Appendix B. Resilient Infrastructure Project Guides

Resilient Infrastructure Project Guides

This *Military Installation Resilience Framework* developed a suite of adaptation project guides to identify future climate resilience infrastructure approaches along the three primary corridors (Pacific Highway, Harbor Drive, and State Route [SR] 75/SR-282).

Various engineering solutions can be incorporated to protect infrastructure and natural shorelines from the detrimental effects of flooding and sea level rise (SLR). As discussed in the framework, incorporating Nature-based Solutions (NbS) with Civil Engineering Projects (CEP) is the recommended approach to adaptation. These approaches are defined as:

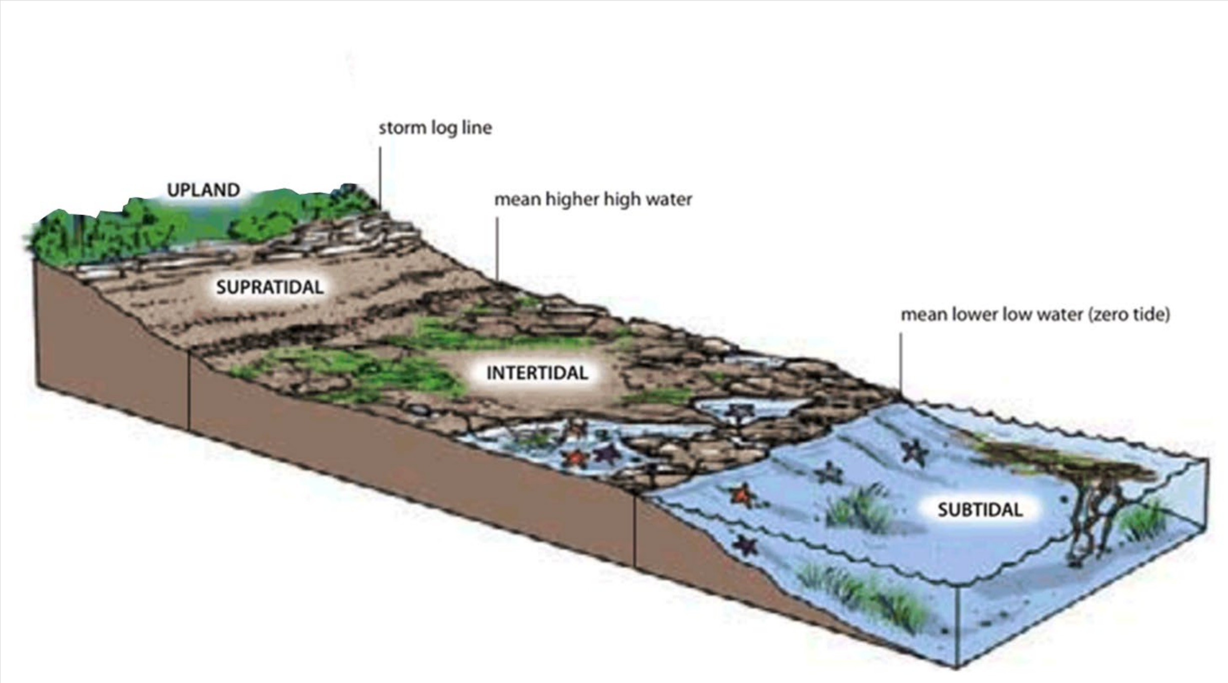
- **NbS** uses sustainable planning, environmental management, and engineering design to incorporate natural features into the built environment to promote adaptation and resilience (FEMA 2023). It can help the region adapt to, address and mitigate the following issues while providing other benefits, as shown in Tables B-2 and Table B-3:
  - Flood protection
  - Erosion
  - Runoff management
  - Wave buffering
  - Water quality
  - Carbon storage
  - Wildlife habitat
  - Groundwater recharge
  - Potential recreational value and aesthetic appeal
- **CEP** involves the development of artificial structures that protect against flooding and erosion, such as concrete walls, drainage infrastructure improvements, or rock walls. These structures are typically complex in design, permitting requirements, and environmental impacts during and after construction. These structures may also be more costly to build and maintain compared to NbS.

To support project implementation, each guide includes a representative image in addition to the following information for each project type:

- Summary (of project type)
- Protection Measures
- Additional Benefits
- Suitable Environment
- Benefits/Limitations
- Construction Considerations
- Monitoring
- Maintenance and Operations
- Costs
- Materials
- Implementation Examples
- Miscellaneous Notes

Resilient infrastructure project types fall into three location zones: upland, intertidal, or subtidal, as illustrated in Figure B-1. Upland describes areas that are never under water, given normal conditions. The intertidal area describes the region that may or may not be underwater depending on the tide. Subtidal describes areas that are always under water.

Figure B-1. Location Zones



Modified from: Frequently Asked Questions: The Atlantic Razor Clam. Connie Lu, Pangea Shellfish Company. July 25, 2019. Accessed from https://www.pangeashellfish.com/blog/frequently-asked-questions-the-atlantic-razor-clam on March 15, 2023.

Table B-1 lists the project implementation zones. Each column represents one of the three coastal regions and potential adaptation projects.

Table B-1. Project Implementation Zones and Potential Adaptation Projects

Upland Zone	Intertidal Zone	Subtidal Zone
Vegetated Dunes	Groins	Living Breakwaters/Oyster Reefs
Beach Nourishment	Wetland Terrace	Eelgrasses/Coastal Wetlands
Flood Walls	Floodable or Elevated Parks	
Seawalls		
Elevate Infrastructure		
Levees		
Trees and Vegetation		

Table B-2 summarizes each project's likelihood to reduce hazards by type, and Table B-3 identifies additional social and environmental benefits for a project solution. Tables B-2 and B-3 are modified from the Center for Neighborhood Technology and American Rivers' *The Value of Green Infrastructure: A Guide to Recognizing its Economic, Environmental, and Social Benefits* (2010) and from the National Oceanic and Atmospheric Administration's (NOAA) *Nature-Based Solutions Practices and Benefits* (2020).

Table B-2. Protection Measures

Type	Project Type	Stormwater Management	Coastal Buffering	Wave Attenuation	Sediment Transport	Erosion Control	Storm Surge	Sea Level Rise	Slope Stabilization	Riverine Flooding
Nature-based Solution	Living Breakwaters		X	X		X	X	X		
	Eel Grasses		X	X	X					
	Coastal Wetlands	X	X	X	X	X	X	X		X
	Wetland Terraces	X	X	X	X	X	X	X		X
	Beach Nourishment		X	X	X	X	X			
	Vegetated Dunes	X	X	X	X	X	X	X	X	
	Urban Trees	X				X				X
Civil Engineering Project	Groins		X		X	X				
	Floodable or Elevated Parks	X	X				X	X		X
	Drainage Infrastructure Improvements	X	X	X						
	Flood Walls		X			X	X	X		
	Seawalls		X			X	X	X		X
	Elevate Infrastructure						X	X		X
	Levees		X	X			X	X		X

Note: Shaded cells with an “X” indicate which hazards are reduced by a given project type.

