Shoreline Resilience Framework for San Francisco Bay

Wildlife Support

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Photo by Shira Bezalel, SFEI

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Version 1

Table of Contents

Glossary

Baylands: The area between the maximum and minimum extent of the tides, including areas that would be subject to tidal influence if not for unnatural obstructions. This includes the present mudflats and marshes and historical baylands (former marshes and mudflats that have been diked and drained).

Ecological adaptation: The process by which a species becomes better suited to its environment, as a result of natural selection.

Ecosystem functions: Biotic and abiotic processes within an ecosystem.

Ecosystem services: Benefits provided by ecosystems to people.

Landscape resilience: The ability of a landscape to sustain desired processes and functions over time and under changing conditions, despite disturbances and stressors.

Resilience: The ability of a system to maintain function after being perturbed by a disturbance: either a long-term trend (e.g., rising sea levels) or a specific event (e.g., storm).

San Francisco Bay: Suisun Bay, San Pablo Bay, Central Bay, South Bay, Lower South Bay

SAV: Submerged aquatic vegetation

Sea-level rise adaptation: The actions taken by a community to reduce vulnerability to sea-level rise impacts. A continuum from gray (levees, seawalls, pumps) to green (marshes, beaches, etc.).

SFEI: San Francisco Estuary Institute (sfei.org/)

Shoreline: Broadly used to encompass all elements of the “shore,” including natural features like marshes, beaches, and mudflats, as well as the “shoreline”, or the “line of defense” from coastal flooding.

Wildlife: Non-domesticated living things, principally plants and animals for this report.

WRMP: Wetlands Regional Monitoring Program (sfestuary.org/wrmp/)

Introduction

Many adaptation planning efforts in the San Francisco Bay Area have a stated goal to increase the resilience of the shoreline to sea-level rise. Given the long history of protecting and restoring the natural shoreline of the Bay and because of the many benefits they offer, “nature-based solutions,” like coastal wetlands and beaches, are championed in many planning efforts, such as Bay Adapt (bayadapt.org/), and seen as the preferred method of increasing resilience. However, the resilience of the shoreline has not been clearly defined. In developing this framework, we ask: How can shoreline resilience be measured? How can it be increased?

A previous effort of the San Francisco Estuary Institute (SFEI) and the Google Ecology Program created the Landscape Resilience Framework (Beller et al. 2015, 2019), which helps translate science into a set of practical considerations for landscape management focused on “maintaining the ability of a landscape to sustain desired ecological functions, robust native biodiversity, and critical landscape processes over time, under changing conditions, and despite multiple stressors and uncertainties.” The goal of the Landscape Resilience Framework is to facilitate the integration of resilience science into a wide variety of efforts, from urban design and green infrastructure to conservation planning and ecological restoration. Principles of resilience, such as process, connectivity, and redundancy, are listed and explained in practical terms. The framework considered all parts of the landscape, from the Bay to the hills.

This present work uses the Landscape Resilience Framework to consider how to manage the natural elements of the shoreline, like marshes and beaches, to sustain desired ecosystem functions. These functions may include protecting the shoreline from erosion, supporting threatened and endangered species, and maintaining critical landscape processes like marsh migration with sea-level rise. Examples of key questions that could be informed using the framework are: how resilient are marshes to sea-level rise now, and how could they be made more resilient?

When shoreline planners and managers envision a shoreline that is more resilient to sea-level rise, what specifically are they hoping will be more resilient? Likely, the ecosystem services that a well-functioning shoreline can provide are services like flood risk reduction, nutrient processing, carbon sequestration, water quality improvement, wildlife support, and recreation and well-being. These services are valuable to human communities, so planners are interested in ensuring their persistence.

The goal of this document is to apply the Landscape Resilience Framework to the San Francisco Bay shoreline and outline the factors that are important in determining the resilience of ecosystem services from natural shoreline features. This document is focused specifically on the resilience of San Francisco Bay marshes to sustain the ecosystem service of native wildlife support.

Here we align conceptual models that describe baylands ecosystem functions with shoreline resilience principles. Physical drivers of change and marsh processes are already well documented in shoreline ecosystems, but applying principles of connectivity, diversity/complexity, redundancy, and scale can offer new insights into the persistence of marsh functions and services. This Shoreline Resilience Framework points to elements of shoreline resilience that can be quantified and mapped and then evaluated across space and time. In this document, elements of shoreline resilience related to one ecosystem service (wildlife support) are listed for each Landscape Resilience principle. These shoreline resilience elements can be developed into quantitative metrics to measure the effectiveness of adaptation actions that have been implemented. More generally, measuring the resilience of ecosystem services to sea-level rise can inform discussions about: (1) tradeoffs between services (both their value and cost of maintenance); (2) the types of adaptation that might be necessary to maintain these services; and (3) where investment will be most effective in supporting these ecosystem services into the future.

The key audience for this framework and the subsequent mapping efforts is planners who are making decisions about shoreline adaptation actions and looking for more information to prioritize and implement those actions most efficiently and effectively. **This document serves as a "first iteration" of the shoreline resilience framework and is by no means a comprehensive framework meant to cover every element of shoreline resilience. It is targeted specifically toward decision-making about physical adaptation interventions like those described in the Adaptation Atlas (SFEI and SPUR, 2019)**: for example, marsh restoration, sediment placement, eelgrass planting, migration space preparation, creek-to-baylands reconnection. Therefore, the framework in its current iteration is focused heavily on geomorphology and physical characteristics and processes. It may later be expanded to cover a wider range of ecosystem services and a broader set of relevant factors, including ecological and sociological elements. Table 1 describes what is and is not included in this iteration of the Shoreline Resilience Framework.

Table 1. Topics covered by and excluded from this iteration of the Shoreline Resilience Framework.

	This iteration	**Future expansions**
Resilience "of what"	San Francisco Bay tidal marshes to sustain the ecosystem service of wildlife support	Other habitats (rocky shore, beaches, headlands, hardened shorelines) and other ecosystem services (flood protection, carbon sequestration, water quality, recreation)
Resilience "to what"	Sea-level rise and combined flooding from creeks	Other climate change impacts (e.g. drought, rising temperatures, heat waves, or

		altered salinity)
Elements included	Landscape characteristics and processes (e.g. elevation) that can be adjusted with a physical intervention (e.g. sediment placement)	Biological characteristics and processes (e.g. invasive species) that could be adjusted with a management intervention (e.g. chemical treatment)
Geography covered	San Francisco Bay (including San Pablo Bay and Suisun Bay)	San Francisco Estuary (including the Sacramento-San Joaquin Delta) or beyond
Scale of analysis	OLUs and individual marshes	Habitat patches

This Framework was developed with input from the Wetlands Regional Monitoring Program (WRMP) Technical Advisory Committee (TAC), a regional group of wetland scientists. Input from the TAC was obtained during an online workshop and subsequent review of a draft. Comments and edits by the TAC have been incorporated into the present document.

Wildlife support

The wildlife support ecosystem service was chosen for the first iteration of the Shoreline Resilience Framework because of the long history of marsh habitat management and restoration in the Bay, resulting in a large body of existing work on the topic to draw from (e.g. Baylands Goals, WRMP) that can help illustrate how the framework can be applied. In future efforts, other ecosystem services will be viewed through the same lens to identify other metrics of importance.

We define wildlife according to the definition in the Landscape Resilience Framework (Beller et al. 2015):

> Plants and animals are of particular concern because they are often better studied and garner more management attention than other species; however, we include other taxa to the degree they support these species. Our emphasis is primarily on native species that are adapted to local ecological conditions, though non-native species are valued to the degree that they support native species or desired ecological functions, or when replacement by analogous native species is infeasible or undesirable. In addition to currently present species, it also includes extirpated species that might be recoverable, as well as species whose ranges may shift to include a given area in the future.

We define wildlife support according to the definition in Resilient Silicon Valley (Robinson et al. 2015). Key ecological functions related to baylands wildlife include:

- providing habitat and resources for a full suite of shoreline-dependent wildlife, including rare and endemic marsh species such as Ridgway's rail and salt marsh harvest mouse;
- nursery and foraging habitat for estuarine and anadromous fish;
- overwintering, migratory stopover, and breeding habitat for waterbirds; and,
- primary productivity.

Fostering the resilience of native baylands wildlife means bolstering the ability of wildlife populations and communities to adapt and persist under changing conditions. This includes maintaining the necessary habitat to sustain wildlife over time. For example, this could include supporting higher accretion rates to ensure marsh elevations keep pace with sea-level rise and ensuring topographic complexity to maintain areas of high marsh. Supporting resilience of native baylands wildlife also means maintaining biological processes that support the ability of wildlife to respond in numerous ways, including ways we may not be able to predict. For example, species may adapt and acclimate to new conditions and, as species' ranges shift over time, wildlife communities may be reorganized to support novel interactions. Ways to support these processes include ensuring abundant resources, large populations, genetic variability, and multiple resource and habitat options. These processes connect to landscape elements such as large marsh patches; habitat connectivity across environmental gradients such as salinity, temperature and elevation; and habitat diversity and complexity with recognizable patterns that wildlife can orient to (landscape coherence; Beller et al 2015).

This document is focused specifically on the ability of baylands to support native baylands wildlife in the face of sea-level rise and other flooding. Sea-level rise creates persistent change in environmental conditions (e.g. habitat quantity, structure, and salinity) over time that will need to be continuously adapted to. In addition, sea-level rise will intensify disturbance from flood events, and these events often result in high wildlife mortality (Goals Project 2015). Resilience planning should account for both ongoing and event-based stressors related to sea-level rise.

