosion is negated. Revetments allow for overtopping at peak tides which contributes to robust habitat formation in the marshes it protects behind while still protecting marsh edges from excessive wave energy. Tidal gaps should be place in line with natural marsh channels.

Figure 25: Marsh toe revetment[33]

[33] Photo source, K. Duhring (2010); http://ccrm.vims.edu/livingshorelines/design_options/marsh_toe_revetment.html

Table 22: Site suitability for marsh toe revetment projects[34]

Site Suitability	
• Low elevation tidal marshes with no major embankment behind • Existing tidal marsh width must be greater than 15 feet • Existing marsh edge erosion or minor upland bank erosion • Very shallow water near marsh edge with a hard sand bottom • Feasible access for installation	**Water Depth:** -2 to 1 feet, near shore **Wave Energy:** Medium **Fetch:** 2 miles **Erosion:** 4-8 feet per year **Cost (per foot):** $$

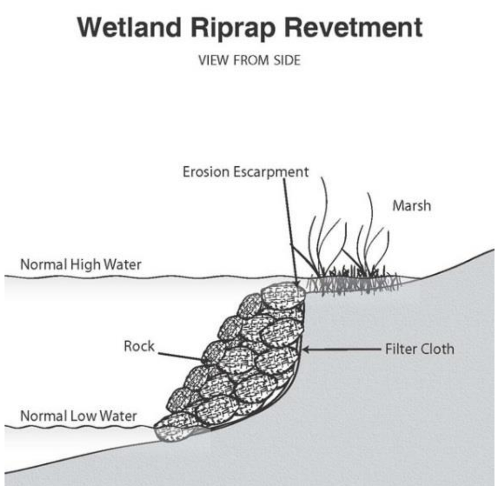

Figure 26: diagram of marsh toe revetment[35]

Table 23: Benefits and challenges of marsh toe revetments

Benefits	Challenges
• Prevents marsh erosion by reducing wave energy • Allows for greater storm surge absorption or water runoff • Increased habitat diversity via nutrient cycling from overtopping • Wave attenuation • Secures sediment and stabilizes vegetation	• Expensive to implement on a large scale • Provides little protection from large storms and projected inundation levels

[34] Table adapted from Living Shorelines for the Chesapeake Bay Watershed (Chesapeake Bay Foundation, 2007)
[35] Diagram source, the North Carolina Department of Environmental Quality; https://deq.nc.gov/about/divisions/coastal-management/coastal-management-estuarine-shorelines/stabilization/stabilization-options

IV. Regulatory Considerations

Improving Humboldt Bay's shorelines is unlikely to be easy or inexpensive, there are a great number of regulatory barriers that any shoreline project must navigate in order to be implemented. Any shoreline protection method(s) chosen will require the project proponent to present it to a series of regulatory and permitting agencies for approval. Because programmatic permitting does not currently exist on Humboldt Bay, permitting is done project-by-project which creates a lot of work and inefficiencies for developers and agencies.

Regulatory Environment

When planning a shoreline protection project, there are a number of agencies to be consulted with. The agencies listed in Table 25 include most of the possible agencies which may have jurisdiction over a portion of a shoreline project in Humboldt Bay.

Table 24: Agencies that may have jurisdiction over shoreline projects in Humboldt Bay

Agency	Local Office	Website and/or Phone
Local Government Agencies		
Humboldt Bay Harbor, Recreation, and Conservation District	601 Startare Dr, Eureka, CA 95501	humboldtbay.org/ (707) 443-0801
County of Humboldt (Public Works - Environmental Services)	1106 2nd St, Eureka, CA 95501	humboldtgov.org/1400/Environmental-Services
City of Arcata (Environmental Services)	736 F St., Arcata, CA 95521	cityofarcata.org
City of Eureka	531 K St, Eureka, CA 95501	ci.eureka.ca.gov 707-441-4160
State Agencies		
California Coastal Commission (North Coast District)	1385 8th St. #130, Arcata, CA 95521	coastal.ca.gov/ (707)826-8950 x8
California Department of Fish & Wildlife - Eureka Office	619 2nd St, Eureka, CA 95501	wildlife.ca.gov/ (707) 445-6493
Caltrans - District 1	1656 Union St, Eureka, CA 95501	dot.ca.gov/d1/ 707-445-6600
North Coast Regional Water Quality Control Board	5550 Skylane Blvd #130 Santa Rosa, 95403	waterboards.ca.gov/northcoast/ 707-576-2220
California Public Utilities Commission	505 Van Ness Ave, San Francisco, CA 94102	Cpuc.ca.gov 415-703-2782
Federal Agencies		
U.S. Army Corps of Engineers	601 Startare Dr #100, Eureka, CA 95501	usace.army.mil/ 707-443-0855
U.S. Fish & Wildlife Service	1655 Heindon Rd., Arcata, CA 95521	fws.gov 707-445-6493

Environmental Impact Assessments, Permits, and Consultations

There is no shortage of permits required when proposing a development in the coastal zone. Below are listed potential permits and consultations that a project may require depending on location, ownership, and species present.