Table B-3. Additional Social and Environmental Benefits

Type	Project Type	Carbon Storage	Water Quality	Aesthetics	Recreation/ Active Transportation	Habitat
Nature-based Solution	Living Breakwaters	X	X		X	X
	Eelgrasses	X	X		X	X
	Coastal Wetlands	X	X	X	X	X
	Wetland Terraces	X	X	X	X	X
	Beach Nourishment			X	X	X
	Vegetated Dunes	X		X		X
	Urban Trees	X		X	X	X
Civil Engineering Project	Groins				X	
	Floodable or Elevated Parks			X	X	X
	Drainage Infrastructure Improvements					
	Flood Walls					
	Seawalls					
	Elevate Infrastructure					
	Levees				X	

Note: Shaded cells with an “X” indicate which additional benefits are achieved by a given project type.

Project Guides

Living Breakwaters (General)	
Summary	A breakwater is a structure that acts as a buffer between open water and the shoreline. Living breakwaters incorporate natural habitat components to provide opportunities for settlement by shellfish, creating complex structures that provide habitat for various marine and aquatic species. Oyster reefs are one form of a living breakwater.
Protection Measures	Coastal Buffering, Wave Attenuation, Erosion Control, Storm Surge, SLR
Additional Benefits	Carbon Storage (by oysters), Water Quality, Recreation (boating, swimming, wildlife viewing), Habitat
Suitable Environment	Living breakwaters can be built offshore, in the subtidal zone, or in the intertidal zone. Living breakwaters should be sited in shallow waters and away from navigational channels.
Benefits	• Often effective at managing erosion and deposition (sediment accumulation) along the shore they parallel. • May accrete sediment on the landward side. • Acts as a habitat for a wide variety of marine life. • Can calm water on the landward side of breakwater, creating opportunities for plant life, wildlife, and recreational opportunities (boating, swimming, etc.).
Limitations	• May interrupt sediment migration and alter nearshore ecosystems downdrift of the breakwater. • Can pose a danger to navigation if they are submerged.
Construction Considerations	• Design breakwater size and position according to local currents and anticipated wave action and wave design height. • If the breakwater will be planted, grass species should be specific for the region.
Monitoring	• Monitor for marine and aquatic species habitat development. • Monitor for impacts from boats.
Maintenance and Operations	• Mostly self-sustaining with occasional maintenance for the physical structure. • Based on findings from ongoing monitoring, there may be additional maintenance and adaptive management required.
Costs	• Costs vary depending on materials used (from $1,000 per linear feet).
Materials	• Allowable materials are determined by the U.S. Army Corps of Engineers and state/local entities • Pre-cast concrete (reef balls), stone, geotextile, harvested oyster shells (known as clutch)
Implementation Examples	• Narrowneck Beach Geotextile Artificial Reef, Queensland, Australia (subtidal, submerged) • Pensacola Bay Living Shoreline Project, FL (subtidal) • See Oyster Reef for additional examples

Living Breakwaters (General)	
Miscellaneous Notes	• Form of a living breakwater can vary. • Generally parallel to the shore they are protecting, but they can be angled to promote a desired sediment accretion, as in a headland breakwater. • Living breakwaters can also be submerged or designed to be visible above the mean high-water line. • Higher breakwaters have an added benefit of offering habitat to shorebirds and seals and offer increased protection in the face of SLR.

Breakwater Comprised of Rocks and Oyster Shells Example

Source: NOAA 2019 (https://www.fisheries.noaa.gov/feature-story/three-living-shorelines-creating-habitat-protecting-gulf-coast)

Oyster Reefs	
Summary	Oyster reefs are a type of living breakwater. They are a natural formation that help protect the shoreline against strong waves and other storm events, while creating habitat for shellfish among other marine flora and fauna.
Protection Measures	Coastal Buffering, Wave Attenuation, Erosion Control, Storm Surge, SLR
Additional Benefits	Carbon Storage (by oysters), Water Quality, Recreation (boating, swimming, wildlife viewing), Habitat
Suitable Environment	Shallow slopes, low tides, low energy environments, sites with circulation patterns that promote larval retention and recruitment
Benefits	• Can improve water quality and resiliency of other marine life (if the oyster population is strong, an adult oyster can filter between 20 and 50 gallons of water per day). • Improves diversity of marine life and enhances fishery production. • Offers 50 times more surface area than the ocean floor, offering a refuge for marine life. • Serves as a barrier to storms and tides, preventing erosion and estuary waters (some have been shown to lower wave heights by 40%). • Offers other benefits, such as carbon sequestration and denitrification.
Limitations	• Need to be in areas with water quality that can support oyster life; success is often based on the water quality and growth conditions at the start. • Will not have desired effect until reefs reach a certain size, which could take some time (about 3 years). • Subject to overharvesting and pollution, which can cause reefs to die out.
Construction Considerations	• Needs hard substrate of some sort larvae can attach to. • Oyster reef designs should consider that lower portions of substrates will experience sediment burial. • Oyster substrate should be elevated on materials more easily sourced than bags of oyster clutch.
Monitoring	• Tests and sampling must be performed to make sure oysters are alive and growing; this involves water quality testing and sampling oysters from the reefs. • Illegal oyster harvesting must be monitored and prevented.
Maintenance and Operations	• Need to protect older oysters to promote the development of disease tolerant strains (put a restriction on size). • Some infrequent maintenance is required for the physical structure.
Costs	• Range (including design): $121,500 per acre to $500,000 per acre[1] • Reef balls: $200 to $450 each
Materials	• Eco-concrete, reef balls

[1] Port of San Diego. 2019: Sea Level Rise Vulnerability Assessment & Coastal Resiliency Report. Available at https://pantheonstorage.blob.core.windows.net/environment/FINAL-San-Diego-Unified-Port-District-Sea-Level-Rise-Vulnerability-and-Coastal-Resiliency-Report-AB691.pdf.

Oyster Reefs	
Implementation Examples	• South Bay Native Oyster Living Shoreline Project, Chula Vista, CA[2] • Naval Base Point Loma Smuggler's Cove Reef Restoration, San Diego, CA
Miscellaneous Notes	• Reefs that are restored tend to have better results than those that are constructed. • If breakwater is constructed in areas of high-wave energy, oyster habitat is only suitable on the leeside of the breakwater. • In the Gulf of Mexico, oyster reefs have been shown to reduce energy of high-power waves by as much as 76% to 93%. • Data about the success of other reefs and the conditions that may have caused this are limited; much will be trial and error depending on site-specific conditions. • Native oyster populations are low in Southern California, meaning reef success is aided by including oyster seed to aid reproduction.

Reef Balls Example

Source: 10 New San Diego 2021 (https://www.10news.com/news/local-news/san-diego-news/port-of-san-diego-installing-300-reef-balls-as-pilot-oyster-living-shoreline-begins).