Intensive ongoing management actions (e.g., invasive species management, active relocations, predator control) will likely be necessary. However, those types of actions are not the focus of this report; instead, this document focuses on the actions that can build more resilient ecosystems through physical changes. These physical actions can help reduce the need for and increase the success of future management interventions.

Principles of shoreline resilience relevant to wildlife support

Here we evaluate the principles of shoreline resilience in light of an important ecosystem service (wildlife support) in order to identify key elements critical to maintaining the provisioning of this service. We are focused on physical processes that can be modified by management interventions (e.g. sediment placement or protection of marsh migration space). These physical elements of the landscape influence biological processes and community structure.

The Landscape Resilience Framework (Beller et al. 2015; Beller et al. 2018) outlines seven principles of resilience that we evaluate here specifically for shorelines. Two of these principles, Setting and Process, are well understood for shoreline ecosystems and we developed these Shoreline Resilience Framework principles based on existing conceptual models of baylands evolution. The Connectivity, Diversity/Complexity, Redundancy, and Scale principles have not been previously evaluated for shorelines in light of wildlife support. These principles of the Shoreline Resilience Framework were co-developed at a workshop with the technical advisory committee of the WRMP. The People principle of the Landscape Resilience Framework is woven throughout this document through the dual focus on ecosystem services (benefits to people) and management interventions (actions by people).

Several previous efforts have mapped out the relationship between environmental drivers, factors, and processes that affect baylands evolution and thus the baylands landscape. Elements of these conceptual frameworks are useful for understanding two of the high-level principles of the Landscape Resilience Framework: Setting and Process. A conceptual model of baylands evolution was developed for the Corte Madera Baylands Conceptual Sea Level Rise Adaptation Strategy (BCDC and ESA PWA 2013, Goals Project 2015). This conceptual model is focused on geomorphic factors affecting the habitats of the baylands ecosystem, or the “complete marsh” as defined in the Baylands Ecosystem Habitat Goals (subtidal, mudflat, tidal marsh, estuarine-terrestrial transition zone) (Goals Project 2015). A version of this geomorphic conceptual model has been adapted for use in the Shoreline Resilience Framework (Figure 1).

Setting

Setting can be viewed as the container that defines environmental and biological parameters of an ecosystem. Setting shapes how the other landscape resilience principles are applied in a given landscape. The Landscape Resilience Framework defines Setting as the unique aspects of a landscape that determine which ecological functions, processes, and biological communities can be sustained (Beller et al. 2015). The shoreline setting can be characterized by the “drivers of change” and “factors that control form and function” that were previously identified in the baylands evolution conceptual model developed for the Corte Madera Baylands Conceptual Sea Level Rise Adaptation Strategy and the 2015 Baylands Goals Update (BCDC & ESA PWA 2013, Goals Project 2015, adapted version shown in Figure 1).

The key elements of the San Francisco Bay physical setting are all interrelated, as outlined in Figure 1. In the case of wildlife support, setting defines which species are capable of tolerating the conditions of the physical and biological environment, also known as the potential niche. Setting also encompasses the driver that is changing in our example analysis: sea level. The conceptual model identifies ways in which rising sea levels are expected to impact shoreline ecosystems and their ability to support wildlife.

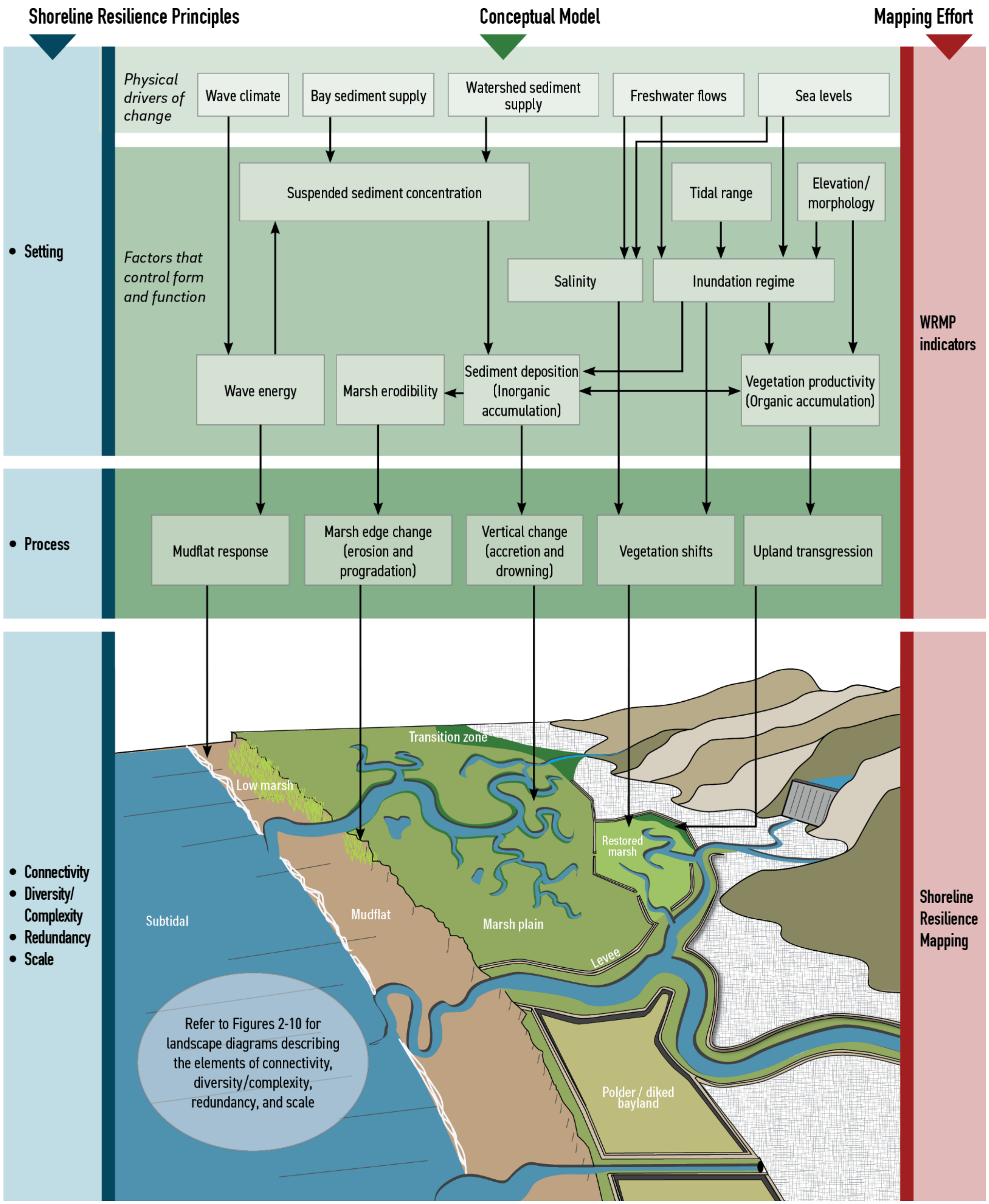

Figure 1. Conceptual model of the physical drivers of baylands evolution. The conceptual model is the backbone of the Shoreline Resilience Principles (left) and elements of this model will be captured by two key shoreline mapping efforts: the WRMP and the upcoming Shoreline Resilience Mapping project (right). The flow chart (top) is adapted from BCDC and ESA PWA (2013) and the landscape drawing (bottom) is adapted from SFEI's Sediment Conceptual Model (SFEI, in prep).

Physical drivers of change

1. **Sea levels**. Changes in sea level impact the inundation regime of marshes. Rates of sea-level rise are projected to accelerate in the second half of the 21st century and beyond. Sea-level rise will also affect salinity as saline waters intrude further into the estuary.
2. **Freshwater flows**. Inflow to the Bay from the Sacramento-San Joaquin Delta and tributaries varies depending on rainfall and human management activities. Climate models are not conclusive about whether a wetter or drier precipitation future is more likely for California; however, more dry years and periods of more intense precipitation are likely (Pierce et al. 2018).
3. **Watershed sediment supply.** Closely related to freshwater flows, the amount of sediment flowing into the Bay from the Delta and other watersheds is a key driver with unknown future direction of change. Human management can also affect watershed sediment supply (e.g., dam construction/removal).
4. **Bay sediment supply.** The Bay sediment pool derives sediment from local watersheds, the Delta, and shallow subtidal areas. Wind waves and currents deposit this erodible sediment on mudflats, marshes, and out into the ocean.
5. **Wave climate.** Wave height, period, and direction. Wave climate varies depending on location.

Factors that control marsh form and physical function

1. **Elevation/morphology.** Elevation, especially elevation relative to the tides, and morphology (landscape form) are key determinants of bayland habitat type.
2. **Tidal range.** The vertical difference in the height of the high and low tides over a tidal cycle. Mean tidal range varies across the Bay, from about 1.7 m (5.5 ft) at the Golden Gate Bridge to 2.6 m (8.5 ft) at the southern end of the lower South Bay (SFEI and SPUR 2019). In some places, the tidal range is limited by human modifications.
3. **Inundation regime**. Frequency and duration of tidal inundation at a particular location. The inundation regime is closely related to elevation and tidal range.
4. **Vegetation productivity (organic matter accumulation).** Biomass production by plants determines the amount and rate of organic matter accumulation, which influences elevation.
5. **Salinity.** Salinity has a strong influence on vegetation and habitat type. Climate change factors including sea-level rise, drought, and extreme precipitation events can all have an impact on salinity.
6. **Suspended sediment concentration.** Determined by incoming sediment supply from the Delta and local watersheds, as well as resuspension by waves, suspended sediment supply is a key factor influencing habitat evolution.