Environmental Impact Assessment

All projects are likely to require an environmental impact assessment (EIA) under either the National Environmental Policy Act (NEPA) or the California Environmental Quality Act (CEQA). Whether the EIA process results in a negative declaration, mitigated negative declaration, or a full environmental impact report/statement will be determined by the lead agency. The Harbor District is the lead agency for most projects occurring within Humboldt Bay, however, the lead agency for your project will depend on the scope of the project, the landowners involved, and the sources of funding.

Local Permits and Consultations

- Humboldt Bay Harbor, Recreation, and Conservation District – Development Permit
  - This development permit is the initial step in the CEQA process. The Harbor District is often the lead agency with development projects in or adjacent to the Bay
- County of Humboldt – Conditional Use Permit
  - The Development Permit is used to show that the project is consistent with the Local Coastal Plan of Humboldt County
- City of Arcata – Conditional Use Permit
  - The Development Permit is used to show that the project is consistent with the Local Coastal Plan of Humboldt County
- City of Eureka – Conditional Use Permit
  - The Development Permit is used to show that the project is consistent with the Local Coastal Plan of Humboldt County
- Tribal Consultation[36] – Letter of Concurrence/Approval
  - According to section 106 of the National Historic Preservation Act, the letter of concurrence must address if the proposed project will adversely affect historic properties

State Permits and Consultations

- California Coastal Commission - Coastal Development Permit/Consistency Determination (federal land owners only)
  - Proposed plans must be consistent with the State Coastal Management Plans and Local Coastal Plans (LCP), further approval by the Coastal Commission

[36] Recently implemented California law A.B. 52 has changed the rules on tribal consultation for development projects. How this will impact shoreline protection development projects is not yet fully known

- Caltrans - Encroachment Permit
    - This permit allows the permittee to hold highway rights-of-way while implementing the proposed planning program
- North Coast Regional Water Quality Control Board – National Pollutant Discharge Elimination System Permit, Water Quality Certification
    - These permits are needed when dredging and filling in national waters. Any changes in water quality must be reported and observed.
- California Department of Fish & Wildlife – Streambed Alteration Agreement
    - This permit is required in areas where river alterations occur; a "river alteration" can include but is not limited to: changing the natural flow of the river, substantial change of content or use of material in stream bed, deposits waste or debris into the river

Federal Permits and Consultations

- US Army Corps of Engineers – Section 10, Section 404 Permit
    - This permit is required for any built structure within or over a navigable water body of the United States
- National Marine Fisheries Service - Endangered Species Act, Section 7 consultation for marine species
    - A section 7 consultation is required for proposed projects that could adversely affect endangered species; this requirement is from the Endangered Species Act
- US Fish and Wildlife Service - Endangered Species Act, Section 7 consultation for terrestrial species
    - A section 7 consultation is required for proposed projects that could adversely affect endangered species; this requirement is from the Endangered Species Act

California Coastal Act and Local Coastal Programs

Compliance with the California Coastal Act is at the heart of any shoreline development project. Some key themes that run throughout the Coastal Act are public access, recreation, and environmental protection. The Coastal Act requires careful planning of coastal development and was passed with an intent to protect the beauty and ecological health of California's coastal zone. This act created the California Coastal Commission, a quasi-judicial body which has jurisdiction over actions proposed within the coastal zone. The Coastal Act recognizes that development in the coastal zone will be necessary to protect infrastructure and coastal dependent industries, but it is also highly restrictive with regard to what projects may be implemented.

For purposes of the Coastal Act, development includes any construction, reconstruction, demolition, dredging, or placement of structures on land or in the water which means that any shoreline protection method within this report is subject to the Coastal Act (Coastal Act § 30106)

Shoreline developments should not interfere with public access (Coastal Act § 30211) or recreation (Coastal Act Article 3). If a proposed project impacts an area which is currently used by the public in some capacity, it is imperative that an approach is identified which will allow the public continued access. Access and recreation are such strong parts of the Coastal Act that it could also be advantageous to add public access or recreation space/amenities to the coast as part of a proposed project where they had not existed before.

Diking, filling and dredging are allowable under certain conditions which include restoration. Many of the shoreline protection methods in this report also have environmental restoration aspects to them which may help in gaining approval for their implementation (Coastal Act § 30233). The Coastal Act does recognize that the construction of hard structural armaments is sometimes necessary and allows for permitting to protect coastal-dependent uses, existing structures, or public beaches subject to erosion (Coastal Act § 30235). Project proponents would do well to inventory their proposals for possible uses addressed in this section.