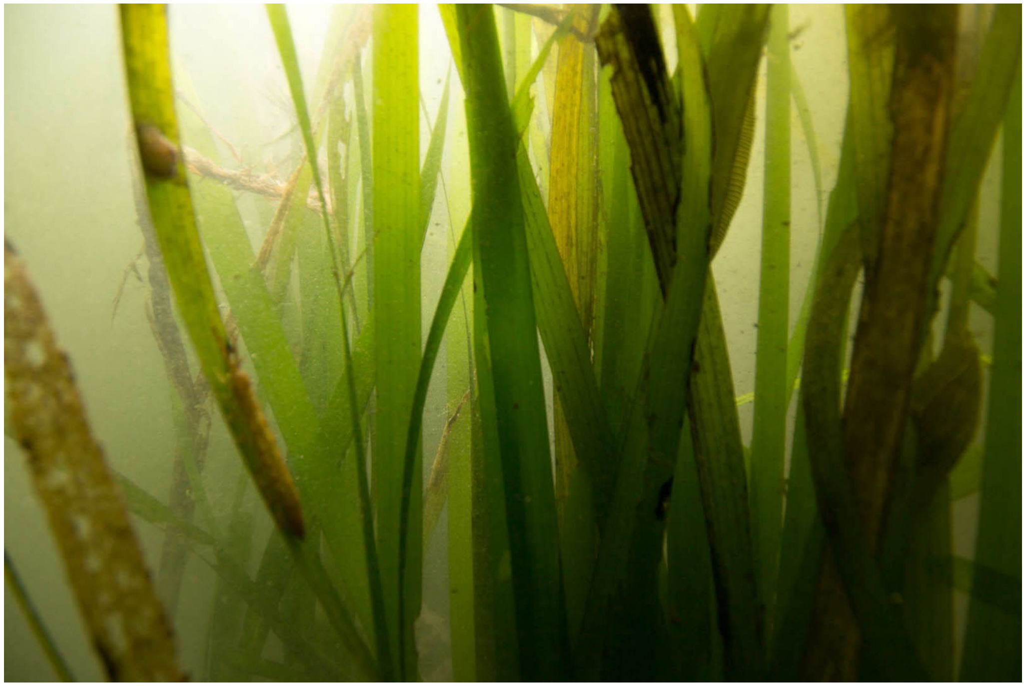
[2] Ibid.

Eelgrasses	
Summary	Eelgrass is a type of temperate marine flowering seagrass that grows on the seafloor, typically in shallow bays and estuaries. Eelgrass beds can provide food sources and habitats for marine life and trap sediment, absorb carbon dioxide, reduce the force of wave energy, and reduce erosion.
Protection Measures	Coastal Buffering, Wave Attenuation, Sediment Transport, Erosion Control
Additional Benefits	Carbon Storage, Water Quality, Recreation (snorkeling), Habitat
Suitable Environment	• Shallow waters (4.6 feet to 39 feet relative to mean lower low water) with adequate light (greater than 10% of surface irradiance), low wave energy, and good water quality. • Sites that are not prone to experience extensive erosion or sediment deposition and where there is little to no boat activity, as anchoring, propeller scarring, and grounding can harm eelgrass beds.
Benefits	• Ecosystem functions can be restored within a few years of establishment. • May provide essential habitat for aquatic species. • Can filter pollution and remove carbon dioxide from water. • Eelgrass meadows store carbon at rates 30 to 50 times greater than terrestrial forests.[3].
Limitations	• Eelgrass is highly vulnerable to climate change; warmer water is a detriment to eelgrass growth. • Drought and high air temperatures can harm eelgrass planted in the intertidal zone. • With SLR, eelgrass beds that do not or cannot migrate toward shallower waters may not survive due to lack of light.
Construction Considerations	• Best practices include experimental transplanting of eelgrass in a pilot plot before a full-scale restoration. • Most commonly used methods include bare root transplant, plug transplant, and seeding. • Seeding is not currently recommended as the primary method, but it can enhance other methods.
Monitoring	• Monitoring of eelgrass beds and surrounding water quality is required to ensure eelgrass health and growth. A common barrier to eelgrass restoration success is macroalgae. • Best practices include evaluating restoration success by comparing it to a reference eelgrass meadow.
Maintenance and Operations	• Eelgrass restoration requires little maintenance once established. However, eelgrass can be easily threatened by surrounding environmental factors like increases in turbidity, sedimentation, and pollution.
Costs	• $16,000 to $45,000 per acre[4]
Materials	• Eelgrass seeds or young plant material
Implementation Examples	• Elkhorn Slough, CA • Orange County Coastkeeper Eelgrass Restoration in Upper Newport Bay, CA • Environmental Assessment for Eelgrass Habitat Expansion, San Diego Bay, CA

[3] Ibid.
[4] Ibid.

Eelgrasses	
Miscellaneous Notes	• Eelgrass is a designated Essential Fish Habitat by the federal government under the 1996 Magnuson-Stevens Fishery Conservation and Management Act. • It is also protected by the California Eelgrass Mitigation Policy and Implementing Guidelines (CEMP), which provides federal agencies consulting with NOAA Fisheries comprehensive and consistent information to ensure no net loss of eelgrass habitat.

Eelgrass Example



Source: California Audubon Society: Eelgrass; accessed on April 18, 2023 (https://ca.audubon.org/conservation/conservation/seas-shores/eelgrass); Image credit: Eric Heupel

Coastal Wetlands	
Summary	Restoring coastal wetlands involves re-establishing salt marsh with extensive regrading and revegetation to allow for self-sustaining hydrology and vegetation. Coastal wetlands can be restored in areas that were previously filled. This type of restoration would require excavation and regrading. They can also be restored in areas that have been washed out, which requires importing sediment. Coastal wetlands are constructed in the intertidal zone.
Protection Measures	Stormwater Management, Coastal Buffering, Wave Attenuation, Sediment Transport, Erosion Control, Storm Surge, SLR, Riverine Flooding
Additional Benefits	Carbon Storage, Water Quality, Aesthetics, Recreation (wildlife viewing, boating), Habitat
Suitable Environment	• Locations with low energy waves in areas that support the natural planted community. • May include riparian banks, marshes, and submerged aquatic vegetation beds.
Benefits	• Fifteen feet of coastal marsh, which can absorb 50% of incoming wave energy.[5] • Can trap sediment allowing it to grow in elevation over time. • Storm floodwater during extreme weather events can limit saltwater intrusion to freshwater systems (aquifers, wetlands). • Can migrate inland in the face of SLR if adjacent to undeveloped land. • May provide habitat to a wide variety of flora and fauna.
Limitations	• Fragmented wetland ecosystems may not provide coastal protections as effectively as continuous healthy expanses of undisturbed natural coastal communities.
Construction Considerations	• Some hybrid protections, like edging (snow fencing, erosion control blankets, geotextile tubes) or sills (stone, sand breakwater, living reef) can help prevent wetland edge loss and may help dissipate wave energy. • The grain size of the sand should match natural marsh sediment.
Monitoring	• Sediment movement and marsh morphology needs to be monitored.
Maintenance and Operations	• Sediment augmentation may be required over time for marsh surfaces and eelgrass beds (costs could be approximately $700,000 per inch/per acre.[6]
Costs	• $16,000 to $45,000 per acre[7]
Materials	• Native plants, clean sediment

[5] NOAA. n.d. Understanding Living Shorelines. Available at https://www.fisheries.noaa.gov/insight/understanding-living-shorelines.
[6] Port of San Diego. 2019: Sea Level Rise Vulnerability Assessment & Coastal Resiliency Report. Available at https://pantheonstorage.blob.core.windows.net/environment/FINAL-San-Diego-Unified-Port-District-Sea-Level-Rise-Vulnerability-and-Coastal-Resiliency-Report-AB691.pdf.
[7] Ibid.

Coastal Wetlands	
Implementation Examples	• Otay River Estuary Restoration Project, CA • Seal Beach Sediment Augmentation, CA • San Dieguito Lagoon Wetland Restoration Project, CA • South San Diego Bay Wetland Restoration, CA
Miscellaneous Notes	• Types include wetland terraces, horizontal levees, eelgrass beds.