7. **Sediment deposition (inorganic matter accumulation)**. Accretion of inorganic sediment is a key determinant of elevation. Inundation regime and suspended sediment concentration affect sediment deposition.
8. **Wave energy.** A wave's energy is determined by wave height, wavelength, and distance over which it breaks. Wave energy influences erosion.
9. **Marsh erodibility.** Marsh erodibility is influenced by vegetation, soil characteristics, and wildlife activity (e.g. crab burrowing). Together with wave energy, marsh erodibility determines the rate of marsh edge erosion.

Many of these elements will be monitored through the Wetland Regional Monitoring Program (WRMP). A crosswalk linking each Setting element with corresponding WRMP indicators is provided in Appendix A. The list above is largely focused on geomorphic setting and is not a complete list of the elements of the shoreline setting that affect biodiversity resilience. For instance, water quality is a key consideration for habitat quality. Water quality encompasses physical, chemical, and biological properties. Human-caused environmental factors (e.g., toxic substances in contaminated sites around the edge of the Bay, nutrient loads impacting algal blooms, etc.) have a strong impact on water quality. These elements are monitored through the San Francisco Bay Regional Monitoring Program.

Human drivers influencing marsh form and physical function

Humans have a major influence on the baylands setting. Though not a complete list, the following are key examples of the types of impacts that human populations and human developments have on the San Francisco baylands setting:

1. **Development context.** Today's baylands landscape exists in the context of extensive human alteration and development, especially over the last two centuries. In the late 19th and early 20th centuries, the baylands were diked, dredged, drained, and filled to create land for urban development, agriculture, and salt ponds. This reduced the size and quantity of marsh patches, disconnected salt marshes from adjacent freshwater marshes and riparian areas, and generally disconnected the baylands from terrestrial habitats and watersheds. Fragmentation of the baylands has led to increased edge effects from disease, contamination, and predation. Much progress has been made in recent decades in restoring diked baylands to tidal action and reconnecting marshes with adjacent habitats; however, the ongoing impacts of historical and current development still have a major impact on the setting of the San Francisco baylands.

2. **Human-created stressors.** Presence of human communities adjacent to marshes affects the baylands setting by altering flows of physical resources and biological pathways. Human infrastructure, like telephone poles, electric transmission lines and towers, radio aerials, and tall buildings create perches for raptors, benefiting these predators to the detriment of prey species. Infrastructure access berms, boardwalks, and relict salt pond berms create access pathways for predators from urban areas to access the interior of

marshes and alter hydrologic patterns and flow of resources. Recreational pathways can also create disturbances, especially where pets are allowed to roam off-leash. Landfills and neighborhoods attract and sustain populations of corvids, skunks, feral cats, and other predators that are detrimental to native marsh species. Humans have also introduced invasive species, which can cause shifts in marsh ecological communities and impact marsh conditions (e.g. turbidity).

3. **Environmental quality.** Human developments around the Bay also contribute to contamination of water and sediment, influencing the San Francisco Baylands setting. Water and sediment quality has improved greatly since the Clean Water Act was passed, but challenges still remain in reducing nutrient loads, contaminants of emerging concern, bacteria, and legacy industrial contaminants in the Bay (SFEI 2022). Development in the watersheds, including increases in impervious surfaces, channelization of creeks, damming of rivers, and other interventions, have also impacted environmental quality in the Bay, including changing water temperatures, sediment loads, and salinity.

Processes

The processes shaping the landscape are influenced by the setting, including both the “drivers of change” and “factors influencing form and function” listed in the previous section. The following processes shape the baylands landscape and influence the other principles of landscape resilience: habitat connectivity, diversity/complexity, redundancy, and scale. Here we focus mainly on processes that influence landforms, which tend to be a combination of physical (sediment and water) and plant processes.

1. **Upland migration.** Also called transgression. The movement of marsh (or other) ecosystems upslope as sea levels rise. Upland migration influences marsh width and is primarily controlled by the rate of sea-level rise and the elevation and slope of the space directly landward of the baylands. Marshes are squeezed, or compressed, when they are unable to migrate upslope.
2. **Vertical change** (accretion and drowning). Accretion is the gradual vertical buildup of baylands with organic and inorganic sediment. Vertical accretion influences marsh elevation and is primarily a function of the rate of sea-level rise, sediment deposition, and organic matter accumulation from marsh plant production. When the rate of sea-level rise exceeds the rate of accretion, marsh drowning occurs. Vertical change is also influenced by land subsidence or uplift.
3. **Marsh edge change** (erosion/progradation). Erosion is the loss of sediment from tidal baylands due to loss of sediment from surfaces or edges. Erosion primarily occurs at the boundary between intertidal and subtidal areas due to wave action. Marsh edge erosion influences marsh width and is influenced by rates of sea-level rise, wave energy and marsh edge erodibility. Marshes can also extend bayward through progradation when sediment surpluses and plant colonization convert subtidal areas into low marsh.

4. **Mudflat change.** The elevation, width, and form of adjacent mudflats affects sediment delivery to the marsh and wave energy and erosion potential at the marsh edge. Mudflat form and extent influences marsh width and is influenced by sea-level rise, wave energy, and sediment supply.
5. **Vegetation shifts.** Vegetation is a key determinant of habitat type and quality, and vegetation shifts may influence marsh elevation through feedbacks on sedimentation and accretion rates. Processes like colonization by new species, plant mortality, burial and decomposition of plant litter, and invasion by exotic species, may be affected by water quality, inundation regime, etc.

Many of these processes will be monitored through the WRMP in the future. A crosswalk linking each Setting and Process element with corresponding WRMP indicators is provided in Appendix A.

Connectivity

Connectivity within the complete marsh (upland to subtidal)

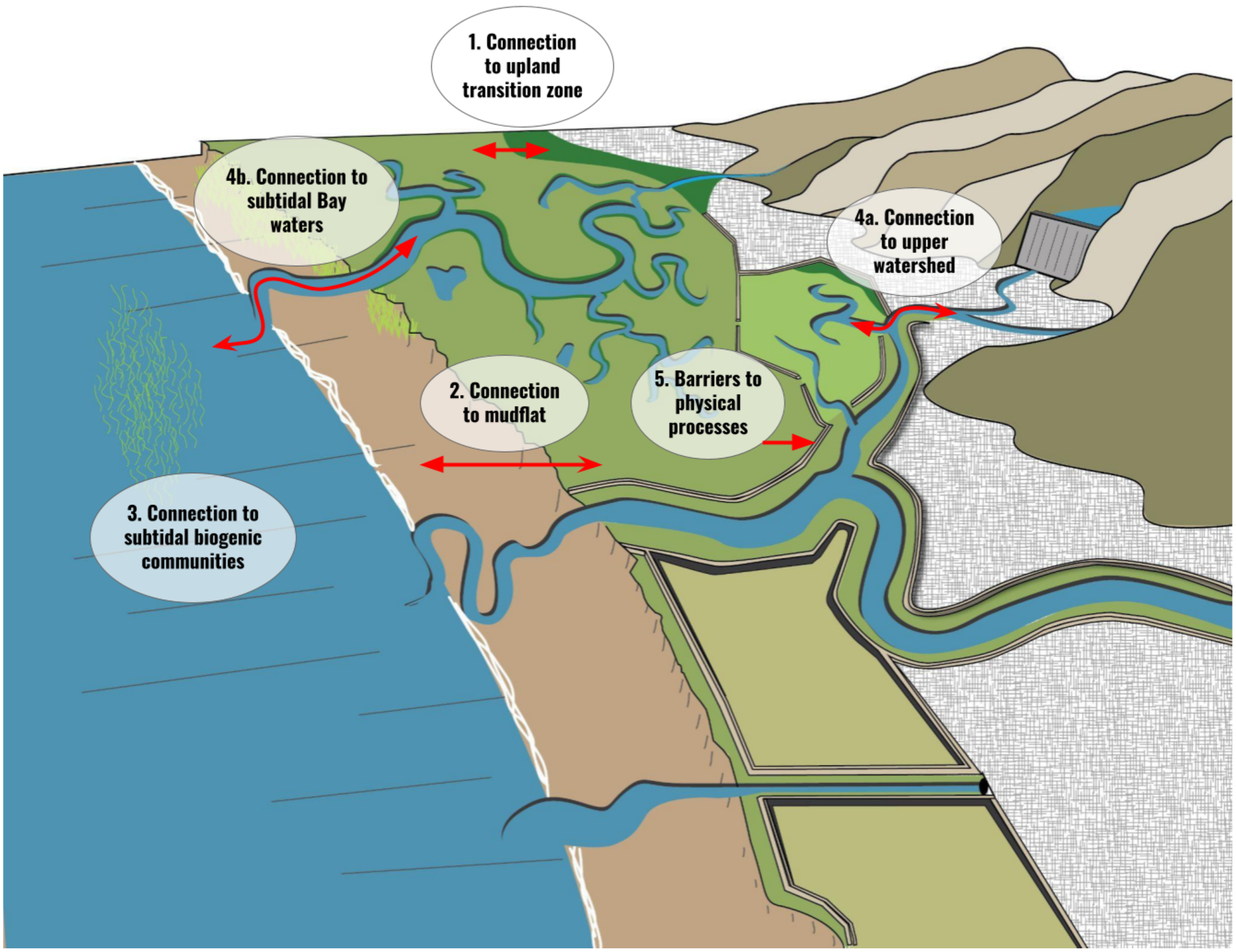

Figure 2. Connectivity within the "Complete Marsh."