As a complement to the Coastal Act, most coastal communities have Local Coastal Programs (LCPs) which are Coastal Commission approved plans for local coastal zone management. Arcata, Eureka, and Humboldt County all have approved LCPs which a development proponent should review before planning and attempting to gain permits for a project. LCPs give a local lens through which to view the Coastal Act.

V. Conclusions and Recommendations

Shoreline protection will buy time and extend the viability of existing infrastructure, however the current rates of sea level rise and subsidence are expected to take back much of the land that was reclaimed by farmers and ranchers over 100 years ago. With this in mind we recommend that the Harbor District also study retreat strategies and how they can be used as alternatives and/or in combination with shoreline protection methods.

According to policy number HSM-5, "Require evidence that shoreline protection proposals protect the environment and meet District requirements", it is our recommendation that further analysis of wave energy be conducted on Humboldt Bay. Jeff Anderson's initial work on the subject has helped to identify the issue of wave energy in regards to undercutting of levees and dikes, as well as to identify current wave energy on the Bay. The information provided for this project is just the beginning of investigating this phenomenon and does not take into consideration varying storm strengths or wave energy in the presence of sea level rise and climate change.

One large roadblock to implementation of shoreline protection projects is the permitting process. We would recommend a study into how the Harbor District, or another local government agency, could help institute a programmatic permitting approach. If a regional general permit were to be developed it could streamline application processes for both agencies and permit applicants, it could save money, and lead to faster project decisions.

Figure 27: Waves breaking against the jetty (photo by Rob Dumouchel)

VI. Glossary

Bank Erosion – Loss of upland soil along a shoreline due to action of water or wind

Baseline Condition – A measure of conditions existing prior to influence or manipulation

Beach Nourishment – Placement of sand along a shoreline to increase width and raise elevation

Breakwater – Offshore stone or concrete structure built parallel to the shore that reduces wave energy

Bulkhead – Vertically oriented shoreline armoring structure that retains soil, usually secured with metal or wood pilings

Erosion – The gradual decomposition of a structure due to wind, water, or other natural agents

Fetch – The distance of open water over which wind blows and waves are generated
Fiber Log – Manufactured, biodegradable log that provides temporary erosion protection, sediment control and a medium for growing plants.

Grade Bank – Reducing the steepness of a slope to allow for wave run-up and enhance vegetative growth

Groin – A wall or mound of rock that is placed perpendicular to the shoreline, angled in the direction of wave approach

Hybrid Structure – Combination of hardened structures and natural material as engineering mediums

Jetty – A large piled structure of stone or concrete that projects from land out into water, often used to protect either side of a coastal inlet

Marsh – an area of low-lying vegetation that is flooded in wet seasons or at high tide, and typically remains waterlogged at all times

Marsh Sill – A low revetment placed near the average low water elevation, and then backfilled with sand to create an artificial tidal marsh

Microbial Mats – Multilayered sheets of microorganisms, often used to improve water quality and aids in management of fish farms

Native Vegetation – Preference of selection towards plants that occur naturally in a project site. This landscape management practice has manifold benefits for ecology and preserves existing habitat

Near Shore Water Depth – The region of land extending between the shoreline and the beginning of the offshore zone. Generally, NSWD is less than ten feet in depth.

Non-structural – An engineering medium comprised of an arrangement of naturally occurring materials that require some management and construction, but do not call for modern construction materials. Also called ‘’soft engineering’’

Revetment – Stone, concrete, or timber armoring method that hardens the slope face of the shoreline, usually placed along an upland bank or shore. Size dictated by wave height/energy

RSP / "Rock Slope Protection" / "Rip-rap" – Angled blocks of rocks of various sizes placed along a shoreline to break wave energy and protect against erosion

Rock Sill – A low revetment placed near the mean low water line elevation adjacent to an existing tidal marsh

Sea Level Rise – The gradual rise of global shoreline inundation levels, as related to the concept of climate change, the effects of which will have long term implications for human settlements along coastlines.

Sill – Partially continuous erosion control structure placed along the edge of marsh fringes

Shoals – Areas with relatively shallow water

Structural – a built arrangement of construction materials and methods that are not naturally occurring. Also called "hard engineering''

Undercutting – The gradual process of erosion at the base of existing levees and dikes that occurs as a result of continuous wave breaks.

Figure 28: Rock breakwater in King Salmon (photo by Rob Dumouchel)

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Jeff Anderson, Northern Hydrology and Engineering

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Figure 29: Touring the White Slough project with Eric Nelson and Aldaron Laird (photo by Rob Dumouchel)