Otay River Estuary Restoration Project Example

Source: U.S. Fish and Wildlife Service 2018 (https://www.fws.gov/story/otay-river-estuary-restoration-project)

Wetland Terraces	
Summary	Wetland terraces are a wetland restoration technique used to convert shallow subtidal bottom to marsh, allowing for erosion protection; it is a way of creating terraces at marsh elevations.
Protection Measures	Stormwater Management, Coastal Buffering, Wave Attenuation, Sediment Transport, Erosion Control, Storm Surge, SLR, Riverine Flooding
Additional Benefits	Carbon Storage, Water Quality, Aesthetics, Recreation (wildlife viewing, boating), Habitat
Suitable Environment	• Shallow water and small water bodies are typically better because less material is needed to break the surface of the water. • Important to locate away from the Navy fleet or shipping lanes.
Benefits	• Can provide an opportunity for natural habitat development by other wetland species at varying elevations. • May improve functionality and resiliency of wetlands as SLR and the tidal influence increases.
Limitations	• Generally, requires extensive permitting to add fill. • Time of year (restrictions for rare, threatened, and endangered resources). • Since they are not typically higher than 3 feet, the habitats are still at risk from high-water events.
Construction Considerations	• Several different shapes can be considered based on site-specific needs; segmented terraces are better for aquatic creatures versus one long terrace. • Orient perpendicular to most damaging and predominant winds. • Would likely need a geotechnical survey to characterize soil as substrate specifics determine terrace design. • Shallow/short terraces may disappear quicker than higher terraces. • Often built no more than 3 feet high and are expected to settle to a height that will benefit the marsh. • Can plant marsh grass along the intertidal perimeter and encourage woody growth on the surface to reduce erosion of new terraces.
Monitoring	• Some studies have used remote sensing to assess land use and cover and changes in wetland mapping.
Maintenance and Operations	• Limited maintenance required. May need to add sediment as some settlement and loss of terrace height is expected over time (e.g., initially 0.3 foot within 6 months, then 1 foot every 10 years after)[8].
Costs	• $6,500 per linear feet (Port of San Diego 2019)
Materials	• Substrate/building material to construct the mounds; the amount necessary depends on the depth of the water body.
Implementation Examples	• Chenier Plain, LA

[8] Westphal, Karen. n.d. Guide to Terrace Ridges as an Adaptation to Sea Level Rise: Tools for a Changing Environment. Louisiana Audubon Society. Available at https://la.audubon.org/sites/default/files/static_pages/attachments/tall_terrace_guide_final.pdf.

Wetland Terraces	
Miscellaneous Notes	N/A

Wetland Terrace Example

Source: Port of San Diego, Environment n.d. (https://www.portofsandiego.org/projects/wetland-mitigation-bank-pond-20)

Urban Trees	
Summary	Planting trees in an urban environment involves the planting and care of trees in urban parks, yards, streets, and remnant parcels. Urban trees can provide social and ecological benefits. This project type generally refers to the implementation of a tree planting program.
Protection Measures	Stormwater Management, Erosion Control, Riverine Flooding
Additional Benefits	Carbon Storage, Aesthetics, Recreation/Active Transportation (provide shade), Habitat
Suitable Environment	Areas with sufficient space for soil volumes and root growth.
Benefits	• Can reduce urban heat island, improve aesthetics, reduce pollution, and create habitat for non-human species in a city. • Trees planted in appropriate soil volumes can retain stormwater influxes and provide increased impervious surfaces.
Limitations	• Tree density is needed to derive potential benefits. • Often have limited planting locations in urban areas. • Drought and lack of irrigation makes urban tree success a challenge.
Construction Considerations	• Tree wells must be sized appropriately to support the tree species' full growth. • Tree wells must also be located to not interfere with existing utilities.
Monitoring	• Urban trees must be monitored for health and any safety hazards an unhealthy tree may present (broken branches, etc.).
Maintenance and Operations	• Trees will require pruning, watering, and pest control. • Specific maintenance will depend on tree type and location.
Costs	• Approximately $4,000 per tree (including materials, labor, and 5 years of maintenance) (City of Los Angeles 2022)
Materials	• Trees, soil material, mulch, irrigation system
Implementation Examples	• Tree San Diego and City of San Diego • University of Sothern California Urban Trees Initiative and the City of Los Angeles
Miscellaneous Notes	• A wide diversity of tree species used in an urban tree planting program will be more resilient than a more limited planting palette. • To achieve many of the benefits discussed, the tree planting palette should include large, dense shade trees that can tolerate hotter, drier conditions.
Urban Trees	

Tree Planting Example

Source: Tree San Diego 2021 (https://www.treesandiego.org/annualreports)

Groins	
Summary	Groins, also spelled groynes, are long, narrow structures that protrude into the water from the beach. Groins prevent beach erosion and trap sediment that would otherwise drift along the beach face. Groins are often successful in stabilizing a beach on the updrift side but aggravate erosion on the downdrift side. To avoid this, several groins are often built in a groin-field.
Protection Measures	Coastal Buffering, Sediment Transport, Erosion Control
Additional Benefits	Recreation (due to wider beaches)
Suitable Environment	• Sandy beaches that are prone to erosion or sediment drifting along the beach face. • Places where there is no source of sand (down-drift of large harbor breakwater or jetty). • Places where intruding sand needs to be managed. • Where there is a divergent nodal region in longshore transport.
Benefits	• Groins can prevent beach erosion on updrift side. • Wider beaches that are more stable may be produced if groin is designed correctly. • Certain materials can be used to mitigate the effects of down-drift erosion. • Groins generally, eliminate the need for additional shoreline armoring if designed correctly.
Limitations	• Erosion on the downdrift side is often aggravated, often causes worse erosion for neighboring beaches. • Several groins might have to be installed to mitigate the effects of downdrift erosion. • SLR increases the chance for these structures to be submerged. • Waterfronts are highly regulated and create permitting and other regulatory challenges.
Construction Considerations	• Groins should be constructed with SLR in mind to ensure that they will not be underwater within its lifespan. • An increase in length can increase the negative impact on the shoreline. • The permeability of the material/structure will result in different equilibriums, with more sand allowed to pass through, there will be less of an impact on the shoreline. • A groin field should be constructed in the downdrift to updrift direction.
Monitoring	• Structural integrity may have to be monitored for those built of less resilient materials. • Monitoring may have to be performed to make sure erosion on the downdrift side of the groin is not too great.
Maintenance and Operations	• Unlike jetties or breakwaters, groins do not require annual maintenance or dredging. • The lifespans of some materials are short (less than 5 years), so it will have to be replaced more often than others.
Costs	• Cost is dependent on the material; wood and stone can be inexpensively sourced, but other materials, such as steel or concrete, may be more expensive. • Oceanside groin is $2.8 million per acre for the full lifecycle cost. This includes assumptions of $1.8 million per acre for initial cost and $1 million per acre for renourishment. Estimates from the East Coast range are from $3,000 to $5,000 per linear foot, depending on material.