The "complete marsh" includes habitats ranging across the baylands from subtidal to upland, with the marsh plain itself just one element of this interconnected system (Figure 2). Connectivity between these habitats is essential for a variety of ecosystem processes and is important for maintaining wildlife populations. For example, nutrients are exchanged between upland, marsh, intertidal, and subtidal habitats, supporting food webs of native species and influencing plant and secondary productivity. Wildlife populations often migrate on various time-scales between neighboring shoreline environments and connectivity is required to meet their habitat requirements. Physical elements of connectivity within the “complete marsh” that are critical for wildlife support include:

1. **Upland transition zones** that allow connectivity between marsh and upland habitats. Where transition zones are undeveloped and protected they can connect marshes to hillslope processes and provide space for marsh migration as sea levels rise. When vegetated with native species, transition zones provide valuable high tide refuge for small mammals and birds. Transition zones are a critical connection for many wildlife species between the upland and highly productive marsh. Development at the back of marshes (e.g. busy highways) can be detrimental to species seeking high tide refuge. Other land use types (e.g. subsided agricultural baylands) may provide some value as high tide refuge but are not resilient to rising sea levels.

2. **Mudflats** that connect subtidal and marsh habitat. Marsh scarp erosion and progradation between the marsh and mudflat helps determine sediment transfer between the marsh and mudflat. Mudflats are the connection by which aquatic species access the marsh at high tide and provide important habitat for fish, waterbirds, and invertebrates.

3. **Subtidal biogenic communities** such as submerged aquatic vegetation (SAV; e.g. eelgrass) beds and native oyster reefs bayward of marshes can affect marsh resilience as SAV and oyster reefs can reduce currents and trap and stabilize fine sediments.

4. **Hydrologic connections** from uplands to marshes to subtidal waters that strongly influence habitat type and quality. For example:
    a. Connectivity to upper watersheds determines delivery of freshwater and sediment to the backshore of tidal marshes, which can increase resilience to sea-level rise and provide a gradient of salinity that supports greater wildlife diversity. Alluvial fans, created where watershed sediment is deposited as streams meet the flatter baylands, can provide marsh migration space and low-slope transition zone and continue to build up over time as sea levels rise.
    b. Connectivity with tidal channels and subtidal bay waters determines delivery of suspended sediment from the Bay and affects habitat conditions. When channel networks are complex and sinuous, they can connect parts of the marsh to one another and facilitate movement of predators, prey, seeds, detritus, nutrients, water and sediment. For example, functional connectivity between subtidal and intertidal channels provides benefits for fish in foraging, avoiding predators, and seeking shelter from extreme conditions like high freshwater flows (Colombano et al. 2021).
    c. Artificial connections such as ditches and channel cuts can create “overconnected” marshes with low channel complexity, drained (oxygenated) marsh sediments, and reduced water residence time.

5. **Barriers to physical processes** that influence connectivity within the complete marsh by inhibiting flows of water and sediment. Barriers may include:
    a. Hardened shorelines (levees and seawalls) inboard of marshes.
    b. Tide gates and undersized culverts
    c. Barriers within the marsh such as road and rail berms, infrastructure access berms, relict berms, causing drainage issues and leading to low elevation, poorly vegetated areas that often breed mosquitoes

Connectivity among marshes

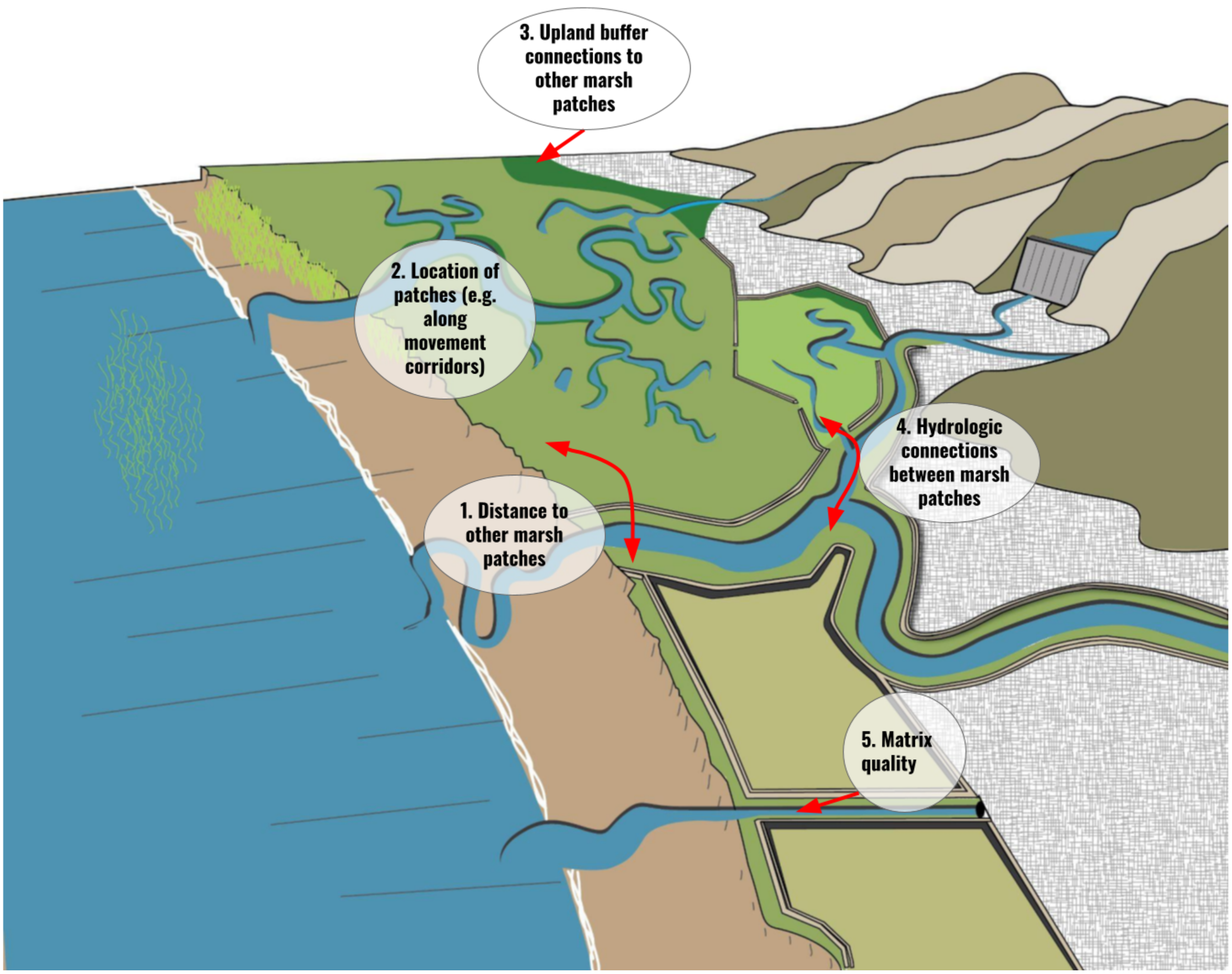

Figure 3. Connectivity among marshes.

In addition to connectivity from the Bay to the uplands and mudflats (across the shoreline), marshes are also connected to one another along the shoreline (Figure 3). This patch connectivity is essential for biological populations to exchange genetic material, providing the genetic diversity required for populations to adapt to changing environments. Different wildlife species have different pathway requirements affecting the level of functional connectivity between marshes. Some general factors affecting connectivity between marshes for wildlife movement include:

1. **Distance to other marsh patches**, allowing for dispersal of species from one patch to the next
2. **Location of patches** (e.g. along movement corridors for fish or birds)
3. **An upland transition zone that connects to other marsh patches**, allowing wildlife movement along a protected corridor between patches.
4. **Hydrologic connections between marshes**, which influence connectivity for aquatic and semi-aquatic wildlife.
5. **Matrix quality,** which influences connectivity between marshes by determining dispersal capability. Different types of barriers divide marshes from one another and impacts of these barriers on wildlife movement are species dependent. For example, water is the crucial barrier limiting movement of salt marsh harvest mouse. Other stressors in the matrix like noise and pollution may also limit dispersal. Barriers may include levees and associated vegetation, roads, tidal barriers, landfills, bridge approaches, railroads, developed areas, large channels, etc.

