# Tracking Coastal Habitat Change Over Time: Considerations for a Statewide Mapping Program




**About this report:**

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# Executive Summary

Managing California's coastal habitats and tracking progress toward achieving regional and statewide goals requires up-to-date and comprehensive mapping to assess extent and track change in total area and habitat distribution over time. To date, mapping of different coastal habitats in California has occurred periodically and often in a piecemeal manner. This lack of comprehensive statewide coverage, lack of consistent methodology, and asynchronous temporal collection makes it difficult to achieve the objectives of California's resource managers.

To remedy this situation, the Ocean Protection Council (OPC) summarized options for routinely and comprehensively mapping the following four coastal habitats statewide: coastal wetlands, beaches and dunes, eelgrass, and rocky intertidal (Figure ES-1). This effort is intended to support OPC's Strategic Plan goals on coastal habitat acreage targets and to support other State agencies in their mandates to track habitat acreages (California's Nature-based solutions climate targets AB1757, 2022 C. Garcia). Expert workgroups were convened for each of the four habitats to provide input on mapping approaches and data sources. This information will help inform the development of ongoing mapping efforts that can be applied in a consistent, practical and effective manner.

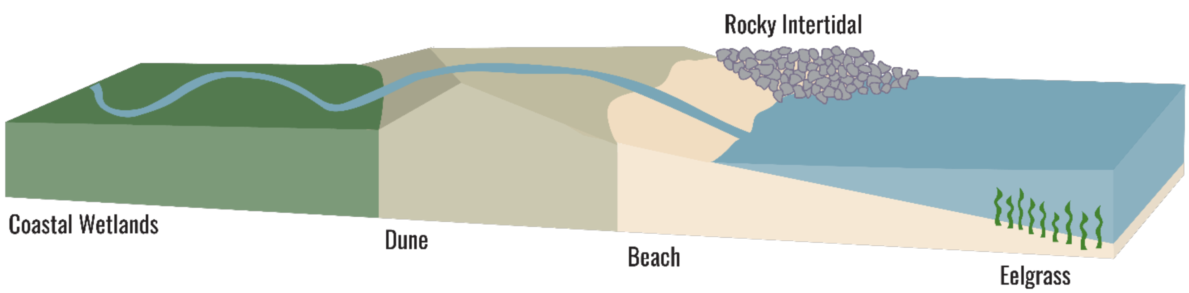


**Figure ES-1: Relationship of coastal habitats for which mapping approaches were evaluated.**

Standard definitions were developed for each habitat and various approaches were considered in terms of their ability to discern important boundary attributes across all regions of California. The workgroups evaluated tradeoffs associated with each mapping approach as well as the suitability of currently available imagery and elevation/topographic data (e.g., Light Detection and Ranging (LiDAR), DEMs derived from structure from motion). Each approach will likely leverage several different geospatial analyses, which are discussed in greater detail within the report.

Mapping approaches were evaluated based on their applicability/ability to discern key boundary attributes and the availability and applicability of major data types. Data derived from satellites, airplanes, Unoccupied Aircraft Systems (UAS), and other field-based sensors and surveys were considered. Each mapping approach considered provides a different level of accuracy and detail. Some types of change may be possible to detect from more coarse mapping of habitat, where others may only be detected through more detailed and higher resolution data and mapping.

## Key Findings for Decision-Makers

The choice of mapping approach and associated data types will depend on the spatial and temporal resolution of the desired change/trend assessment (i.e., mapping overall habitat annually versus detailed mapping that captures sub-habitats and seasonal dynamics). Ultimate choices will also be influenced by the resources available to obtain necessary data and process/analyze the data to produce maps. Determining, at the outset, the output/map specifications that are needed to answer the driving question will set up a long-term mapping process that is robust to changes over time in data and analysis methods. Key findings include:

***Mapping approaches***

- California's coastal habitats, except for eelgrass, can be mapped using satellite-based, plane-based, or a combination of the two approaches.
- Plane-based approaches can support more detailed mapping and classification and can be used to more accurately quantify extent and distribution. Plane-based approaches also support assessment of changes due to restoration, erosion, and accretion of habitats. Current efforts in California that track acreage over time typically leverage plane-based approaches.
- The ideal approach will likely leverage a combination of both plane and satellite imagery to capture the level of classification and spatial detail needed to address mapping and monitoring questions.
- For eelgrass, site-based (e.g., UAS) remote sensing combined with field surveys is likely necessary to capture the patchy distribution in both intertidal and subtidal habitats. For more subtidal habitat components and within intertidal environments surveyed at high tide, side scan sonar with integrated GPS tracking deployed from piloted vessels can be used.

***Capturing habitat boundaries***

- Moderate resolution satellite data (i.e., Sentinel-2) cannot reliably capture habitat features smaller than $5m^2$ or narrower than ~5-10m and therefore cannot be used as a standalone option to address the goals outlined in this report. Higher resolution satellite imagery could discriminate smaller scale (1-2m) habitat features/boundaries.
- Boundaries based on vegetation can be characterized by spectral imagery or using LiDAR data. Elevation based features are best categorized by LiDAR data, but limited information can be inferred by aerial imagery.

***Implementation***

- In general, satellite data are more readily available for the full extent of habitats at a higher temporal resolution, with notable exceptions of public plane-based imagery collections (e.g., NAIP), but can have lower spatial resolution than plane and UAS data. In contrast, bespoke plane-based data can be costlier, but provides a higher spatial resolution and can allow for more customization.

- Development and support of the necessary data infrastructure to manage mapping products and analyses over the long-term is critical.
- Continued engagement of an Advisory Group similar to the expert panels used to develop this whitepaper will also be helpful to guide and interpret monitoring and mapping efforts and apply them to decision-making over the long term.

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**Table 1: Table of acronym definitions used in the whitepaper.**
*For definitions of mapping terms, refer to Appendix B.*

| Acronym | Definition |
|---|---|
| AOI | Area of Interest |
| BCDC | San Francisco Bay Conservation and Development Commission |
| BHM/BHM2020 | Baylands Habitat Map 2020 |
| BLM | Bureau of Land Management |
| CARB | California Air Resources Board |
| CARI | California Aquatic Resource Inventory |
| C-CAP | Coastal Change Analysis Program |
| CCC | California Coastal Commission |
| CDFW | California Department of Fish and Wildlife |
| CMECS | Coastal and Marine Ecological Classification Standard |
| CNRA | California Natural Resources Agency |
| CoSMoS-COAST | USGS Coastal Storm Modeling System for predicting large-scale coastal change; usgs.gov/centers/pcmsc/science/cosmos-coast |
| CRAM | California Rapid Assessment Method; cramwetlands.org |
| CSDA | Commercial Satellite Data Acquisition |
| CSP | California State Parks |
| DEA | Digital Earth Australia |
| DEM | Digital Elevation Model |
| EFH | Essential Fish Habitat |
| ESI | Environmental Sensitivity Index |
| FAA | Federal Aviation Administration |
| GIS | Geographic Information Systems |
| GNSS | Global Navigation Satellite System |
| GPS | Global Positioning System |
| HAT | Highest Astronomical Tide |
| LiDAR | Light Detection and Ranging |
| LLW | Lower Low Water |
| MHW | Mean High Water |
| MLLW | Mean Lower Low Water |
| MPA | Marine Protected Area |
| NAIP | National Agriculture Imagery Program |
| NOAA | National Oceanic and Atmospheric Administration |
| NPS | National Park Service |

| Acronym | Definition |
|---|---|
| NTRIP | Networked Transport of RTCM via Internet Protocol. A protocol used for streaming corrections over the Internet from a base station to a rover to achieve cm-level accuracy; https://support.pix4d.com/hc/en-us/articles/4633640503709 |
| NWI | National Wetland Inventory |
| OBIA | Object-Based Image Analysis |
| OPC | Ocean Protection Council |
| PCA | Principal Components Analysis |
| PEMP | Pacific Marine and Estuarine Fish Habitat Partnership |
| SAV | Submerged Aquatic Vegetation |
| SCC | California State Coastal Conservancy |
| SCCWRP | Southern California Coastal Water Research Project; sccwrp.org |
| SFEI | San Francisco Estuary Institute; sfei.org |
| SfM | Structure from motion |
| SLR | Sea level rise |
| sUAS | Small Unoccupied Aerial Systems |
| UAS | Unoccupied Aerial Systems |
| USACE | US Army Corps of Engineers |
| USEPA | US Environmental Protection Agency |
| USFWS | US Fish and Wildlife Service |
| USGS | US Geological Survey |
| Water Boards | California Regional Water Quality Control Boards |
| WRMP | San Francisco Estuary Wetlands Regional Monitoring Program |

# Background and Overview

## Introduction and Objectives

California's coastal habitats provide critical functions for habitat and species, water quality improvement, climate change resiliency, and carbon storage, among other functions. Changes in the distribution and abundance of these habitats are driven by numerous factors, including but not limited to climate change, development, extreme weather events, and management and restoration actions. Managing these resources requires up-to-date and comprehensive mapping of their extent and distribution, both current and as they change over time. These maps are important for tracking temporal trends, prioritizing management actions, and serving as inputs to models and assessment tools. To date, mapping of different coastal habitats in California has occurred periodically and often in a piecemeal manner. This lack of comprehensive statewide coverage, lack of consistent methodology, and asynchronous temporal collection makes it difficult to achieve the coastal habitat conservation and restoration objectives of California's resource managers.