Groins	
Materials	• Stone groins can be sourced from leftovers of construction projects. Due to spaces between rocks, some sediment may still be able to pass through the groin. These groins are highly capable of absorbing wave energy. • Concrete groins are most common and very resilient; have smooth and neat appearance; can be reinforced with steel; can be very heavy, so site has to be able to support the weight of the concrete. • Wooden groins are smaller and more affordable; some water may pass through; plastic can be used as an alternative, so it does not rot or discolor. • Steel groins are strong, sturdy material that will not allow water to pass; steel vulnerabilities make it non-ideal for lone construction material. • Rubble-mound groins are similar to stone; can be mix of concrete, rock, and other; larger and wider than wood or steel groins; absorbs wave energy efficiently. • Sandbag groins are temporary measures, as they have a much shorter lifespan than other materials
Implementation Examples	• Currently, there are 49 groins in California, and 84% of them are located in the Southern California. Examples include Ventura Pierpont Groins, Las Tunas Groins, Groins of Santa Monica, Surfside Timber Groins, Newport Beach Groins, and Oceanside Groins.
Miscellaneous Notes	• Groins have varying success; therefore, an extensive study of the site should be conducted during design to ensure the correct material is used and is constructed in the correct length. • Often times, groins are thought to be synonymous with jetties. However, they are different, and jetties have significantly more negative impacts. Thus, groins have a negative public perception. • Groin construction will alter the habitat currently in the construction zone, but a new one will be created after the construction is complete.

Groins

Groin Example

Source: National Park Service n.d. (https://www.nps.gov/articles/groins-and-jetties.htm)

Beach Nourishment	
Summary	Beach nourishment compensates for beach erosion by replacing sand that naturally migrates along sandy shorelines. Beach nourishment is most effective in conjunction with other strategies to slow erosion and stabilize sand.
Protection Measures	Coastal Buffering, Wave Attenuation, Sediment Transport, Erosion Control, Storm Surge
Additional Benefits	Aesthetics, Recreation (due to wider beaches), Habitat
Suitable Environment	Sandy beaches with some kind of erosion prevention that provides culturally or economically important coastal access.
Benefits	• Typically effective in conjunction with dunes or other coastal defense solutions. • Long history of beach nourishment in Southern California.
Limitations	• May need to place larger volumes of sand more frequently over time. • Minimally effective at preventing flooding due to larger flood events that overtop the beach. • Does not provide protection from back bay flooding. • SANDAG has already established that beach nourishment alone cannot protect transportation assets.[9] • Public does not have access to the beach during the nourishment process. • Beach ecosystem may be disturbed during construction. • Environmental permitting efforts can be extensive.
Construction Considerations	• The Regional Beach Sand Project found that sand grains coarser than the native sand was more effective at stabilizing beach; also found that beach width was widened for 4 years, reverting back to its previous width in the fifth year. • Using non-native sands, which provide some benefits, may also alter the surrounding ecosystem.
Monitoring	• Monitoring is required to determine how long beach widths can be maintained.
Maintenance and Operations	• Restored beaches require maintenance through periodic renourishment.

[9] SANDAG. 2019. Regional Transportation Infrastructure Sea Level Rise Assessment and Adaptation Guidance. Available at https://resilientca.org/case-studies/sandag-regional-sea-level-rise-adaptation/.

Beach Nourishment	
Costs	• $19 per cubic yard[10] • $300 to $1,000 per linear foot[11] • $600 to 900 per linear foot[12]
Materials	• Sand/sediment source that is clean of contaminants and is proper grain size.
Implementation Examples	• Regional Beach Sand Project I (2001) - 2.1 million cubic yards on 12 San Diego area beaches, 6 offshore borrow sites • Regional Beach Sand Project II (2012) - 1.5 million cubic yards on 8 San Diego area beaches, 3 offshore borrow sites • Surfers' Point Managed Shoreline Retreat Project
Miscellaneous Notes	N/A

Beach Nourishment Example

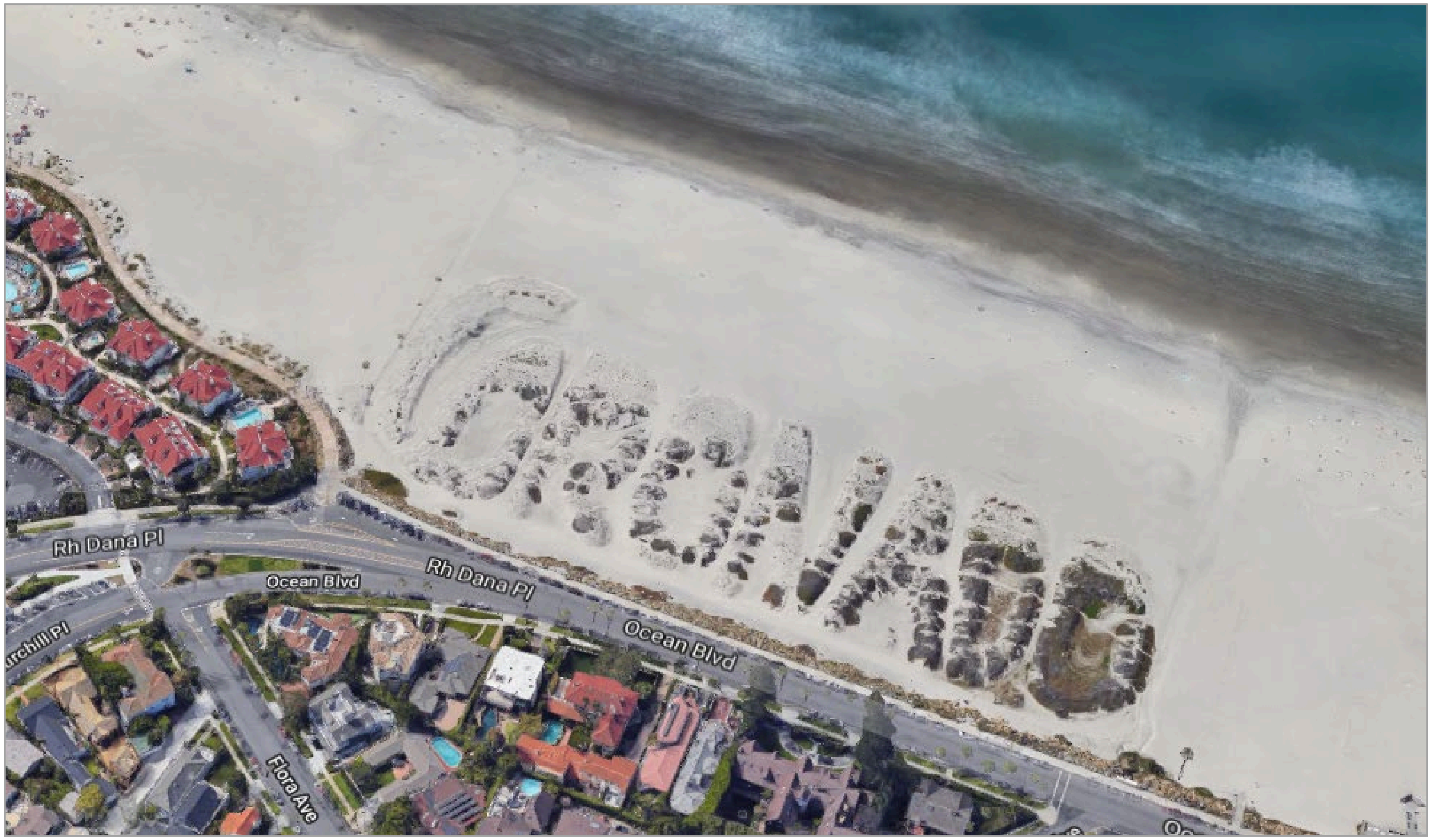
Source: U.S. Army Corps of Engineers 2021 (https://www.spn.usace.army.mil/Missions/Projects-and-Programs/Ocean-Beach-Beach-Nourishment/)

[10] Port of San Diego. 2019: Sea Level Rise Vulnerability Assessment & Coastal Resiliency Report. Available at https://pantheonstorage.blob.core.windows.net/environment/FINAL-San-Diego-Unified-Port-District-Sea-Level-Rise-Vulnerability-and-Coastal-Resiliency-Report-AB691.pdf.
[11] Naval Facilities Engineering Command Headquarters. 2017. Installation Adaptation & Resilience Climate Change Planning Handbook. Available at https://www.fedcenter.gov/Documents/index.cfm?id=31041.
[12] Federal Highway Administration. 2019. Nature-Based Solutions for Coastal Highway Resilience: An Implementation Guide. Available at https://toolkit.climate.gov/reports/nature-based-solutions-coastal-highway-resilience-implementation-guide.