Diversity/complexity

Diversity/complexity of channel networks

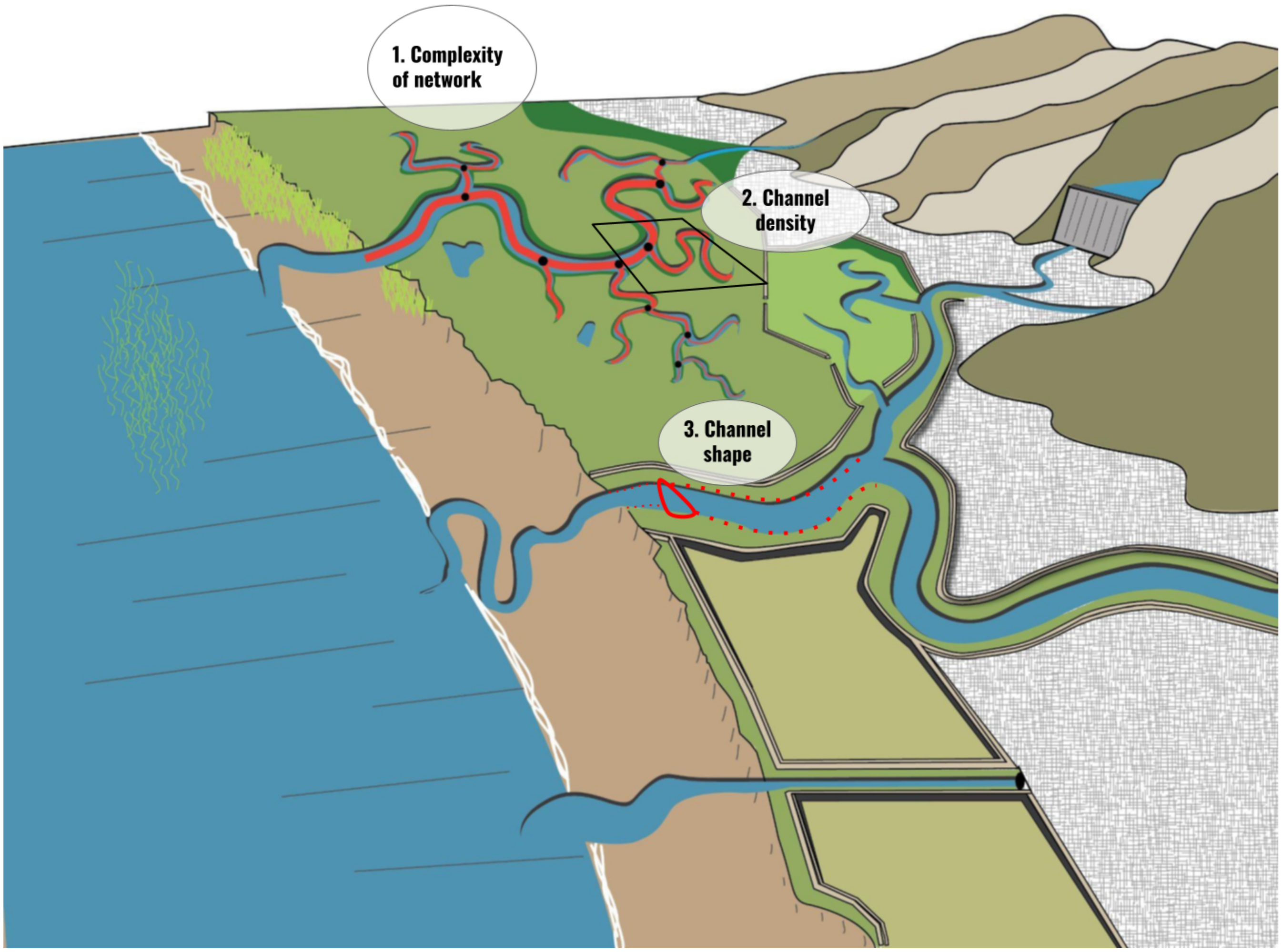

Figure 4. Diversity/complexity of channel networks.

Channels facilitate movement, foraging, and seed dispersal (elements of connectivity) within the marsh for many organisms. They also affect the flows of water, sediment, nutrients, plant community structure, microhabitats, distribution of food, and territorial behavior (Figure 4). Elements of shoreline resilience related to the diversity/complexity of channel networks include:

1. **Complexity** of channel networks (including channel branching), which drives factors including energy dissipation, habitat complexity, and land-water exchange and residence time. These factors in turn affect benthic-pelagic food web dynamics.

a. Diverse channel orders and sizes provide more variation in topography, moisture gradients, vegetation communities, habitat diversity and complexity, food distribution and connectivity for multiple taxa. Antecedent geomorphic and sediment properties can influence channel formation and diversity. Some wildlife species' behavioral ecology is tightly tied to tidal channels, and their territory size, foraging behavior, and nesting behavior depend on the channel network. In general, dense, sinuous and diverse channel networks and a high marsh plain (as is typical in mature tidal marshes of the Bay Area) are associated with high habitat value for marsh wildlife. Therefore, having a range of channel conditions within close proximity can increase habitat value, especially for some fish species. Higher channel diversity can also lead to a higher diversity in the range of pools (size/depth) remaining in channels at low tide.

2. **Density** of channels (area of channel per unit area of marsh) affects distribution of sediment, water, and organisms across the marsh.

3. **Shape** of channels, which varies in cross-section and planform..

   a. Channel depth affects water volume for fish, marsh drainage, and aeration potential for neighboring marsh vegetation.
   b. Sinuosity creates complexity in depth and velocity and creates velocity and predator refuge opportunities.
   c. Slumping of channel edges occurs due to natural marsh channel evolution and due to human impacts (walking in marsh, etc.). Slumping of channels can impede water flow. Slumping of channel edges creates structural habitat complexity in tidal channels
   d. Overhanging channel banks are important areas for marsh wildlife to forage under cover and hide.
   e. The in-channel bars on the sides of larger tidal channels, often colonized by low-marsh plants, are also important areas for wildlife to forage under cover.

Topographic complexity

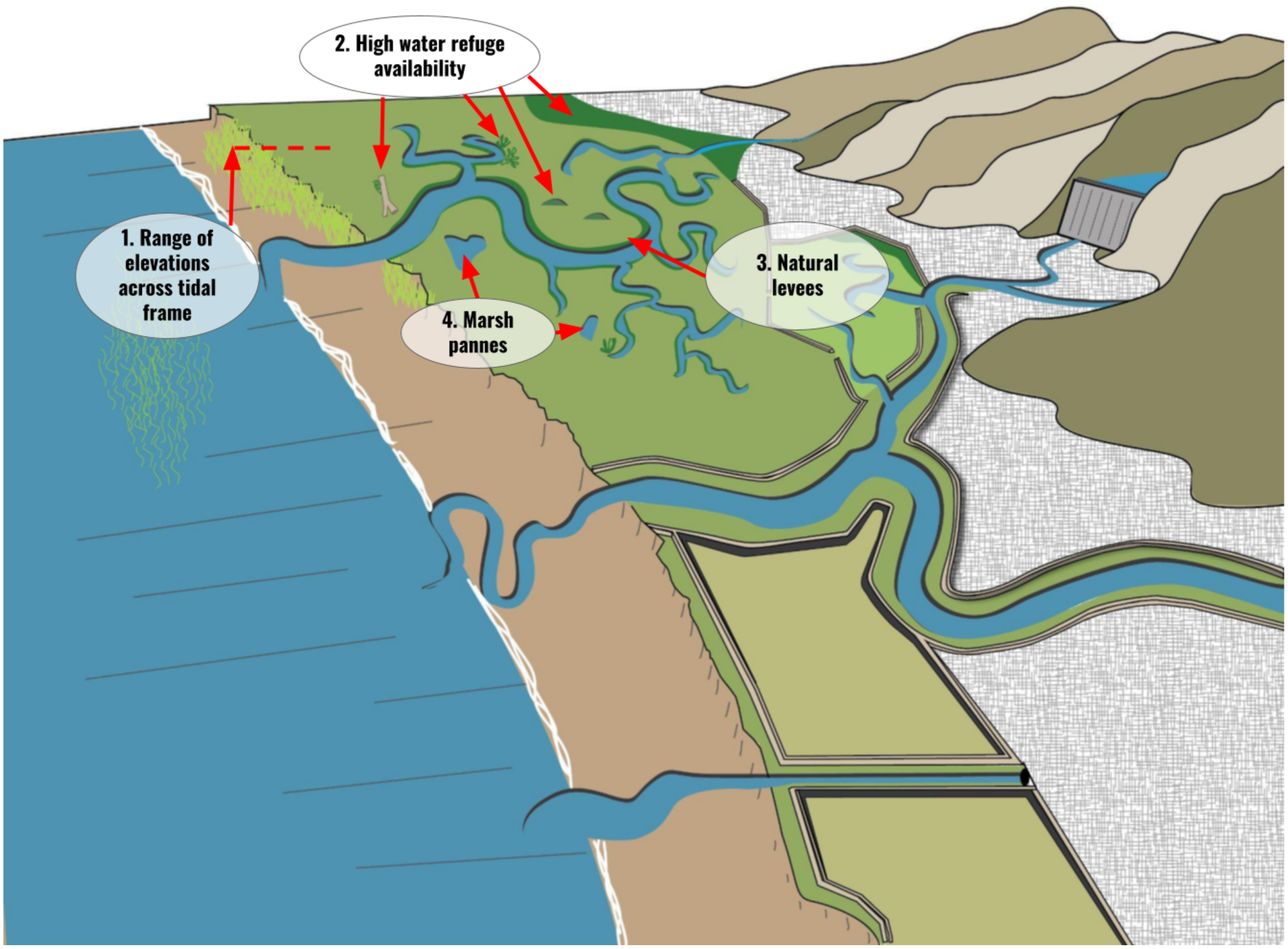

Figure 5. Diversity/complexity of elevation

Elevation relative to the tides is a key driver of habitat type and a key component of marsh resilience (Figure 5). Elements of baylands resilience related to diversity and complexity of elevation include:

1. **A range of elevations across the tidal frame** drives higher structural habitat diversity.
    a. Marsh elevation determines the types of vegetation that can establish. These different types of vegetation have different heights and structures, which affects habitat quality for birds and small mammals. Structural complexity slows water flow, traps sediment, and allows higher wildlife diversity. Older marshes contain an entrained vegetation layer where, slightly above the marsh plain, living and

senesced plant matter form a denser mat. The entrained layer contributes to the slowing of tidal flows and sedimentation and buffers shorelines from erosion. It also provides important structural habitat for terrestrial marsh wildlife, like mice.

   b. The scale of elevation heterogeneity matters. Elevation is a key determinant of plant community type, which then drives responses in the behavioral ecology of wildlife. Marshes often have large-scale elevation complexity, with a transition zone and areas of low marsh near the bay shore, and also smaller-scale elevation complexity with channels of different sizes, low marsh bars within large channels, and natural levees. Both scales are important for determining which wildlife species can find suitable habitat and the quality of that habitat.
   c. Marsh plains at relatively high elevations in the tidal frame are associated with higher resilience to sea-level rise (elevation capital).
2. **High water refuge availability.** Taller plants and sometimes higher-elevation areas within the marsh are used by terrestrial wildlife (especially birds and small mammals) during high water events, and may also be used as nesting habitat. High water refuge may take a variety of forms, including:
   a. Higher stature vegetation along natural levees.
   b. Adjacent protected transition zone habitat (also discussedin the Connectivity section).
   c. Marsh islands or mounds (higher-elevation areas within the marsh), whether natural or artificial, can provide these essential microhabitats for high marsh plants to establish.
   d. Wrack or large woody debris can provide high water refuge.
3. **Natural levees** are created when tides overtop the channel bank and coarser sediment deposits along channel edges. The natural levee allows different plant species (e.g. gumplant) to establish. Vegetation growing on natural levees is often taller than vegetation in the marsh plain, creating important habitat structure for high water refuge and nesting.
4. **Marsh pannes** are natural ponds in the marsh plain usually less than a foot deep that fill with water during very high tides. They can also form due to artifical changes to natural drainage. Marsh pannes provide habitat for invertebrates and fish, foraging opportunities for waterbirds, and habitat for some high marsh plants. Evaporation of water in these ponds over time causes increased salinity.