In response to this need, OPC convened a series of expert workgroups to provide input on mapping approaches and data sources for four priority coastal habitats; coastal wetlands, beaches and dunes, eelgrass, and rocky intertidal. The information synthesized by these workgroups will help inform future mapping efforts that will have 1) statewide applicability; 2) the ability to track past and future temporal trends/changes in area; 3) practicality for routine application at regular intervals; and 4) the ability to be conducted in a semi-automated manner. While it is also possible to track changes in habitat health and condition, effects of restoration activities, and impacts of general land use, this whitepaper focuses on tracking the shifts in habitat acreage (https://www.californianature.ca.gov).

This whitepaper provides an overview of mapping approaches and data components applicable to all the priority habitats and then outlines specific details and considerations for each habitat type. Each mapping approach provides a different level of accuracy and detail. Some types of habitat change may be detected from more coarse mapping, where others may only be detected through more detailed and higher resolution data and mapping. These differences and the tradeoffs among the mapping approaches are described below.

The implementation of mapping approaches described in this whitepaper would require the continued engagement of an Advisory Group, similar to the expert panels used to develop this whitepaper, to guide and interpret monitoring and mapping efforts and apply them to decision-making.

## Agency Needs

Through legislation, executive order, and other administration policy priorities, California has set ambitious targets for conservation, enhancement, and restoration of its coastal habitats. 30x30, OPC's Strategic Plan, and the State's Nature-Based Solutions Climate Targets all call for action to increase the extent and resilience to climate change of California's coastal ecosystems. State agencies, including OPC, CARB, and CNRA, have been tasked with developing and implementing programs to track progress toward these goals in a quantitative, ecologically robust, and repeatable way. A comprehensive coastal mapping program would meet other agency needs as well, such as project performance tracking, permitting support, mitigation monitoring, and habitat tracking for sensitive species management.

This whitepaper was produced to inform development of programs for tracking habitat extent and change over time. There is a need to quantify these ongoing changes in habitat extent as they are continuously impacted by various natural and anthropogenic processes. The magnitude of these changes will vary over time and across habitat types and specific locations within California, showing temporal gains and losses across different parts of the State's coastline. This will impact the State's ability to manage and plan activities to support conservation and restoration of these habitats. In addition to this use, it is anticipated that agencies could use mapping products to support permit evaluation and mitigation/restoration performance assessment, map potential sensitive species habitats, and support park and reserve management Various agencies may utilize the maps eventually generated from this effort in different ways (see Appendix C). Furthermore, these datasets and maps of coastal habitats should be made publicly available for researchers and the public.

# Overview of Habitat Mapping and Tracking Change

Geospatial habitat maps are created by delineating and classifying habitat areas based on their spatial location. This can involve ground-based field work, where habitat areas are surveyed and recorded using GPS. For larger spatial extents, such as statewide mapping of coastal habitats, remote sensing data may be more appropriate to delineate and classify habitat areas. Remote sensing data can originate from a variety of sources, including satellite imagery, plane-based LiDAR, UAS (drones), kayak-based sonar, or handheld cameras, among others. Once remotely sensed data are collected for the area of interest to map, they are used to delineate units of analysis, which are then classified according to standard definitions for each habitat type. The remote sensing data should provide information relevant to aspects of each habitat definition.

Following the mapping process, verification data and ground-truthing from field visits or higher-resolution remote sensing data can be utilized to conduct accuracy assessments, ensuring that the mapping products meet established accuracy standards. Field visits and/or higher-resolution remote sensing data can be especially important for tracking the relatively subtle changes in the extent and distribution of habitats driven by climate change. Field-level monitoring procedures established by members of the California Wetland Monitoring Workgroup and California Estuary Monitoring Workgroup are in many cases designed to be utilized together with remote sensing data to effectively track changes in wetland condition, abundance, and distribution.

To track change over time, habitat maps would ideally be updated annually. For some habitats seasonal updates can be helpful in discerning long-term vs. short-term changes, and maps should be revised following regional stochastic events, such as large floods or storm surges. When selecting a method to map habitats and track changes over time, several key factors should be considered. These include: the selection of appropriate geospatial analysis methods for habitat mapping; the availability and suitability of data types over time; the establishment of consistent well-defined habitat boundaries and habitat definitions/classification systems; and a thorough understanding of the tradeoffs associated with different mapping approaches to ensure alignment with the mapping objectives. Each of these factors is described in more detail in the following sections.

# Types of Geospatial Analysis for Habitat Mapping

Several analyses can be combined to make a geospatial map, including traditional manual heads-up digitizing and more recent and automated image analysis and classification approaches. Methods can be applied to a wide range of different data sources as well. Available data and the recommended GIS habitat mapping analyses will change over time as technology evolves, so the determination of appropriate mapping approaches should be reassessed periodically. Recent advancements in deep learning, object detection, semantic classification, and instance segmentation present new opportunities to map habitats more quickly, consistently, and in a repeatable way. This is critical for supporting goals of tracking change over time of coastal habitats. Present-day relevant geospatial analyses are summarized below, along with general strengths and weaknesses.

A. **Heads-up digitizing** involves manually outlining the attribution of polygons from imagery, such as satellite or aerial photographs.
   - ***Strengths*****:** Can be detailed and accurate, can account for location-specific differences.
   - ***Weaknesses*****:** A slow manual process which may make it impractical for statewide application, harder to consistently apply, and errors can occur based on individual mappers.

B. **Object-based image analysis (OBIA)** is an automated approach that uses segmentation algorithms to group areas of similar values/signatures into discrete objects (i.e. polygons) based on spatial context (feature shape, size, relationship to adjacent objects, etc.) across an entire area of interest. In this mapping context OBIA refers to more than just identifying instances of objects, but rather delineating boundaries of class/habitat types.
   - ***Strengths*****:** Allows opportunities to incorporate multiple ancillary layers that may not align to a specific pixel scale, can incorporate multiple scales of analysis into one mapping product, can reduce noise, and make it easier to get to usable vector outputs.
   - ***Weaknesses*****:** Can be computationally intensive, can require extensive parameter tuning, and high density of data input.

C. **Instance segmentation** takes OBIA a step further where it generates specific pixel by pixel boundaries for each individual "object" within the same class.
   - ***Strengths*****:** Useful when needing to count individual instances of habitat (e.g., counting number of beaches).
   - ***Weaknesses*****:** May not be necessary or helpful to reach the goal of tracking acreage of a habitat type.

D. **Pixel-based image analysis** is similar to OBIA but is based on individual pixels versus discrete objects.
   - ***Strengths*****:** Typically, faster and simpler to implement than OBIA and works well in large homogeneous and less complex settings and for less complex classification goals.
   - ***Weaknesses*****:** Does not leverage contextual information of the landscape nor information related to feature shape or spatial context.

E. **Spectral unmixing** is used to separate mixed pixel spectra in a hyper spectral image into their individual components and their factional abundances.
   - ***Strengths*****:** Can help address issues of mismatches of scale/horizontal resolution between imagery and features/classes of interest. It can help to map very specific features and their prevalence within a mixed pixel.
   - ***Weaknesses*****:** Maximum use only when using hyper spectral imagery, which is not currently available on the scale of the full California coast, but statewide efforts such as the California Satellite Methane Project data could be leveraged. Hyper spectral imagery does not seem to be necessary to map the coastal habitats of interest as currently defined. If the goal is to delineate the boundaries of a habitat, this approach does not help improve the actual resolution of the delineation of features.

F. **Machine learning/Deep learning classification** uses algorithms (e.g. random forests and support vector machines) to analyze images and automatically classify habitats based on image attributes. Deep learning is a subset of machine learning which outpaces more traditional machine learning when used with "big data". Deep learning utilizes neural networks with multiple layers to analyze complex patterns to extract more nuanced information and leverages optimization to minimize errors. Both Machine learning and Deep learning fall under the term of artificial intelligence (AI), but do not necessarily incorporate large language models which are often currently being referred to when the term AI is colloquially used.
   - ***Strengths*:** Does not require a strong understanding of the fundamental differences among classes, works particularly well where the data are complex and there are subtle variations that differentiate between classes, is easy to apply if high training data exists across habitat variability, and can be scaled easily across large areas as long as training data covers variability across areas of interest.
   - ***Weaknesses****:* Requires high-quality validation (training and testing) data that cover full variation across the areas of interest, or erroneous results may occur.

G. **Rule-based classification** is similar to machine learning classifications but uses a set of predefined rules based on characteristics like vegetation type, topography, and spectral values as opposed to an algorithm.
   - ***Strengths*:** Is more easily explained and understandable to an audience and provides better transparency, often requires less processing time and resources than machine learning classification approaches.
   - ***Weaknesses*:** Does not work well where boundaries are less well understood, or data is unavailable to support definition boundaries.

H. **Semantic classification** provides a more nuanced approach to classification than simply assigning classes pixel by pixel. It uses the larger contextual information of objects and their surroundings, or scene, and their spatial relationships to improve classification. Instance segmentation and OBIA are often involved in this classification approach.
   - ***Strengths*:** The context of objects in space provides significant information beyond the spectral or elevational value of a pixel or point considered in isolation. This can lead to more accurate and meaningful classifications of a landscape. The coastal habitats of interest also often occur adjacent to one another which lends their mapping to this type of approach.
   - ***Weaknesses*:** Processing can be more involved and requires advanced GIS specialists.

These different categories of analyses are not mutually exclusive. Instead, more than one of these analyses can be, and often are used, in a single mapping approach. For example, within a single mapping effort/approach, an OBIA could be paired with a rule-based classification for most habitat map classes, while machine learning classification could be later used to resolve more challenging mapping needs, such as distinguishing habitat classes with subtle boundaries that shift over space and time (e.g., Coastal Wetland versus Beach). Manual refinement of the data to address data artifacts or limitations of the automated portions of an approach may occur as a final step.