Vegetated Dunes	
Summary	Dunes provide a barrier to waves, currents, and storm surges protecting the coastal environment. They can absorb wave energy and contribute sand to natural sediment migration along a shore. Implementing this strategy may involve rehabilitating existing eroded/biologically impaired dunes or artificially constructing a dune system that has been lost entirely.
Protection Measures	Stormwater Management, Coastal Buffering, Wave Attenuation, Sediment Transport, Erosion Control, Storm Surge, SLR, Slope Stabilization
Additional Benefits	Carbon Storage, Aesthetics, Habitat
Suitable Environment	Wide beaches with natural sources of sand can be used to provide a temporary source of sand to promote dune formation.
Benefits	• Often protects inland assets from storm surge and high winds that can cause erosion. • Can naturally migrate inland in the face of SLR. • Can provide valuable habitat.
Limitations	• Might be limited in their effectiveness if they are not continuous. • Fragile and can be damaged by excessive recreational activities.
Construction Considerations	• Native plants need to be prioritized (invasives can be detrimental to dune environment and geometry). • Sterile straw plugs or other temporary structures can be used to help establish native plants in dunes without vegetation. • Many sites require foredunes as well as dune fields or barrier dunes, which all require different plants/environments due to the stie conditions. • Construction needs to stabilize sand in the short term while plants are established.
Monitoring	• Monitoring should be performed for both the physical and ecological evolution of the dune. • Vegetation extents need to be monitored throughout the year and after major weather events. • Surveys of physical properties should be conducted in the winter season and after large weather events.
Maintenance and Operations	• Maintenance of dune height is recurring if a natural source of sand accretion is not in place, such as a wide beach and/or updrift sand sources. • Some weeding of dunes is recommended to limit the impact of invasive species.
Costs	• Costs will include sand nourishment (if needed), geotextiles/rocks, plant species, and labor to build the dunes.
Materials	• Geotextile tubes, rock, and stacked trees (Christmas trees) can be used to reinforce a dune base
Implementation Examples	• Cardiff State Beach Living Shoreline Project, Surfers' Point Managed Shoreline Retreat Project • Humboldt Coastal Dune Vulnerability and Adaptation Climate Ready Project (dune rehabilitation and migration)

Vegetated Dunes	
Miscellaneous Notes	N/A

Vegetated Dune Example



Source: Google Maps; retrieved on March 31, 2023 (https://www.google.com/maps/@32.6826312,-117.1855394,1527m/data=!3m1!1e3)

Floodable or Elevated Parks	
Summary	Floodable parks use land that is frequently flooded to accommodate SLR by creating recreational spaces that are intended to be inundated. Elevated parks create recreational space that is built up from sea level. Both of these alternative park options create a piece of land that can be inundated, protecting other infrastructure inland.
Protection Measures	Stormwater Management, Coastal Buffering, Storm Surge, SLR, Riverine Flooding
Additional Benefits	Aesthetics, Recreation, Habitat
Suitable Environment	Places with large areas along the coast near sensitive infrastructure that are susceptible to SLR.
Benefits	• Combines NbS and CEP to manage the effects of SLR on a community. • Typically creates space that can safely accommodate incoming sea water during storm surge and flood events. • Native plant species that are flood resistant can be incorporated into the park, so that the ecology helps the park adapt to the inundation. • Incorporation of green infrastructure is common in these projects.
Limitations	• The public may not have access immediately before and after major flood events. • Requires a significant amount of land/may require land acquisition. • Changes in hydrology may negatively affect the park.
Construction Considerations	• Detention ponds, retention ponds, or tide pools should be able to be incorporated into the design. • Elevated parks are typically constructed with a seawall at the edge of water. • If incorporating playgrounds, design so that they rely less on standard equipment and more on landforms or materials that are easy to maintain.
Monitoring	• Monitoring may have to take place after large storm events to determine when the park can be safely accessible to the public again.
Maintenance and Operations	• After storm events, maintenance should be performed to ensure that no safety hazards presented themselves during the event. • Resources, such as trash cans and restrooms, should be provided and cleaned on a regular basis.
Costs	• Cost of land acquisition, landscaping, and materials is to be incorporated into the park.
Materials	• Native plant species, resilient materials
Implementation Examples	• Mission Rock, San Francisco, CA

Floodable or Elevated Parks	
Miscellaneous Notes	• Typically, the design infrastructure is "against nature," but floodable parks are designed to "work with nature" to protect infrastructure. • It is important to know and understand flooding patterns in and around the park area when designing and constructing the park.

Floodable Park Example (Before and After)

Source: Grist 2016 (https://grist.org/cities/denmark-preps-for-climate-change-by-building-parks-that-can-transform-into-ponds/)

Flood Walls	
Summary	Flood walls act as barriers that protect surrounding homes, businesses, and infrastructure, from being damaged by flooding. Flood walls specifically protect against severe weather events. Additionally, flood walls can also act as a permanent or deployable barrier that protects infrastructure against extreme weather events by preventing water from entering undesired locations.
Protection Measures	Coastal Buffering, Erosion Control, Storm Surge, SLR
Additional Benefits	N/A
Suitable Environment	Flood walls are particularly popular in urban areas or condensed areas since they may require little space.
Benefits	• Provides protection against extreme weather events and SLR. • Can be incorporated into the features of the location. • Design is flexible and can be permanent or deployable. • Protected structures can still operate during construction. • Protect businesses and homes from damage, generally allowing them to remain unharmed during large weather events or in the case of extreme SLR. • More resistant to erosion than levees.
Limitations	• Could impede pedestrian pathways. • If they need to be increased in size, the whole structure must undergo maintenance. • May have negative impacts on the ecosystem — may limit connectivity and cut off wildlife corridors. • More expensive to construct than levees and requires deeper excavation. • If placed on beaches like seawalls, they can disrupt the erosion and natural replenishment of sand, causing the beaches to narrow and eventually vanish.
Construction Considerations	• SLR scenarios should be considered so that the walls are not flooded within their life expectancy. • Resilient materials should be chosen to resist corrosion due to contact with sea water, wave energy, and floods. • Flood walls can be built up to 20 feet high, but they are typically around 4 feet high, especially if they are constructed for residential purposes.
Monitoring	• Yearly monitoring should be conducted for permanent walls to make sure they are still structurally sound and that no animals have created a burrow within the wall(s). • Walls should also be checked for cracks and signs of tunneling.
Maintenance and Operations	• Deployable/mountable walls have high operational and maintenance requirements; will need to be constructed and taken down before and after major flood events. • Twice a year, the fasteners and anchors should be inspected for fouling/other damage and screws missing. • Once a year, the barrier should be inspected for damage, and the condition of the gasketing and status of any structural damage should be noted and repaired.