Diversity/complexity of salinity patterns

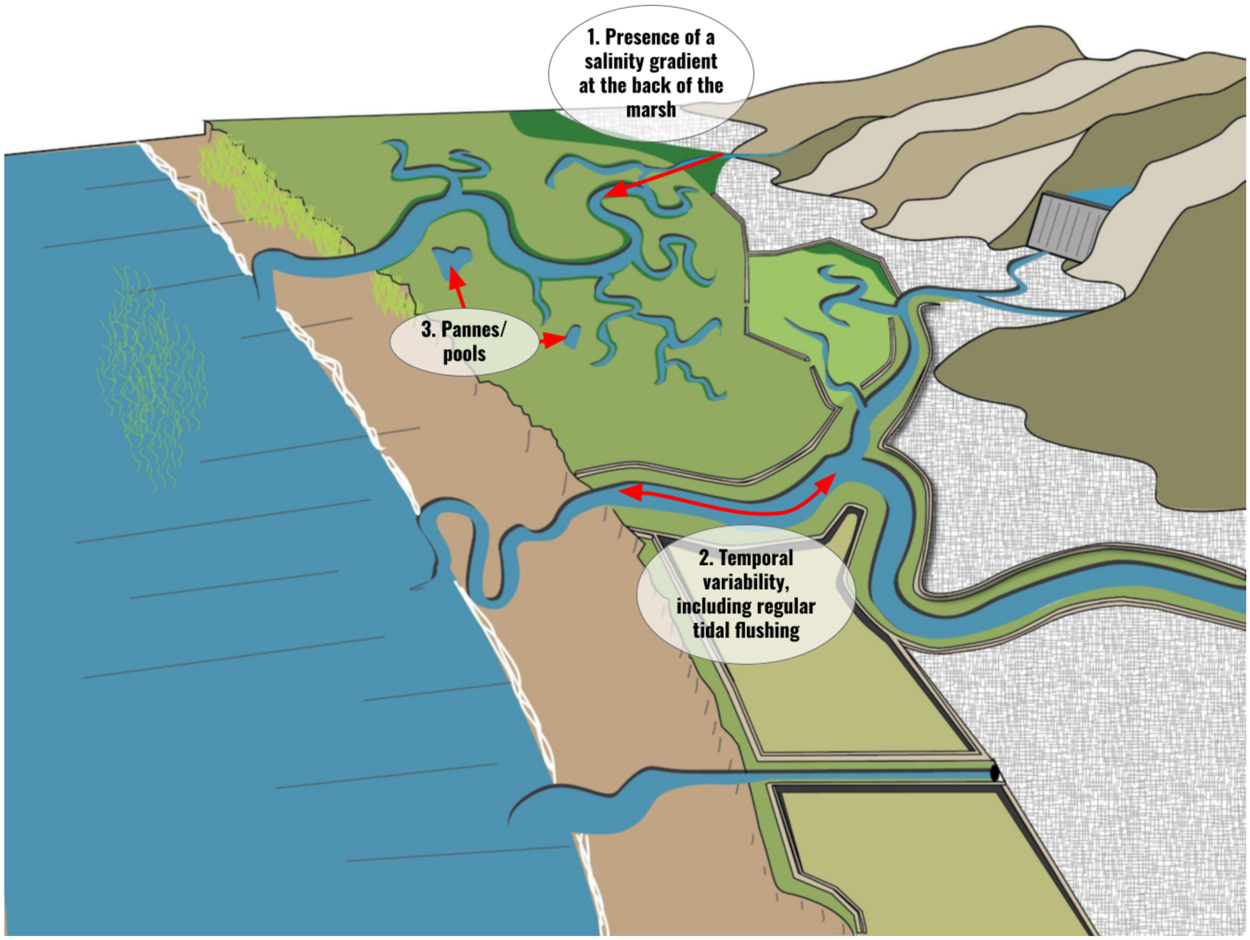

Figure 6. Diversity/complexity of salinity patterns.

Historically, many of the tidal marshes of the Bay were adjacent to freshwater habitats including wet meadows, vernal pool complexes, and riparian wetlands (Beller et al. 2013). Today, most of these freshwater wetlands have been lost to development and stormwater is routed directly to the Bay, bypassing tidal marshes. Sea-level rise is likely to increase marsh salinity, particularly in the upper estuary, changing plant communities and seed germination cues for wetland plants. Salinity affects vegetation type and productivity, influencing the physical structure and resilience of the marsh as well as habitat type (Figure 6). Elements of shoreline resilience related to the diversity and complexity of salinity include:

1. **Presence of a fresh-brackish-salt or brackish-salt marsh gradient** at the back of the marsh (from tributaries, freshwater seeps, wastewater or stormwater discharges). Presence of a salinity gradient affects vegetation communities, creating variation in

habitat types, wildlife communities, biogeochemistry, and greenhouse gas fluxes. Barriers to hillslope runoff (e.g. stormwater channels) can interrupt this natural salinity gradient. Lower salinity marshes are associated with higher belowground plant productivity and therefore higher rates of organic matter accumulation, which can increase marsh resilience by building elevation relative to the tides. Connectivity to upper watersheds can allow better adaptive evolution of marshes in the context of rapid climate change.

2. **Temporal variability** in salinity is also a determinant of vegetation diversity. Salinity varies on an interseasonal and interannual basis (wet and dry periods, wet and dry years, drought, precipitation) and on a daily (tidal) basis. Variation in salinity affects survival and productivity of vegetation, which impacts soil stability, organic matter accumulation, and wave dissipation. Tidal connectivity (regular tidal flushing) reduces hypersalinity in salt marshes.
3. **Presence of marsh pannes** allows longer water residence time and creates hypersaline patches that allow vegetation diversity, unvegetated spaces, increased invertebrate diversity, and habitat for fish and birds.

Redundancy

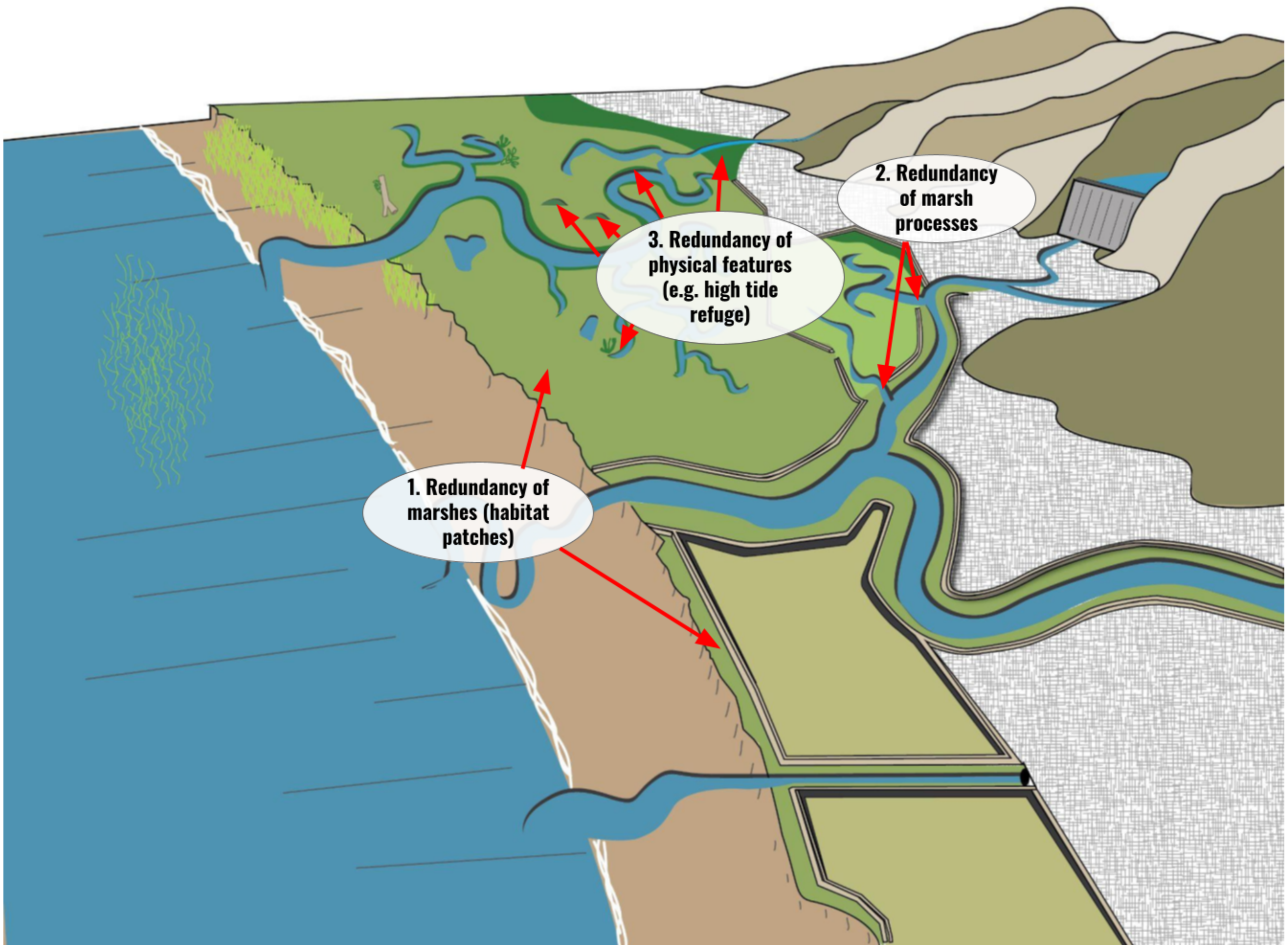

Figure 8. Redundancy.