## Geospatial Analysis to Assess Relative Tidal Elevations

In addition to the generalized analysis types described above, other more specific geospatial analyses and models that exist can be used in habitat mapping. By combining updated tidal models (based on tidal datums recalculated on a rolling basis) and updated LiDAR allows for mapping of relative tidal elevations which can be used to detect the extent of current and potential tidal influence (e.g., fully tidal wetlands, muted tidal wetlands, and nontidal former tidal wetlands behind barriers). An example of this is Pacific Marine and Estuarine Fish Habitat Partnership's (PMEP) Coastal and Marine Ecological Classification Standard (CMECs) map of Current and Historical Estuary Extent (link to maps here).

Another such analysis involves integrating tidal modelling with earth observation data to derive the extent and elevation of the exposed intertidal zone. Traditionally, tidal models are used in a tool, such as NOAA's VDatum (vdatum.noaa.gov), to create contours on an existing Digital Elevation Model (DEM) that represent specific tidal stage extents on that DEM. However, it is also possible to pair tidal models with imagery to be able to identify and attribute the tidal height when that imagery was acquired. Using a time-series of images acquired at different tidal stages and ordered based on tidal height, it is then possible to determine for each pixel where the time-series transitions from wet to dry. This enables the elevation for that pixel to be determined based on the attributed tidal model height to create a full DEM for the exposed intertidal zone. This type of analysis has been explored and developed by Geoscience Australia (see DEA Intertidal product suite). Through collaboration between Geoscience Australia, SFEI, and others, this method is currently being applied in California to supplement existing tidal wetland mapping efforts.

# Potential Data Types

The geospatial analyses described in the previous section can accommodate different and multiple data types. The selection of mapping methods depends in large part on how well available data sources align with the required mapping specifications for the habitat of interest. Various types of remote sensing and locally collected georeferenced data are available, with spectral imagery and terrain elevation and topography data being some of the most useful for coastal habitat mapping.

Examples of data types considered in this whitepaper include plane-based multispectral imagery such as orthomosaics from National Agriculture Imagery Program (NAIP), plane-based LiDAR collected under USGS's 3-Dimensional Elevation Program (3DEP), satellite-based Sentinel 2 (public) and higher resolution (private) multispectral orthoimagery, bespoke small unoccupied aerial systems (sUAS) imagery, and bespoke LiDAR data.

**Spectral imagery** typically comes in the form of orthoimagery, although oblique imagery can also be useful. A few examples of spectral imagery include Landsat satellite-based imagery, NAIP plane-based imagery, and bespoke sUAS collected imagery. Spectral imagery can come in black and white (single band), true color (three band/RGB), or "multispectral" (four bands or more). Hyperspectral imagery (which can include 100s to 1000s of spectral bands) is not typically collected routinely, is cost prohibitive, but ongoing projects such as the California Satellite Methane Project data could be leveraged. Hyperspectral imagery may not be necessary for mapping these general of classes, however, could enable mapping of more specific habitat subclasses. Imagery can help differentiate habitats and landscape features that reflect different spectral bands, or "look" different. Imagery can be collected and used to derive structural/elevation data using photogrammetry, when there are multiple images of the same area/object that have been taken from different known locations. Imagery can also be leveraged to estimate intertidal elevations when the imagery collection timing metadata is paired with tidal models and assessments of inundation extent. Furthermore, information on inundation frequency or phenological patterns can be assessed when the temporal frequency is high enough to capture the pattern of interest. This can be summarized in several ways; one example is through a Principal Components Analysis.

**Terrain elevation and topography data** can be extremely useful for mapping habitats that are defined by their hydrologic connectivity and geomorphic structure. The USGS 3D Elevation program (3DEP) is a good example of a source of elevation data within the United States. Elevation data often comes in the form of Light Detection and Ranging (LiDAR) data, which is collected in a point cloud and then used to derive raster DEMs. This type of data can also be derived from traditional photogrammetry, which uses imagery of the same location taken from different perspectives to infer the three-dimensional structure of the landscape. Alternatively, elevation can be derived using structure from motion (SfM) software that uses photogrammetric analysis to derive elevations from photos taken at different locations.

Both spectral imagery and terrain elevation and topography data can be collected on different types of platforms, such as satellites, occupied aircraft (planes and helicopters), and even sUAS, commonly referred to as drones. Typically, sensors placed on satellites have lower resolution (10-30m/pixel) than those placed on occupied aircraft (1-5m/pixel), and occupied aircraft sensors typically have lower resolution than sensors placed on sUAS (<1m/pixel). Ground based platforms like terrestrial laser scanning can provide resolution on the scale of centimeters, useful for mapping microtopography.

**Locally collected georeferenced data** are produced by tracing habitat boundaries by foot, boat, or by SCUBA divers and integrating individual traces into two dimensional polygons. Field data can be collected with GPS coordinates with specified spatial resolutions and are useful for training, validation, and supporting other types of data inputs. Subtidal, locally collected data are typically collected with handheld cameras, drop cameras, or towed cameras, and postprocessing of the data includes annotation, mosaicking, or structure from motion. Subtidal habitats can also be mapped using side-scan or multi-beam sonar arrays, another type of remote sensing sensor, which typically has internal GPS transponders. The reflectance information gathered by the sonar array can then be georeferenced as it is processed. Locally collected georeferenced data are critical validation data for mapping subtidal habitats, such as eelgrass. GPS data are most commonly acquired using handheld or platform-mounted receivers that have various degrees of geolocation accuracy. Commercial-grade receivers (i.e., navigational GPS) and cell phones offer 3 – 5m accuracy, while survey-grade receivers (i.e., mobile Real-Time Kinematic (RTK) GPS, Trimble RTX), can achieve sub-cm accuracy with NTRIP (Networked Transport of RTCM via Internet Protocol). NTRIP is an application-level protocol that supports streaming Global Navigation Satellite System (GNSS) correction data over the internet to calculate its position with high accuracy by enabling RTK survey without needing to establish a direct radio link between the base station and the rover, and post-processing corrections. For tracking change over time, high accuracy georeferencing is important in order to accurately align datasets collected at different times.

**Tide models and environmental sampling/measurements,** such as tide gauges, can also be relevant for coastal habitat mapping. Published tidal datums are usually calculated across a 19-year tidal epoch and are not updated very frequently. Thus, field data from tide gauges are necessary to track water level changes on a time scale that OPC and other managers are interested in. Tide gauge data can be used to calculate current local values for tidal models which can then be used to inform relative tidal elevation (e.g., using VDatum software).

As all types of data becomes more widely collected and at higher resolutions (temporal, spatial and/or spectral), more detailed and accurate mapping can be accomplished, but will require additional computational resources, storage for larger datasets, etc. Matching the data resolution and characteristics with what is required to produce a product that matches the specifications necessary to address the question of interest is important to be most efficient with data collection, processing, storage and maintenance costs.

## Factors for Consideration

When selecting suitable data inputs for a mapping effort, there are several factors to consider: frequency of collection (e.g., return rate), seasonality of collection, spatial (horizontal and vertical) resolution, spectral resolution, cost of data acquisition, spatial extent easily covered by the sensor platform, availability of ongoing funding for future collections, ability to share the data publicly, and many more. It is necessary to utilize data that matches the needs and goals of the question being asked of the map (e.g., spatial scale, spectral signature, return time, extent, etc.). Determining at the outset the output/map specifications that are needed to answer the driving question will set up a long-term mapping process that is robust to changes over time in data and analysis methods. As technology advances, the methods and data will—and probably should— change, and consistency in mapping specifications will allow for comparisons to past maps and address questions of change over time. Input data is expected to become higher resolution, cheaper to collect, and generally more widely available in the future. We can also expect processing infrastructure hardware and software to become more adept at handling larger datasets.

Irrespective of data sources and mapping methodology, regular ground truthing, training and/or validation elements are essential for reliable mapping. The higher the uncertainty in distinguishing the habitat boundary, the more ground truthing should be required to ensure accuracy. Furthermore, at the outset of any mapping effort, including remotely sensed method best practices would suggest that remotes sensing data and on the ground measurements should be calibrated together.

# Habitat Definitions

To ensure that detected changes reflect actual landscape alterations and not inconsistencies in habitat class definitions, it is crucial to maintain established definitions for habitat classes across mapping efforts. Maintaining consistent habitat class definitions enables the comparison between habitat maps, even as data sources change over time -- provided the data inputs support the characteristics specified in the definitions. This section describes the definitions for the four targeted coastal habitats (Coastal Wetlands, Beaches and Dunes, Eelgrass, and Rocky Intertidal; Figure 1) and provides information on demarcating habitat boundaries. Definitions can be applied consistently throughout the state.

However, boundary limits may vary by region. Regionally specific boundary attributes are discussed in each habitat section below.

In California's dynamic coastal environments, the four target habitats often occur adjacent to and intermixed with one another. Dunes often are highest in relative tidal elevation and can be in front of and connected to coastal wetlands. Beaches are typically seaward of dunes but can exist without adjacent dunes. The relative tidal elevations of rocky intertidal habitat overlap with those of beaches, and intermixing of the two habitat types is common. Eelgrass can be immediately adjacent to beaches or may occupy intertidal areas (particularly in cooler climates) and typically extends out into subtidal soft sediments.