Flood Walls	
Costs	• For a 5-foot wall, the approximate cost is $400 to $600 per linear foot.
Materials	• Typically reinforced concrete, but could also be bricks, plastic, wood, or cement blocks
Implementation Examples	• St. Helena, CA floodplain of Napa River
Miscellaneous Notes	• Implementation along the shoreline is highly controversial. Flood walls are often built to preserve private property at the expense of public areas. • Installation of walls may require the movement or destruction of other infrastructure in the area.

Removable Floodwalls Example

Source: Global Times 2019 (https://www.globaltimes.cn/content/1161479.shtml)

Seawalls	
Summary	The primary function of seawalls is to prevent erosion of the shoreline and to stabilize the soil. They can also act as flood barriers that protect homes, businesses, and infrastructure from large bodies of water, such as the ocean or a gulf, and from being damaged during severe weather events.
Protection Measures	Coastal Buffering, Erosion Control, Storm Surge, SLR
Additional Benefits	N/A
Suitable Environment	Seawalls are typically built along shorelines in locations that are prone to erosion or near urban areas with vulnerable infrastructure or homes.
Benefits	• Provides protection against coastal flooding and erosion. • Typically prevents erosion (if well-designed). • Often requires much less space than other coastal defense mechanisms. • Possible to increase the height of seawalls as SLR increases. • Aims to protect businesses and homes from damage, generally allowing them to remain unharmed during large weather events or in the case of extreme SLR.
Limitations	• Can be expensive to build. • Scour at the foot of the seawall may become a prominent issue. • Seawalls are immovable defenses, may restrict natural processes, such as habitat migration, and can cause coastal squeeze, which results in the reduction of area of intertidal habitats, such as beaches and salt marshes. • Overtopping can occur; if excessive, the overtopping will remove soil from behind the wall, weakening the foundation. • Seawalls can reduce beach access to the public.
Construction Considerations	• Resilient materials should be chosen to resist corrosion due to contact with sea water, wave energy, and floods. • The shape is important; smooth surfaces will reflect wave energy and irregular surfaces will scatter the direction of wave reflection. • Seawalls will constantly be under severe wave stress.
Monitoring	• Monitoring can be performed by qualified engineers or with remote sensors and wireless tracking. • Seawalls should be inspected every 5 to 6 years.
Maintenance and Operations	• Marine structural engineers should check seawalls for damage every 5 to 6 years and during real estate transactions. • Checks should be conducted for cracks, stabilization, stability of anchors, leaning, joint separation, and berm failure, as well as other structural features.
Costs	• Costs depend on material, location, height, etc.
Materials	• Often include steel walls, monolithic concrete barriers, rubble mound structures, brock or block walls or gabions

Seawalls	
Implementation Examples	• Solana Beach, La Jolla, Del Mar
Miscellaneous Notes	• Over 10% of California's coastline is protected by seawalls. • Technology for "Living Seawalls," which use textured materials designed to promote biodiversity, is evolving and has been piloted by the Port of San Francisco.

Rock Seawall Example

Source: San Diego Union Tribune 2022 (https://www.sandiegouniontribune.com/communities/north-county/oceanside/story/2022-05-09/surfrider-appeals-oceansides-approval-of-beachfront-revetment)

Drainage Infrastructure Improvements	
Summary	Existing stormwater infrastructure can fail and cause localized flooding during normal rain events due to insufficient sizing or material failure. Coastal storm surge and SLR can cause interior flooding by driving backflow through unprotected outfalls. Localized storm drain improvements can address these issues at high-risk locations while more comprehensive and long-term solutions are planned. Localized drainage infrastructure components include floating wave attenuation, flap gates/tide gates, mobile pumping stations, and upsizing subsurface drainage lines and structures.
Protection Measures	Stormwater Management, Wave Attenuation, Coastal Buffering, Storm Surge, Riverine Flooding
Additional Benefits	N/A
Suitable Environment	Drainage improvements should be planned for unprotected coastal outfalls and interior locations prone to regular flooding after a rain event or storm surge.
Benefits	• Smaller scale investments in drainage infrastructure improvements can increase capacity through system. • Drainage improvements can prioritize localized areas to address different issues. • Flap gates or tide gates protect against tidal flooding but also allow fish in and out of coastal defenses. • High-volume portable flood control pumps provide temporary or seasonal protection for spot flooding and remove localized floodwaters post-storm. • Temporary pumps can also protect permanent pumping stations that need to be raised or rebuilt on higher ground.
Limitations	• Comprehensive solutions will ultimately last longer and provide greater protection. • Flap gates do not pass floating debris very well and require periodic clearing of debris behind gates. • Fully integrated stormwater pumping stations are more efficient and economical for long-term solutions. • Stormwater management requires extensive interagency/municipal coordination which can lead to regulatory challenges.
Construction Considerations	• Improvements/replacements in drainage lines should occur from structure to structure rather than partial replacements or patches. • For siting, identify vulnerable roadways where culverts/other structures have become pinch points during storm events, causing localized flooding.
Monitoring	• All drainage infrastructure requires monitoring, especially during and after storm events, to ensure it is working as intended.
Maintenance and Operations	• Flap gates are designed to automatically close when the water on the front side of the flap is of greater depth than that on the back side. The hinged flap can cause timber, logs, or trash to catch between the flap and the seat at low flow. For gates to operate properly, accumulated trash must be periodically removed. Upgraded drainage infrastructure should also be regularly inspected for debris removal and structural integrity.