Redundancy allows for recovery from disturbance. Multiple replicates of populations, habitats or processes provide insurance or alternatives in case one element is diminished or lost. In populations, this is known as the "rescue effect" (Brown and Kodric-Brown 1977). Redundancy of the processes, physical elements, and biological elements (like populations or role within a food web) discussed thus far can increase resilience of complete marshes (Figure 8). As with diversity, it is important to consider the scale at which redundancy is measured; for example, multiple similar marsh patches may not provide redundancy if they are too far apart for organisms to move between them. Elements of redundancy relevant to shoreline resilience include:

1. **Redundancy of marshes (habitat patches)** so that multiple complete marshes, and other types of baylands habitats, are present around the full extent of the intertidal zone within each subembayment: Suisun Bay, North Bay, and South Bay. Different patches will face different stressors, so having multiple patches increases resilience.

2. **Redundancy of marsh processes** (tidal flows, sediment supply), which supports maintenance of habitat quality. For example, marshes with multiple points of tidal connectivity (culverts, tide gate, or levee breaches) maintain tidal connectivity even if one tide gate breaks or one culvert is blocked. Likewise, marsh restorations relying on multiple sediment sources (e.g. both sediment placement and natural sediment supply) are more likely to maintain elevation relative to the tides than restorations relying only on one sediment source.

3. **Redundancy of physical features,** which allows for consistent habitat quality across the marsh and creates suitable habitat for many individuals within the marsh. These features include:
    a. Repeated elements of marsh structure (channels networks, creek connections, pannes, pools, natural levees, marsh mounds, large woody debris)
    b. Multiple types of high tide refuge and upland transition zone supporting different species and areas of the marsh during high water events (both within the marsh plain and at the backshore)

There are other elements of redundancy that are important but do not fit within this framework because they cannot be addressed with a physical intervention. However, these elements are not captured by other elements of the framework and may warrant further expansion in a later iteration of the Shoreline Resilience Framework:

- **Redundancy of populations**, which is key to maintaining genetic variation and metapopulation stability. Multiple populations reduce the risk of catastrophic effects from stochastic events like disease outbreaks, extreme weather events, etc, because some populations may be less impacted than others. Redundant populations present at the same time allow for recolonization from other source populations in places where local extinction has occurred.

- **Redundancy of species** occupying similar roles in the trophic structure or performing similar roles in the ecosystem. This allows ecosystem functions to persist when one species is impacted by disturbance.

Scale

Spatial scale

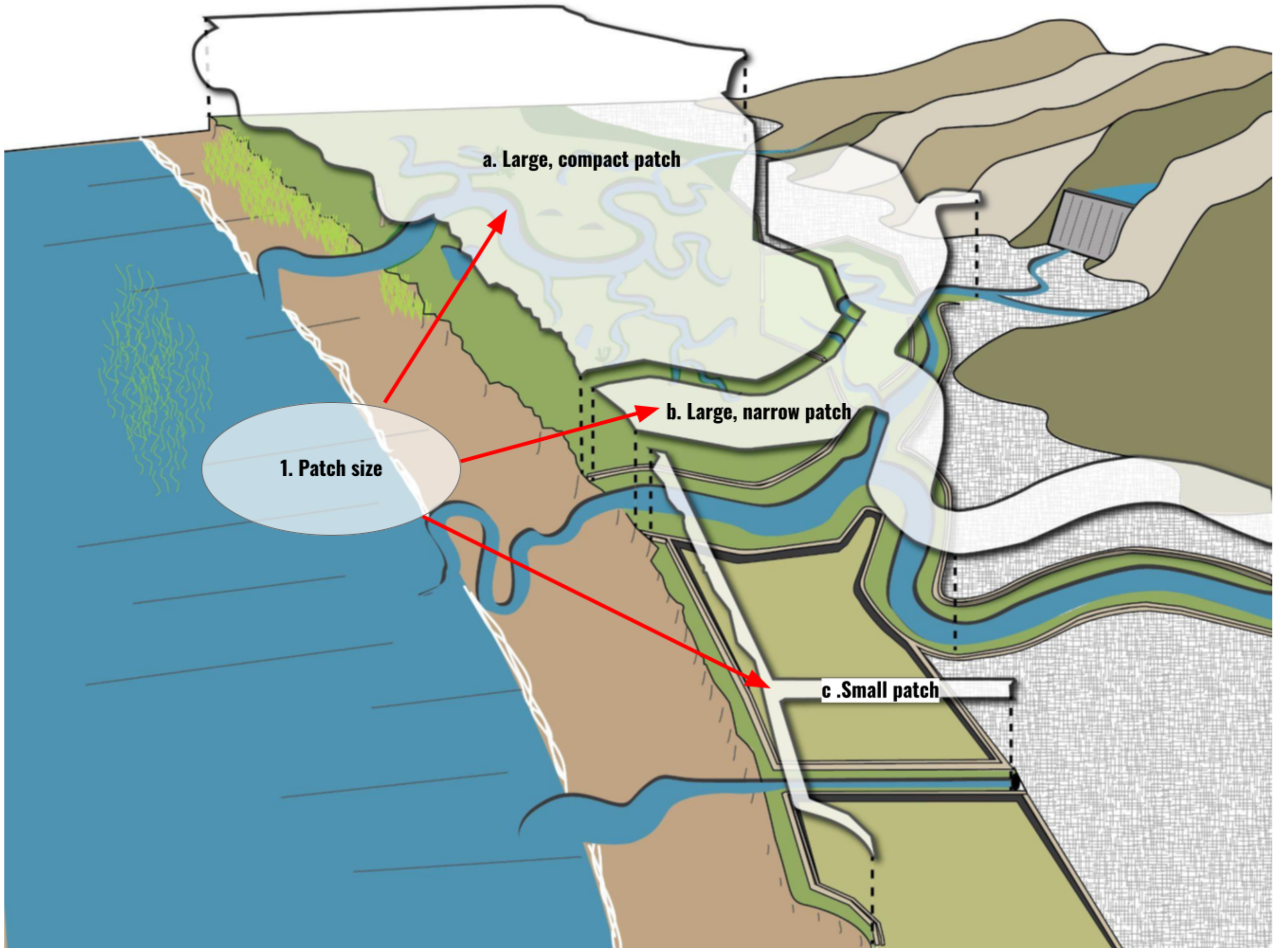

Figure 9. Spatial scale.

Many of the other factors supporting landscape evolution and biological adaptation (connectivity, process etc) can be examined at multiple spatial scales. For example, in addition to connectivity within and between marshes at the regional or landscape scale, larger-scale connectivity to the ocean and other estuaries at the hemispheric scale is relevant to the resilience of bird and fish populations. At the smaller scale, using local (site as opposed to regional-level) tidal datums can allow determination of more accurate expectations for habitat response. One of the most important elements of spatial scale is patch size (Figure 9):

1. **Patch size,** which affects carrying capacity for wildlife populations.
    a. Large, compact patches allow a range of microhabitats that allow wildlife more likelihood of finding suitable habitat in response to variable environmental conditions, including those from climate change. Larger patches are generally more stable, resilient, and host greater diversity of physical features (e.g. channel networks) and wildlife. Large, compact marshes are less susceptible to edge effects (e.g. invasion, disturbance, pollution) that can negatively impact marsh species. The size of a patch that will support a viable population varies for different species. For example, according to the (USFWS 2013), marsh patches greater than 150 acres in size have been shown to be viable for salt marsh harvest mouse, while patches approximately 1,100 acres and greater are viable for Ridgway's rail. Habitat patches greater than about 250 ac (100 ha) support denser Ridgway's rail populations (Goals Project 2000, USFWS 2013).
    b. Large patches that are long and narrow are less protected from edge effects. However, they can serve as movement corridors and stepping stone habitats connecting between larger, more compact, more complex patches.
    c. Small patches are also less protected from edge effects but can serve as stepping stone habitats. The relevance of stepping stone habitats to wildlife support varies by species; birds and fish can move easily even between relatively disconnected habitat patches, while small mammals (e.g. salt marsh harvest mouse) require more stepping stones for dispersal.