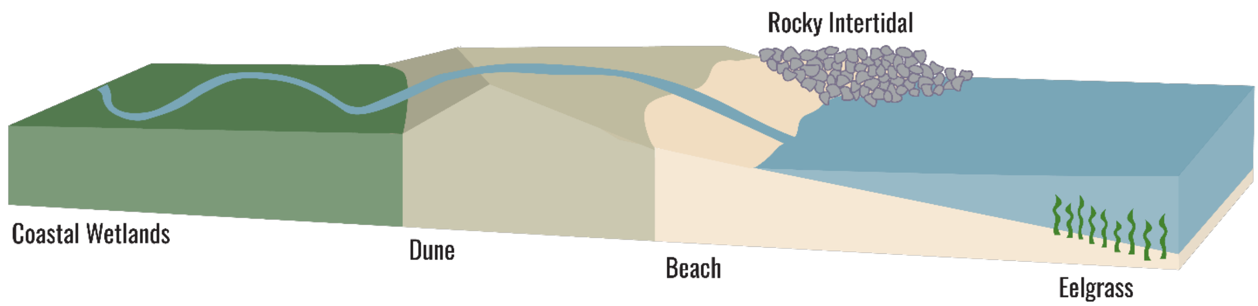


**Figure 1: Infographic depicting the connectivity of coastal habitats.**

## Habitat: Coastal Wetlands

### Coastal Wetlands: Habitat Definition

There are many definitions of wetlands, but generally, wetlands are land that is covered or saturated by water for all or portions of a year. According to the California state definition from the State Water Resource Control Board (SWRCB), wetlands are 1) saturated by groundwater or inundated by shallow surface water and/or groundwater for duration sufficient to cause anaerobic conditions within the upper substrate; 2) exhibit hydric substrate conditions indicative of such hydrology; and 3) either lack vegetation or have vegetation dominated by hydrophytes. Note that not all of these characteristics of wetlands can be detected by remote sensing at all scales, thus sometimes simpler functional definitions must be used for a mapping effort.

Coastal wetlands are influenced by coastal processes including tides, waves, salt spray, and fog. Types of coastal wetlands that are common in California include wetlands with and without tidal connections (Figure 2), bar-built estuaries (Figure 3), and stream and river mouths (among others; Figure 4). See Appendix D for definitions of various wetland types.

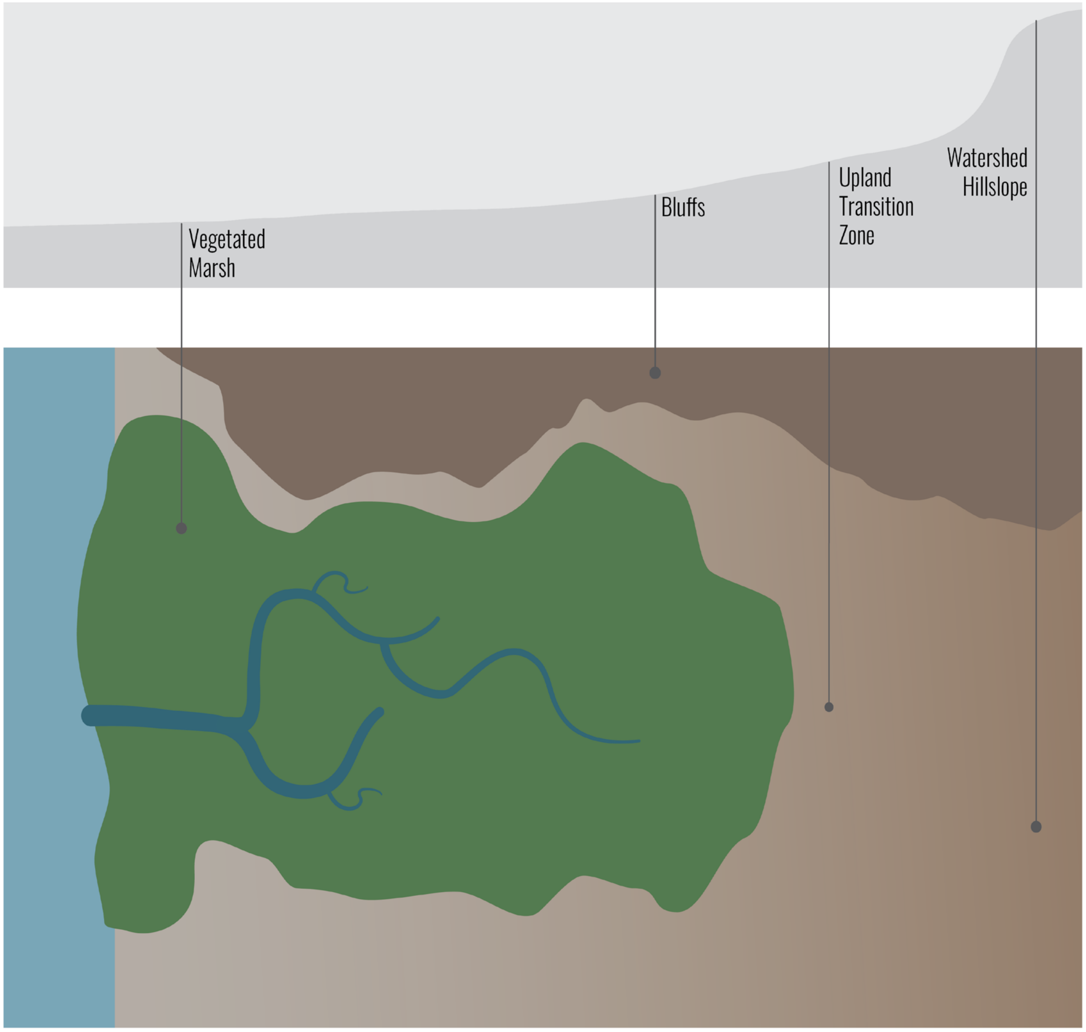

**Figure 2: Infographic of a tidal marsh coastal wetland.**

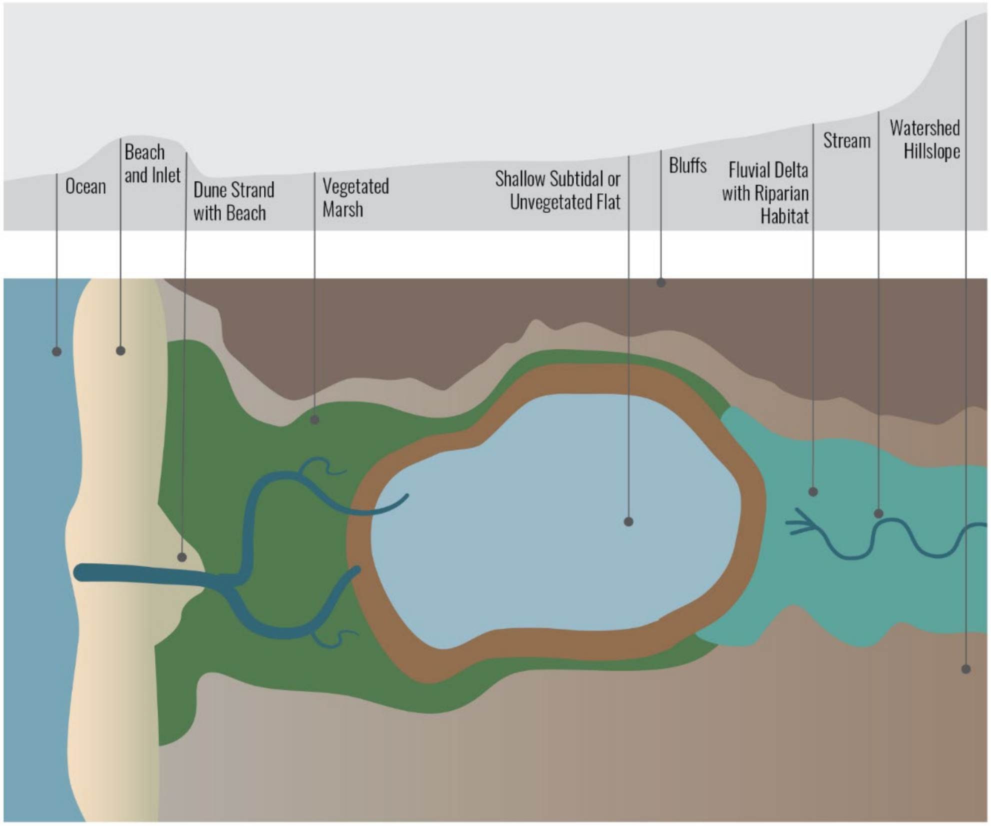


**Figure 3: Infographic of a bar-built estuary coastal wetland.**

Determining how to categorize coastal wetlands may be dependent on the tradeoffs between higher mapping costs and the additional functionality and utility of mapping that is achieved with greater classification specificity, in addition to management needs. The OPC Habitat Mapping Expert Panel recommends narrowing this mapping effort to the combined current and historical extent of West Coast estuaries (e.g., PMEP, CMECs datasets), which covers the wetland types that are the primary conservation and management focus of OPC and its partners: wetlands with fully tidal connections, wetlands with limited to no tidal connections (within areas that were historically tidally connected), and bar-built estuaries.

The OPC Habitat Mapping Expert Panel also recommends the use of a hierarchical classification system that allows mapping of more detailed habitat features while also enabling comparisons and change detection assessments at higher, more general, classification levels. This is important, for example, because accuracy levels are expected to be higher at more general classification levels. The Baylands Habitat Map (SFEI, 2025) for the San Francisco Estuary Wetlands Regional Monitoring Program has taken this approach (Appendix E). Another example is the Estuarine Marine Protected Area (EMPA) program's classification system and the Coastal and Marine Ecological Classification Standard (CMECs) (Federal Geographic Data Committee, 2012).