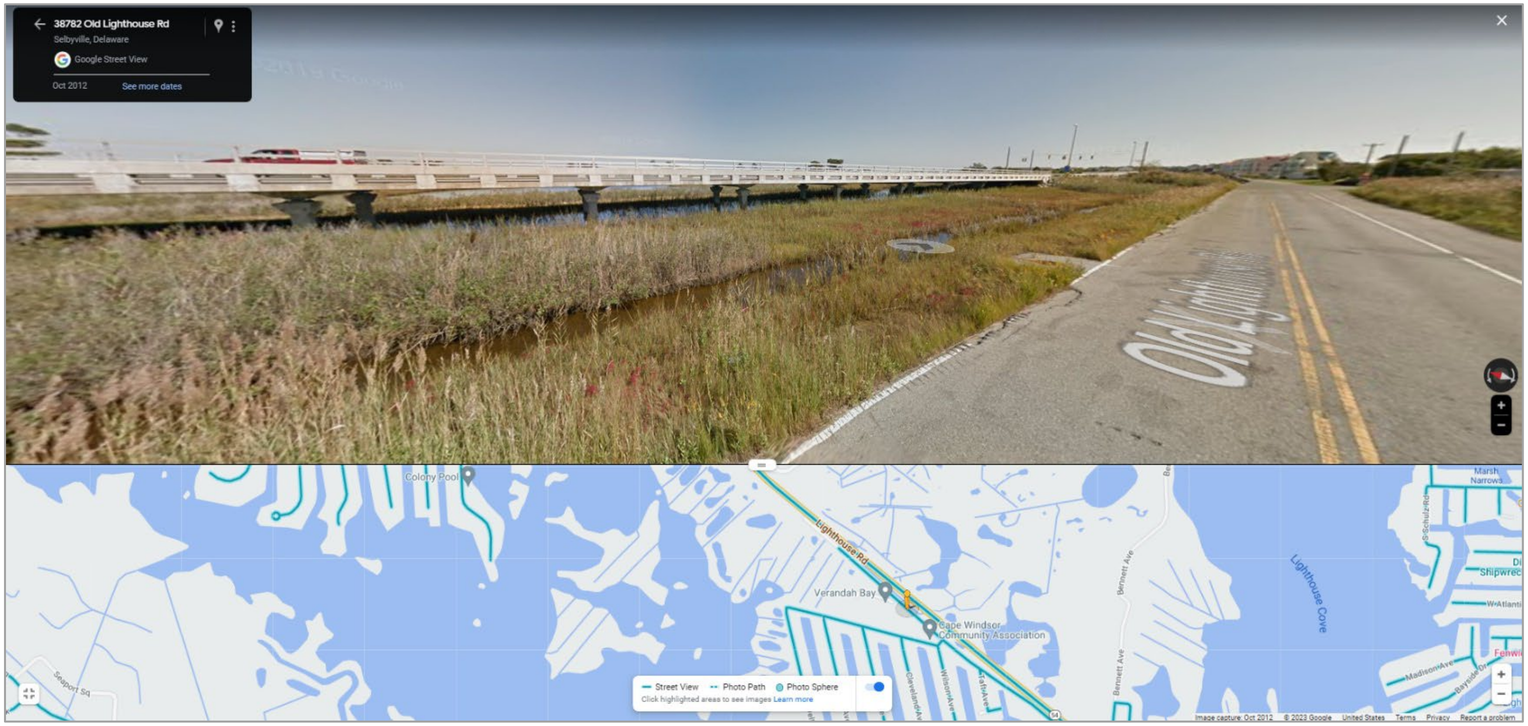
Drainage Infrastructure Improvements	
Costs	• Flap Gates: Cost depends on material (steel, aluminum, timber) and size of gate. Construction cost for installation of one 5 foot by 4 foot-steel-flap gate from a 2021 coastal protection project in New Jersey was $15,000. • Temporary pumps: Cost depends on size/capacity. Typical cost for high-volume portable pumps can be anywhere from $5,000 to $15,000 per pump. • Costs for upsizing subsurface drainage lines and structures depends on size, location, and material.
Materials	• Varies; can include steel, aluminum, timber, and concrete
Implementation Examples	• Drainage improvements are regularly installed/used around California and throughout the country.
Miscellaneous Notes	N/A

Drainage Improvement Project Example

Source: A. Morton Thomas and Associates, Inc. n.d. (https://amtengineering.com/services/environmental-water-resources/drainage-improvement-plans/)

Elevate Infrastructure	
Summary	Elevating infrastructure involves constructing roads or other infrastructure to be above the water level of significant storm or flood events.
Protection Measures	Storm Surge, SLR, Riverine Flooding
Additional Benefits	N/A
Suitable Environment	Roads that are prone to flooding, are key evacuation routes, or that are critical to city infrastructure.
Benefits	• Maintenance is similar to current maintenance costs. • A phased implementation approach is feasible. • Elevated roads can serve multimodal traffic.
Limitations	• Final product has a fixed elevation. • Can reduce access to coastal amenities. • May require vertical realignment of intersections with local access roads. • Typically, requires erosion protection along coastal side embankment. • Water runoff could more adversely impact adjacent low-lying communities, so might require more extensive water retention strategies.
Construction Considerations	• SLR projections should be considered so that the roads are not flooded in routine storms. • Appropriate hydraulic analysis should be conducted to ensure the proper erosion protection is used and installed.
Monitoring	• In addition to the monitoring required for a typical roadway, the embankments (if applicable), erosion protection, and supports that were used in the creation of the elevated road will have to be monitored.
Maintenance and Operations	• The maintenance will be similar to that of a regular road.
Costs	• An urban area, two-lane road, is typically $3 to $5 million per mile. • A four-lane highway will cost $4 to $10 million depending on the location. • These costs are for typical roads, although elevated roads can be assumed to be on the higher end of the approximate price range.
Materials	• Road materials and fill
Implementation Examples	• Lighthouse Road, Selbyville, Delaware
Miscellaneous Notes	N/A

Lighthouse Road Elevated Infrastructure Example



Source: Google Maps; retrieved on April 18, 2023 (https://www.google.com/maps/@38.4567436,-75.0725394,3a,75y,73.04h,79.01t/data=!3m10!1e1!3m8!1s7cEuIhmVuTY-mXp1JZpjAA!2e0!6shttps:%2F%2Fstreetviewpixels-pa.googleapis.com%2Fv1%2Fthumbnail%3Fpanoid%3D7cEuIhmVuTY-mXp1JZpjAA%26cb_client%3Dmaps_sv.tactile.gps%26w%3D203%26h%3D100%26yaw%3D122.90077%26pitch%3D0%26thumbfov%3D100!7i13312!8i6656!9m2!1b1!2i36https://www.google.com/maps/@38.4567436,-75.0725394,3a,75y,73.04h,79.01t/data=!3m10!1e1!3m8!1s7cEuIhmVuTY-mXp1JZpjAA!2e0!6shttps://streetviewpixels-pa.googleapis.com/v1/thumbnail%3Fpanoid=7cEuIhmVuTY-mXp1JZpjAA&cb_client=maps_sv.tactile.gps&w=203&h=100&yaw=122.90077&pitch=0&thumbfov=100!7i13312!8i6656!9m2!1b1!2i36)

Levees	
Summary	Levees are human-made ridges or earthen embankments that run parallel to rivers to prevent flooding or along shorelines to prevent damage from crashing waves.
Protection Measures	Coastal Buffering, Wave Attenuation, Storm Surge, SLR, Riverine Flooding
Additional Benefits	Recreation (bike paths)
Suitable Environment	Levees should be constructed in areas that are vulnerable to floods and/or damage from crashing waves.
Benefits	• Bike paths and roads can be placed on top of levees. • Green infrastructure can be incorporated by designing earthen levees.
Limitations	• Typically requires additional infrastructure, such as a pump station and a force main. • Generally has high maintenance costs. • Must address groundwater for pavement protection. • Significant stakeholder coordination necessary for placement. • Potential for failure (one weak spot in construction can lead to levee failure).
Construction Considerations	• SLR projections should be considered so that the walls are not flooded in routine storms. • Resilient materials should be chosen to resist erosion due to contact with sea water, wave energy, and floods. • Native species may be introduced to help stabilize the soil. • Appropriate hydraulic analysis should be conducted to ensure the proper erosion protection is used and installed.
Monitoring	• Analysis to determine where levee vulnerabilities are recommended. • Comprehensive evaluations along with routine visual monitoring and routine instrumentation monitoring. • Additional monitoring during flood events. • Must patrol the levee when water levels are high.
Maintenance and Operations	• Erosion protection repairs (rock and riprap) • Vegetation management and soil compaction • Rodent and pest control • Pump station and flap gate operations and repairs • Environmental and federal permitting, reporting, and compliance
Costs	• Depends on the size and location of the levee, typically millions of dollars
Materials	• Often include soil and/or rocks on a cleared and level surface • In places that have strong flow, can be made of wood, plastic, or metal • In places of particular danger, reinforced concrete may be used
Implementation Examples	• Sacramento-San Joaquin Delta Levees • San Diego River 3 Levee System

Levees	
Miscellaneous Notes	N/A

Sacramento River Delta Levee and Islands Example

Source: U.S. Bureau of Reclamation; provided by The Nature Conservancy (https://casalmon.org/restore-floodplains-and-estuaries/)