Time scale

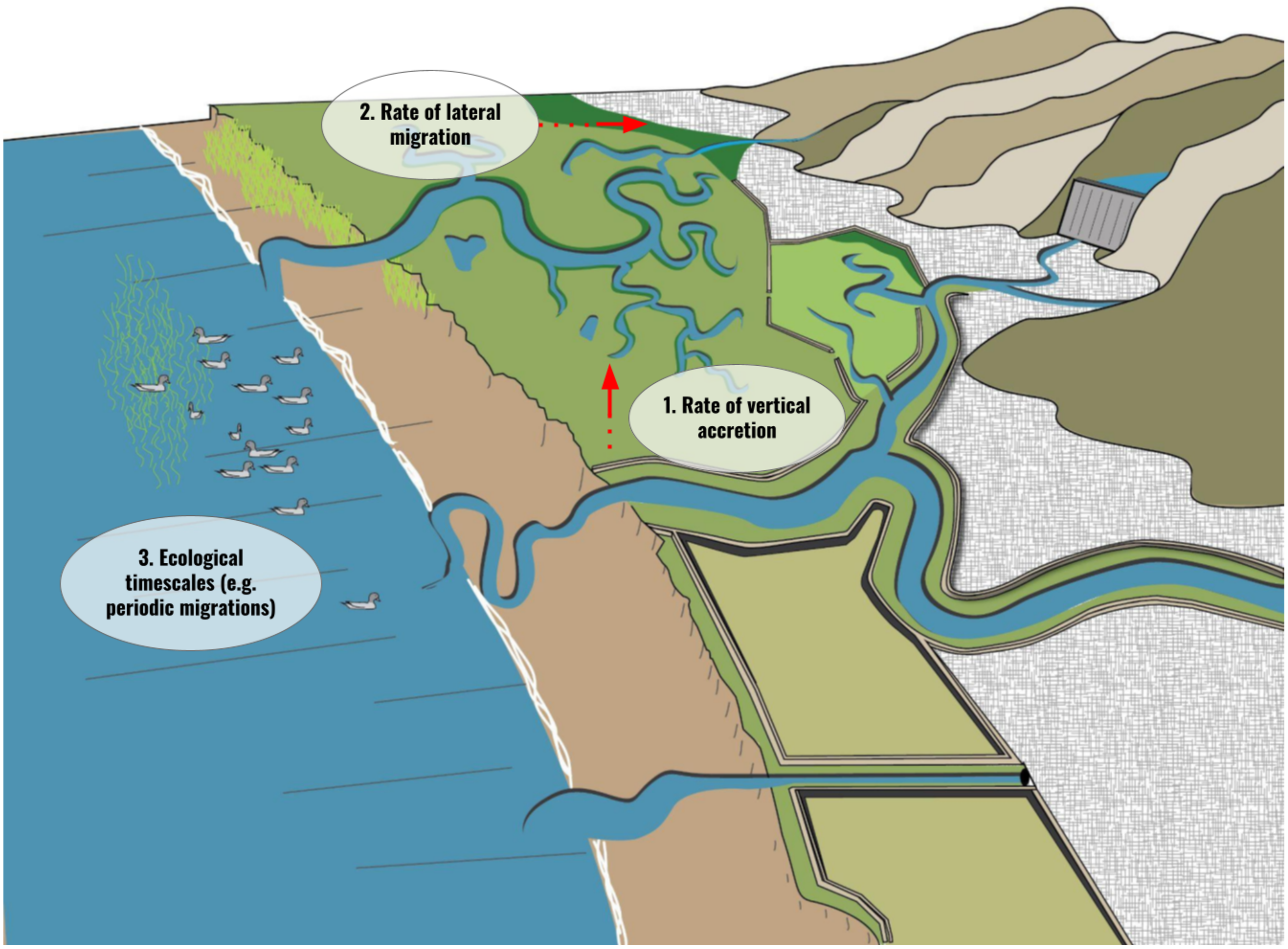

Figure 10. Time scale.

Many of the relevant factors to shoreline resilience change over time in addition to across space. The timing of human actions and natural processes in relation to larger environmental changes (e.g. rates of sea-level rise) is relevant to the ability of ecosystems to survive and adapt (Figure 10). Elements of temporal scale relevant to shoreline resilience include:

1. **The rate of vertical accretion** of inorganic and organic sediment in marshes, tidal flats, and subtidal channels, which is a key determinant of success for marsh restoration projects. The sooner tidal action is restored to diked areas, the more time there is for sediment to build up before the rate of sea-level rise accelerates in the latter part of the century. This increases the potential for marshes to keep pace with sea-level rise,

because marshes that start out at higher elevations, with more elevation capital, are more resilient. In some cases, subsidence slowing or reversal projects (e.g. sediment placement or creation of peat building freshwater wetlands), can be pursued in deeply subsided areas prior to restoration or to raise elevations to intertidal and also reduce tidal prism if/when levees eventually fail.

2. **The rate of lateral migration** of bayland habitats upland and inland as sea levels rise. Understanding both the spatial and temporal scales of marsh migration that can be expected is important to ensuring habitat continuity.
3. **Ecological timescales** relevant to planning, which range from daily cycles to long-term evolutionary scales at which processes like adaptive differentiation progress. Some of these ecological timescales are periodic (seasonal migration, necessity to reproduce and recruit every year, etc.) and thus require continuity in management actions without big gaps. Different temporal scales are relevant to different species or habitat conditions (for example, successional trajectories offer different benefits at different stages that can be measured in time since disturbance/restoration etc.). Some ecological timescales are driven by physical process timing. Notably, aquatic food web development is highly correlated to water residence time. Thus marshes with large enough channel networks to have long water residence time may allow a more robust secondary consumer population and ultimately greater local productivity.
4. **Adaptive evolution** is perhaps the most critical long-term ecological process to plan for, facilitating the natural ability of wildlife populations to persist as conditions change.

Planning timelines at the project and regional scale should be aligned with ecological timescales, but must also account for political and funding cycles, environmental permitting and review, and other administrative time scales. Given initial elevations, likely accretion rates, and rates of sea-level rise, expectations of restored habitat types may need to be adjusted; not all projects pursued may result in the development of marsh plains but may provide subtidal or mudflat habitat. Planning can account for habitat shifts, targeting management to benefit different wildlife species as accretion and vegetation establishment progresses. Adaptive management can plan for ecological factors with longer, slower changes as well as for event-based changes.

Conclusion

This document connects various previous efforts to identify key features of shorelines that are critical for resilience: specifically, the continued ability of shorelines to provide wildlife support in face of ongoing sea-level rise. We focus on physical factors involved in shoreline resilience where physical interventions may strengthen the ability of the shoreline to provide services into the future. Ultimately, the resilience of the shoreline to provide wildlife support requires room for populations to adapt, respond and evolve to the changing physical conditions brought about by sea-level rise.

By aligning efforts, including the Landscape Resilience Framework and process-based conceptual models, we have identified key elements that can aid in quantifying shoreline resilience and the levers that can be adjusted to strengthen resilience into the future. Identifying the key elements responsible for resilience of service provisioning is the first step towards quantifying, mapping and maintaining those elements through management interventions.

Following the completion of this Framework, metrics will be developed to map a range of shoreline resilience elements that have been identified. These maps will be used to inform decisions about where and how adaptation strategies can be employed to improve shoreline resilience to sea-level rise.

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Appendix A

Table A-1. Setting and Process elements and corresponding WRMP indicators

Principle	SubPrinciple	Category	Covered by WRMP Indicator
Setting	Drivers of change	1. Relative sea-level rise	15. Spatial and temporal trends in the rate of sea level rise.
		2. Freshwater flows	
		3.Watershed sediment supply	13. Spatial and temporal trends of SCC in tidal marsh channels in relation to watershed yields of SS and SSC in estuarine shallows and bays.
		4. Bay sediment supply	13. Spatial and temporal trends of SCC in tidal marsh channels in relation to watershed yields of SS and SSC in estuarine shallows and bays.
		5. Wave climate	
	Factors that control form and function	1. Elevation/morphology	2. Map of tidal wetland elevations and elevation capital
		2. Tidal range	14. Spatial and temporal trends in the frequency, duration, and depth of tidal inundation of marsh plains.
		3. Inundation regime	14. Spatial and temporal trends in the frequency, duration, and depth of tidal inundation of marsh plains.
		4. Vegetation productivity	7. Percent cover, height, and patch characteristics of major dominant veg. groups within sub-basins.
		5. Salinity	16. Spatial and temporal trends in aqueous salinity of tidal marsh channels and porewater salinity along gradsects. 18. DO in tidal marsh channels.
		6. Suspended sediment concentration	13. Spatial and temporal trends of SCC in tidal marsh channels in relation to watershed yields of SS and SSC in estuarine shallows and bays.
		7. Sediment deposition (inorganic accumulation)	13. Spatial and temporal trends of SCC in tidal marsh channels in relation to watershed yields of SS and SSC in estuarine shallows and bays.
		8. Wave energy	
		9. Marsh erodibility	6. Map of changes in the lateral extents of natural foreshores (tidal marsh and beach).
Process	N/A	1. Upland migration	3. Map of estuarine-terrestrial transition zones and migration space.
		2. Vertical change	2. Map of tidal wetland elevations and elevation capital 12. Spatial and temporal trends in marsh plain and tidal flat vertical change and accretion rates
		3. Marsh edge change	6. Map of changes in lateral extents of natural foreshores
		4. Mudflat change	12. Spatial and temporal trends in marsh plain and tidal flat vertical change and accretion rates

		5. Vegetation shifts	7. Percent cover, height, and patch characteristics of major dominant veg. groups within sub-basins. 8. Direction and magnitude of changes in percent cover, height, and patch characteristics of major dominant veg. groups within sub-basins. 9. Changes in drainage network length, channel density, channel width, numbers and sizes of pannes, size of un-vegetated areas of tidal marsh plains. 10. Distribution and abundance of selected non-native, invasive plant species.