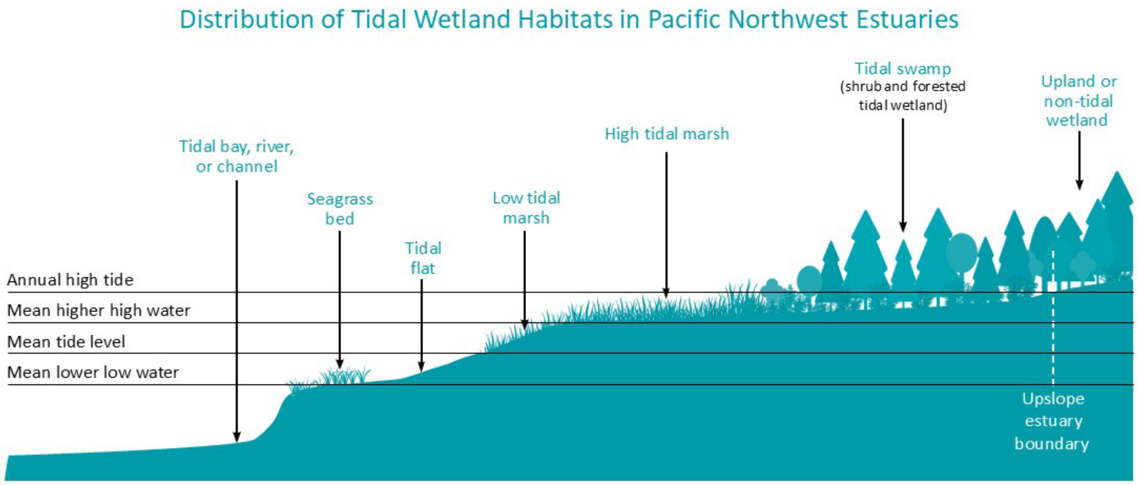


**Figure 4: Schematic diagram of the distribution of tidal wetland habitats relative to elevation and tides in the Pacific Northwest Estuaries.**
*Diagram not to scale. Original diagram by Laura S. Brophy; graphical assistance from Bonneville Environmental Foundation. Image credit: Laura S. Brophy, CC BY-SA 4.0. Note that this diagram does not include bar-built or lagoon coastal wetlands.*

## Coastal Wetlands: Boundary Demarcation and Mapping

Together, historical bayland/estuary boundaries based on DEMs, U.S. Coast Survey "T-sheets" (https://shoreline.noaa.gov/t-sheets.html), and modeled tidal influence are a good approach for delineating the Area of Interest (AOI) for coastal wetland mapping (Figure 4). This should include the Sacramento-San Joaquin River Delta ("the Delta") as it is tidally influenced. Bar-built estuaries are an exception to this approach based on relative tidal elevation; however, their locations are well established so they may be manually added to the AOI (Heady et al. 2015, O'Connor and Clark 2019).

## Coastal Wetlands: Key Considerations/Needs

This section highlights the unique aspects of coastal wetlands that inform any evaluation of mapping approaches, including:

- ***Sub-habitats:*** There are several sub-habitat types that could be further specified and broken out under "Coastal Wetland." These include, but are not limited to, marsh plain (high and low), tidal scrub-shrub, tidal forest, channel, panne/pond, mudflat, muted/managed marsh, etc. The OPC Expert Mapping Panel recommends organizing habitat types in a hierarchical framework so that they can be compared using classifications with varying levels of detail. Some mapping approaches may be able to support higher levels of complexity/detail (number of classes) regarding classification than others.

- ***Mapping interval and temporal frequency:*** California has a Mediterranean climate that experiences significant seasonal swings in major coastal processes such as watershed runoff, wave action, and sediment transport. In bar-built estuaries, these processes can drive significant *intra-annual* shifts (between seasons, weeks, or even days) in the extents and distributions of habitats and sub-habitats (marsh plain, channel/open water, mudflat/sandflat, etc.) that can in some cases exceed the time-averaged shifts in the extents and distributions of habitats on an *inter-annual* (between years) basis. This variability across temporal scales makes it particularly challenging in bar-built estuarine wetland habitats to detect meaningful change over short (generally less than 3-5 years) time scales and makes it impossible to identify a data collection time window (e.g. June-July) within which habitat extents can be consistently compared between years. In contrast, fully tidal wetlands (and in most cases, wetlands with limited to no tidal connection) tend to be relatively less dynamic on an intra-annual basis, and as such are better suited to repeated mapping and change detection techniques. For example, see the wetland mapping efforts of the San Francisco Estuary Wetlands Regional Monitoring Program (WRMP) (https://www.wrmp.org/).

Repeated, inclusive mapping and change detection of California coastal wetland habitats must consider these dynamics, and strike a balance between frequency, accuracy, uncertainty, and costs. Repeated mapping on an interval ranging from one to five years will likely be suitable for statewide mapping of coastal wetland habitats. It is likely that meaningful mapping of and change detection in bar-built estuarine wetlands will require methods that supplement those that are effective for tidal and limited/non-tidal coastal wetlands, perhaps through an approach that can be implemented more frequently, such as leveraging publicly available satellite remote sensing that has higher temporal resolution, but lower spatial resolution. Using this approach mapping would not require mapping at a higher frequency, but could use a past time series of data to characterize the wetland type or subtype based on its inundation and tidal connectivity patterns.

- ***Spatial precision:*** If possible, smaller features such as tidal channels and tidal pannes/ponds could be mapped at a 5$m^2$ minimum mapping unit. A minimum mapping unit is the size of the smallest feature that would be mapped. This has been achieved for California's largest estuary, the San Francisco Estuary, using 0.6m resolution imagery and other data inputs in the Baylands Habitat Map. Using more coarse scales to assess the extent of coastal wetlands is possible, but can make it harder to account for smaller coastal wetland habitat features and track incremental change over time.

- ***Spatial discrimination:*** The ability to distinguish between vegetation type, geomorphic structure, and tidal connectivity are the primary drivers for selecting suitable mapping approach and input data for mapping coastal wetlands.

## Habitat: Beaches and Dunes

### Beaches and Dunes: Habitat Definition

*Coastal dunes* are dynamic landforms that include hills or ridges of sand that form inland from beaches (Figure 5). They are a natural part of the sandy shoreline, created by complex interacting abiotic and biotic processes, including wind and waves moving sand to and from the beach (Figure 5). Sediment supply, wind, and vegetation are the three principal boundary conditions for coastal dune system formation and development (Gao and Konlechner 2020). Dunes may be vegetated or unvegetated and are often highly dynamic over time. Vegetation is part of a dynamic feedback loop with sand accretion, allowing for the establishment of sand hummocks over time.

Mapping efforts should focus on naturally formed and replenished systems (natural processes) and not include anthropogenic dunes (e.g., temporary anthropogenic features such as winter berms are not classified as dunes). There are many types of dunes that can be classified based on their formation processes, positions, and permanence. Coastal dune geomorphology, especially foredune establishment and evolution, is also dependent on the surfzone-beach-dune interactions, a model originally formulated by Hesp (1982). Foredunes (or 'frontal dunes') are shore-parallel landforms that are typically the foremost (oceanward) ridges or portions of dunes along the backshore of the beach (Martínez and Psuty 2004, Hesp and Walker 2021). They are formed through aeolian sand deposition (Hesp 2024) and are generally vegetated with plants tolerant of salt spray, winds, and sand burial (Martínez and Psuty 2004). All naturally occurring dunes should be included, although classification is beyond the scope of this effort.

*Beaches* are the highly dynamic areas of typically open sandy substrate extending from the most seaward extent of the intertidal zone and a portion of the subtidal zone (e.g., mean low water; MLW) inland to a transitional habitat or hard boundary. They may support vegetation in the coastal strand zone, and often accumulate wrack or kelp deposition, which is important to beach ecology (Figure 5). Beaches have been heavily impacted and altered through anthropogenic disturbances such as nourishment (beach filling), grooming (raking), or the addition of hard structures such as groins, jetties, and sea walls (armoring).

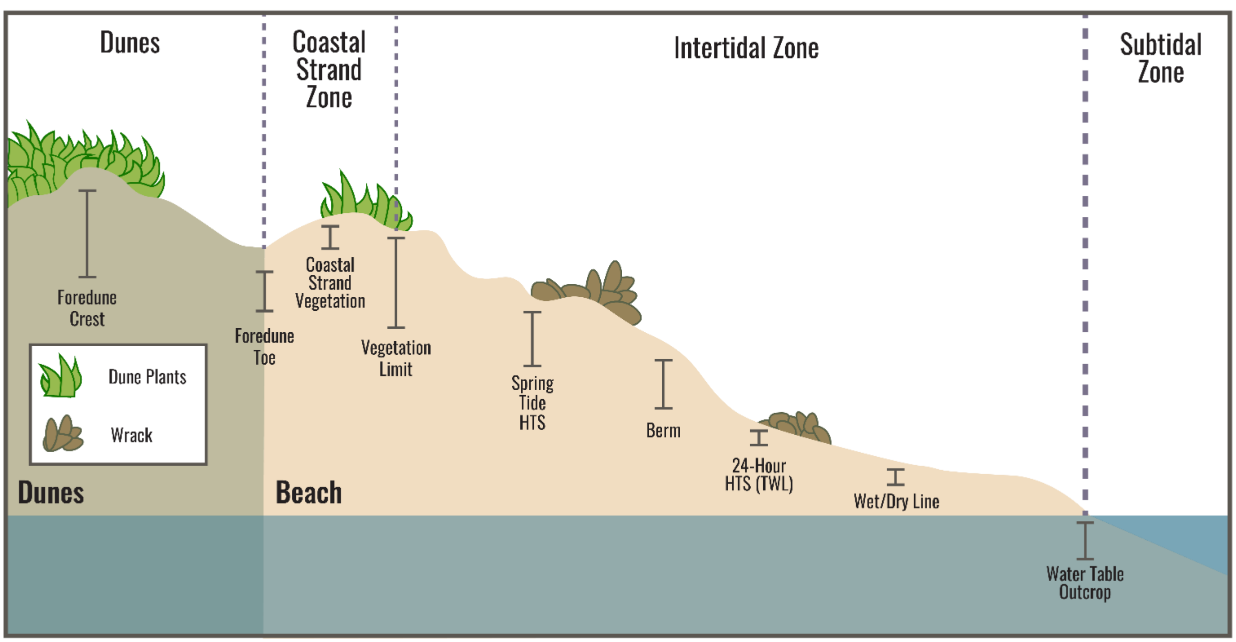


**Figure 5: Beaches and dunes schematic.**
*The dune habitat is delineated by the left-most dotted line. The beach is both coastal strand and intertidal. Graphic modified from Sarah Sampson's version.*

## Beaches and Dunes: Boundary Demarcation and Mapping

Ideally to capture the seasonal fluctuations of dunes and beaches, they would need to be mapped as least annually, and twice each year if there is a desire to capture the variability of the dune toe or vegetation boundary, to correspond with the maximum expected beach width (fall) and the maximum expected vegetated area (spring). Potential index frequencies could be in January-April to capture minimum beach width and July-October to capture maximum beach width. The precise index frequency may vary by region since seasonality in beach width is not consistent statewide (Warrick et al. 2025). Mapping should occur during a low (neap) tide; the precise tide range will likely be variable regionally, but efforts should be made to target a consistent tide range across mapping events. This can potentially be supplemented with event-triggered mapping following large storm events. However, the magnitude of storm events that would trigger event-based mapping should be defined up front.

> ***Dune:*** The dune toe can be based primarily on the downward inflection in slope and can be supported by the beginning of the vegetation line when it corresponds to the location of the oceanward dune toe. These two often will not co-occur depending on the dune state (erosional versus accretional). Mapping approaches should account for these potential differences. The inland limit can be defined by changes in slope and elevation (e.g., Patton et al. 2019), transition to climax plant communities (e.g., forest or shrub) or developed land cover (e.g., infrastructure or anthropogenically altered landscapes). A shift in substrate type can also be indicative of the dune boundary, although this may be difficult to demarcate, particularly in climbing dunes. Development of an elevation model (based on bare earth DEM) can be extremely helpful in delineating dune boundaries.
>
> ***Beach:*** Beach extents start at the mean lower low water mark (MLLW), which will likely require elevation data to accurately map. In practice, it is common to map the mean high water (MHW) based on image analysis and estimate the MLLW location using measured or modeled beach slope. The inland extent of the beach can be demarcated by either a dune toe or the end of sandy to cobbly substrate (i.e., where hardscape or vegetation begins or at an inflection point with adjacent habitat). Note that hard rocky substrate can seasonally function as a beach but would typically be included as part of rocky intertidal habitat.

Given the dynamic nature of dunes and beaches, it may be helpful to delineate boundaries relative to fixed georeferenced points so that changes in extent can be mapped relative to fixed points.

## Beaches and Dunes: Key Considerations/Needs

This section highlights the unique aspects of beaches and dunes that inform any evaluation of mapping approaches, including:

- ***Sub-habitats:*** There are a number of sub-habitats that could be identified but do not need to be distinguished when mapping overall extent. For dunes, these include incipient dunes, transitional dunes, and relic dunes. Dunes can include foredunes and backshore environments. Beaches can similarly vary based on their persistence (seasonality) and on the dominant substrate type (which may also vary seasonally).

- ***Mapping interval:*** Mapping should occur during periods of the year that capture the minimum and maximum extent of beach and dunes. Seasonality in beach width is not consistent statewide. Many regions have their annual minimum in the spring and maximum in the Fall, but the mapping interval may need to be adjusted based on the region of the state.

- ***Temporal frequency:*** To capture overall extent, dunes can be mapped annually. However, twice per year mapping is necessary to capture the dynamism of beach and dune habitats.

- ***Spatial precision:*** Demarcation of beaches requires mapping the shoreline (MHW) based on imagery (<3m/pixel resolution to discriminate) and estimating MLLW using beach slope. Detecting the dune toe requires elevation models with sub-meter accuracy.

- ***Spatial discrimination:*** The ability to discriminate vegetation, subtle changes in slope and elevation, and substrate type are key factors affecting the selection of mapping methods.

## Habitat: Eelgrass

### Eelgrass: Habitat Definition

Eelgrass (*Zostera* spp.) is a common type of seagrass or submerged aquatic vegetation (SAV) inhabiting the shallow soft sediments of California's open coast, as well as enclosed estuaries and embayments. Eelgrass forms contiguous beds or meadows that can stretch hundreds of meters across a seascape, as well as smaller, isolated or semi-isolated patches. Beds can expand by clonal somatic growth along the plant's rhizome or recruitment of new plants from seed dispersal. Eelgrass is a perennial plant that is relatively sensitive to light availability (i.e., water clarity and water depth), physical and chemical disturbance, water temperature, and salinity. The size and robustness of eelgrass beds can also be negatively impacted by chemical pollutants, disease, and invasive species (e.g., *Carcinus maenas*, *Z. japonica*). As such, the spatial scale of the habitat is temporally dynamic—expanding and contracting from year to year—but also potentially disappearing from established areas or reappearing in previously unvegetated sediments due to fluctuations in environmental conditions and anthropogenic influences. Across the length of California, eelgrass will grow in both intertidal and subtidal sediments (Figure 6), with the relative ratio of intertidal to subtidal increasing as one moves northward into cooler climates.

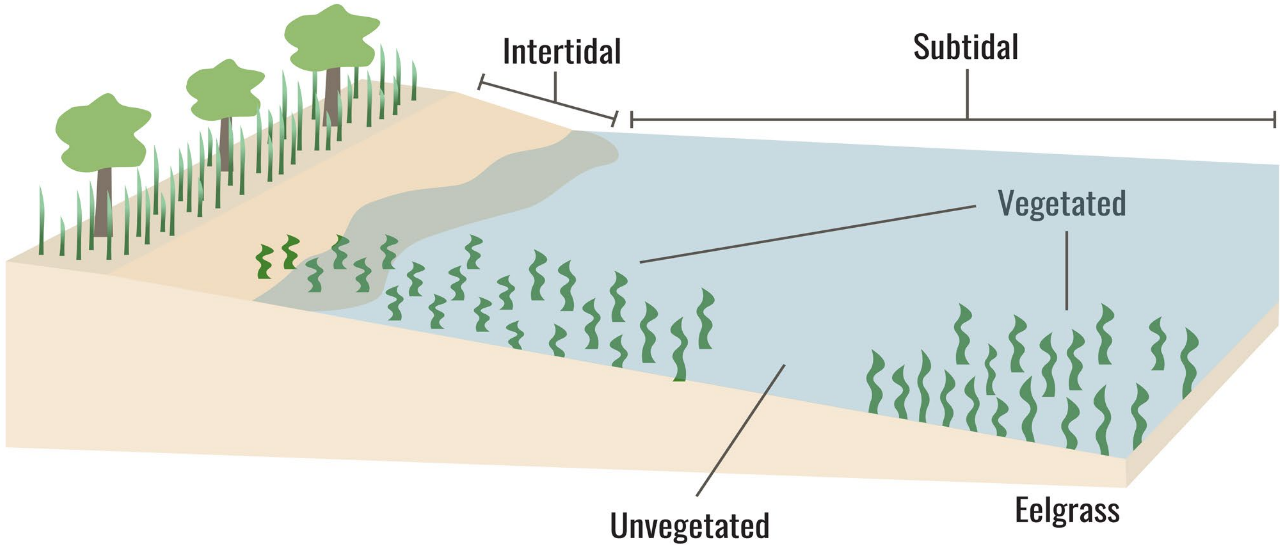


**Figure 6: Schematic of eelgrass habitat at low tide.**
*Illustrates subtidal and intertidal components of the bed, as well as the distinction between vegetated and unvegetated sediments. Graphic modified from Integration and Application Network (ian.umces.edu/media-library).*

## Eelgrass: Boundary Demarcation and Mapping

Mapping efforts for eelgrass need to include areas where 1) eelgrass has been previously detected (unless they are no longer suitable for eelgrass) and 2) previously unvegetated soft sediments that could reasonably support eelgrass beds to capture the window of potential habitat for ephemeral eelgrass. The upper (landward) limit of this window of potential habitat would be relative to MLLW at a given location. The lower (seaward) limit of the potential habitat window is, in a practical sense, generally a function of light penetration and therefore water depth and turbidity level. This depth point varies from region to region and oceanographic setting (Table 2). The conservative/most-inclusive windows of potential habitat would extend subtidally too.

**Table 2: Suggested windows of potential eelgrass habitat.**
*Regions delineated from the upper to lower boundaries, relative to mean lower low water (MLLW), across the length of the California Coast.*

| Region | Upper (Landward) Boundary | Lower (Seaward) Boundary |
|---|---|---|
| Coastal Channel Islands | +1m MLLW | -30m MLLW |
| Coastal Mainland | +1m MLLW | -20m MLLW |
| Embayments between Tijuana River Estuary and Point Conception | +1m MLLW | -10m MLLW |

| Region | Upper (Landward) Boundary | Lower (Seaward) Boundary |
|---|---|---|
| Embayments between Point Conception and Point Ano Nuevo | +1m MLLW | -6m MLLW |
| San Francisco Bay | +1m MLLW | -3m MLLW |
| Embayments (excluding SF Bay) between Point Ano Nuevo and the CA-OR border | +1m MLLW | -5m MLLW |

With respect to creating an inventory of eelgrass, the habitat can be defined as any (vegetated) sediments where the plants are growing. However, even healthy eelgrass beds can be patchy, with a given bed having sparsely vegetated parts. Common practice in California, as detailed in the California Eelgrass Mitigation Policy (CEMP 2014), is that five contiguous meters of sediment without any eelgrass plants would be considered unvegetated and therefore not part of any eelgrass inventory.

## Eelgrass: Key Considerations/Needs

This section highlights the unique aspects of eelgrass that inform any evaluation of mapping approaches, including:

- ***Sub-habitats:*** Any mapping technique needs to accommodate both the intertidal and subtidal portions of the beds, with overlap between the survey platforms applied. It is likely that no one method can fully cover each (sub)habitat, so a complete approach may require the integration of multiple techniques.

- ***Mapping interval:*** Eelgrass plants, and therefore the beds they comprise, grow and senesce throughout the year. The timing and intensity of this cycle varies along California's latitudinal gradient. Synching of mapping/image capture across the latitudinal gradient to a point in the growth cycle (e.g., maximum growth) will be needed to ensure an accurate and comparable statewide inventory. While using satellite-based data makes this coordination more feasible, it can also be achieved using other data collection methods.

- ***Temporal frequency:*** Individual eelgrass beds are presumed to have a large degree of interannual variability, though the degree of variability is unknown across the length of the state. As such, annual mapping would provide the most consistent trends in eelgrass inventory. Less frequent mapping could be appropriate once a better understanding of temporal variability is achieved, but it may also introduce greater variability into trend data.

- ***Spatial precision:*** One to two square meter (2x2) spatial resolution would be ideal for capturing the highly irregular boundaries of eelgrass beds. A five (5x5) square meter resolution would produce smoother bed boundaries and is the maximum size that would still allow for the separation of vegetated and unvegetated sediments defined above.

- ***Spatial discrimination:*** The ability to distinguish between vegetated and unvegetated sediments is the primary data/image interpretation requirement for mapping eelgrass beds. Secondarily, in many instances the edges of eelgrass (*Zostera* spp.) may be mixed with other species of SAV (e.g., *Ruppia maritima*) or macroalgae. Related taxa such as surf grass (*Phyllospadix scouleri*) may also be difficult to distinguish from *Zostera* in aerial imagery. Data interpretation methods will need to be able to distinguish eelgrass beds from other species of SAV or other types of primary producers.

# Habitat: Rocky Intertidal

## Rocky Intertidal: Habitat Definition

*The rocky intertidal* zone is an area between marine and terrestrial habitats (Figure 7) where organisms living within this zone are well adapted to alternating exposures to both the air and sea" (NPS 2021) between high and low tides and contain a number of "zones" defined by the amount of time they are exposed to marine tidal waters and air exposure. These zones include the Splash/Spray Zone, High Tide/Intertidal Zone, Mid Tide/Intertidal Zone, and Low Tide/Intertidal Zone.

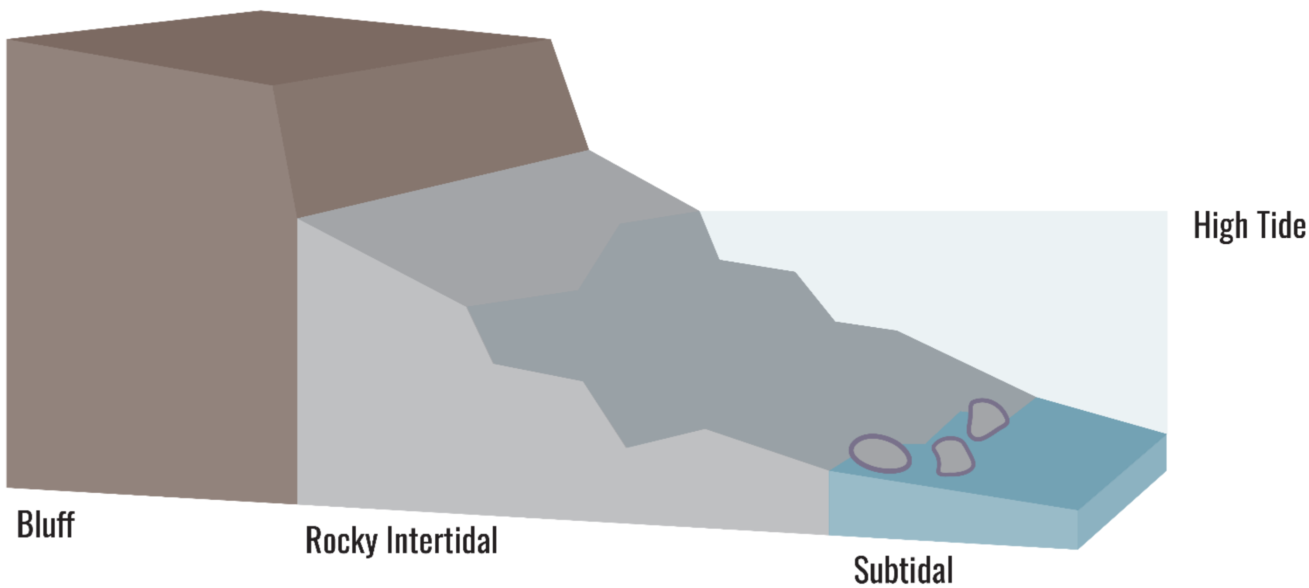


**Figure 7: Rocky intertidal zone schematic.**

Much of the rocky intertidal habitat along the California coast is 10m-20m wide on average. Thus, data sources should ideally have a horizontal spatial resolution close to 1m to capture variability in extent in these narrow widths of habitat (NPS 2016, NOAA 2024).

There is a difference between habitat area versus habitat surface area. Habitat area refers to the horizontal or two-dimensional extent of a habitat when viewed from above. Habitat surface area refers to the contoured three-dimensional surface of the rocky habitat. The same rocky intertidal habitat will have a much greater habitat surface area than habitat area. The more detailed and complex the three-dimensional structure of the habitat is captured, the more habitat surface area can be calculated.

Other important considerations to address when defining the rocky intertidal habitat include:

- Substrate type (rock versus sediment) and vertical gradient (slope and geomorphic variability).
- Rock type (slate versus granite).
- Seasonal fluctuations or pulses of sand that may cover rocky intertidal habitat.
- Natural versus unnatural rocky intertidal habitat and the inclusion of riprap.
- Salinity criteria to restrict the extent up-estuary to which rocky intertidal habitat should be mapped. There was a general consensus from the OPC Habitat Mapping Expert Panel that around 18-40 ppt is a good definition that incorporates the polyhaline range. However, there was some discussion to also include 15 ppt depending on seasonal influences of rain, etc. For the San Francisco Bay, there is a recommendation to limit the boundary demarcation around Angel Island.

Rocky Intertidal mapping should be coordinated with beach mapping to avoid overlaps between mapped extents since the two habitats neighbor one another and are often interspersed. Having compatible minimum or target mapping units may make it easier to determine how to lump or differentiate rocky intertidal from and beach habitat in mixed habitat settings.

## Rocky Intertidal: Boundary Demarcation and Mapping

From a biological perspective rocky intertidal extends from lower low water (LLW) to the extent of consistent splash/spray zone. Past efforts have considered this to be maximum high-water level within the last tidal epoch. Hard substrate type additionally dictates habitat suitability. The State or others may use other more jurisdictional boundaries such as private property boundaries, easement lines etc.

There was a discussion of including all islands and small sea stacks (thousands of them) that are managed by the Bureau of Land Management (BLM). Although it was noted that these would ideally be included, it is likely infeasible to do so given the proposed mapping approaches. This is because many of the sea mounts are irregularly dispersed, obscured by inundation, and small and difficult to detect in a consistent manner. Furthermore, many plane-based remote sensing data collections, which likely would more closely match the spatial resolution needed for these smaller features, do not regularly collect data farther offshore where these sea stacks occur.

## Rocky Intertidal: Key Considerations/Needs

This section highlights the unique aspects of rocky intertidal that inform any evaluation of mapping approaches, including:

- ***Sub-habitats:*** Distinct vegetation and wildlife communities can form in the rocky intertidal based on exposure and other physical and structural properties of the surfaces. Tidal exposure creates zonation (subtidal, low, mid, high, splash/supratidal), where dominant species are adapted to conditions within each zone. Features like tide pools, shaded faces and crevices, algal mats, and mussel beds can create microhabitats within these zones.

- ***Mapping interval:*** Seasonal variation in growth of different algal species will change the appearance of parts of the rocky intertidal community throughout the year. To ensure comparability over time, mapping should be timed to synchronize collection across years and consider the latitudinal variation in the growth season to ensure comparability.

- ***Temporal frequency:*** Three-dimensional properties of the rocky intertidal will change very little over annual timescales except in areas like boulder fields or near beaches where sand transport may bury or expose rock surfaces. Accordingly, most areas may only need to be mapped for structure every ~5 years, but a finer temporal scale may be desired in the more dynamic areas. The rocky intertidal community could be mapped annually to examine substrate and monitor ecological changes.

- ***Spatial precision:*** Meter or sub-meter resolution is preferred to determine substrate and delineate habitat boundaries. Finer (cm-scale) resolution is desired for capturing 3D structure.

- ***Spatial discrimination:*** The ability to discriminate distinguish among substrate types and detect subtle changes in zonation across elevation are key factors affecting the selection of mapping methods.

# Habitat Mapping Approaches and Tradeoffs

This section describes three habitat mapping approaches, detailing the habitat classification needs and limitations, potential data inputs, pros and cons of the approach, and habitat specific considerations. Refer to Appendix F for a summary of the status of current mapping efforts for the four habitats and Appendix G for examples of using mapping approaches in concert for coastal wetlands and rocky intertidal habitats.

The different mapping approach categories described here generally move from lower horizontal spatial resolution to higher horizontal spatial resolution. For example, a mapping product that uses primary satellite imagery is likely to have a larger minimum mapping unit or lower spatial resolution than a mapping product that primarily relies on plane-based imagery. This is because, generally, satellite-based imagery has a lower spatial resolution than plane-based imagery. However, both higher and lower resolution maps can be highly accurate. Higher resolution maps can capture smaller features that lower resolution maps cannot. While higher resolution maps are inherently more spatially precise in describing the boundary between habitat classes, they are not necessarily more accurate. Therefore, Accuracy Assessments are important tools for assessing both spatial and classification accuracy of mapping products, which is particularly important when those mapping products are used for change detection analysis.

## Approach #1: Satellite-based Mapping

**Statewide General Habitat Extent Mapping using Spectral Signature**

*Applicable to all coastal habitats, except for the full boundary of eelgrass.*

**Outcome:**

Map of major habitat features that can be used to estimate extent and distribution.

**Addresses needs/uses**: Track habitat changes resulting from conservation, restoration and management activities in relation to State targets; effectiveness and outcome assessment of management activities. See below for more information on tradeoffs and limitations.

**Description of Mapping Approach:**

Habitats of interest can be mapped using satellite imagery combined with image analysis and classification methods. This method can use freely available, moderate spatial and temporal resolution satellite data and/or commercial satellite data with substantially improved spatiotemporal resolution . Pairing imagery with tidal datum models (as described in the "Types of Geospatial Analysis for Habitat Mapping" section) could help improve classification by providing intertidal elevations. This approach could provide a relatively high-resolution map of habitats but would provide limited information about their health or condition. A habitat model specifically trained using local data would provide better mapping resolution. Such a model could be pixel-based, and similar pixel-based efforts exist at lower resolutions, but OBIA could potentially improve the mapping accuracy.

This approach could be further augmented by combining higher temporal resolution satellite imagery with tidal models to provide some estimation of intertidal elevations and topography. This additional step would address some of the limitations of this approach (e.g., lack of elevation data within the intertidal zone to support elevation-based definitions of habitats) but would increase the analysis complexity.

**Classification Need/Limitations:**

The limitations associated with satellite-based mapping are directly related to the native spatial resolution of the dataset used. Moderate resolution satellite data (i.e., Sentinel-2) could not reliably capture habitat features smaller than $5m^2$ or narrower than ~5-10m. Higher resolution satellite imagery could discriminate smaller scale (1-2m) habitat features/boundaries. Consequently, higher spatial resolution satellite imagery, or moderate resolution satellite imagery paired with higher spatial resolution plane-based sensor data (i.e., NAIP and 3DEP LiDAR), will likely be required to meet many of the State's habitat tracking needs.

It is commonly assumed that sun-synchronous satellites (e.g., Landsat, Sentinel-2, other platforms such as Planet) collect a sufficient number of images over coastal regions to capture the full range of tidal conditions at a given location over time. However, this assumption is not true, and the tidal bias that is actually observed varies significantly both geographically and seasonally. This can be illustrated by modeling the extent of the tidal range seen across Australia by the Landsat sensors for over 30 years (Figure 8). For instance, in Panel b, the historical Landsat archive contains no observations of tides within the lowest 1m range in Northern Queensland.

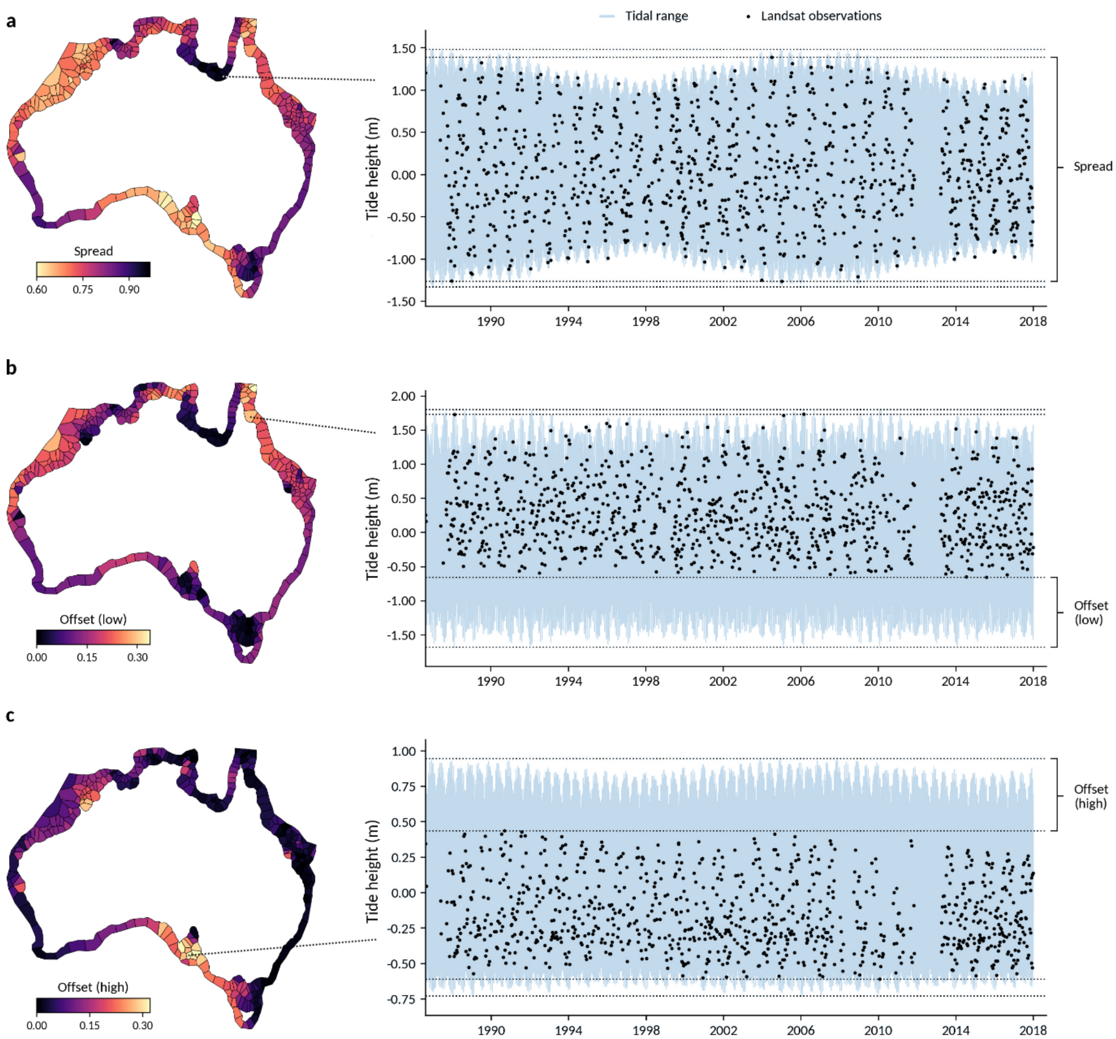


**Figure 8: Modeling of the tidal range extent seen across Australia by Landsat sensors.**
*Landsat observations for over 30 years are displayed as black dots, Tidal modeling is displayed as blue lines (Bishop-Taylor et al. 2019).*

The issue remains prevalent even with daily observations from constellations, such as PlanetScope, where strong seasonal patterns can occur depending on location or tidal regime. For instance, low tide only being observed over a certain 2-3 months of a year. This has implications for survey planning and ongoing monitoring applications, particularly over broad geographic areas. How this issue impacts on a given study area should be considered when selecting appropriate data sources and time frames.

**Data Inputs:**

- Sentinel-2, Landsat, and higher resolution options such as PlanetScope provide multispectral imagery and moderate-to-high temporal resolution. Some options such as Planet offer a daily repeat cycle while Sentinel-2 has a 5-day repeat cycle.

  - Sentinel-2 imagery has a 10m/pixel spatial resolution and is publicly available. The sensor acquires multispectral imagery in 13 bands spanning the visible and SWIR wavelength spectra (442 – 2,202 nm).
  - Landsat 8 and 9 imagery can be pansharpened to 15m/pixel and is publicly available. The sensor acquires multispectral imagery in 11 bands spanning the visible, SWIR and thermal IR wavelength spectra (430 – 13,800 nm).
  - Other platforms such as PlanetScope offer a higher spatial resolution at 3m/pixel coupled with a daily repeat cycle but is a commercial data product. Recently launched PSB.SD satellites acquire multispectral imagery in 8 bands spanning the visible and NIR wavelength spectra (443 – 865 nm).

  Federal partners, through NASA's Commercial Satellite Data Acquisition (CSDA) program and USGS EarthExplorer, can assist with access to this data. However, that access is negotiated on a yearly basis, which provides some risk to reliance on this dataset.

- Tide models, such as NOAA's VDatum paired with coastal tide gauge, can produce high quality tidal models. These models can be combined with coastal DEMs to help define coastal wetland extents and subtypes. Ideally, this information could help differentiate tidal versus non-tidal coastal wetlands in the classification.

- Existing elevation data may provide benefits when used as an ancillary dataset, but regular collection of this data is not considered necessary for Mapping Approach #1. It is important to consider how comparability may change if elevation data is incorporated some years and not others.

**Pros:**

- Can be inexpensive
- Potential for statewide coverage (depending on platform)
- Public data input option (Sentinel-2)
- Can be conducted at multiple temporal scales (monthly, annual, and on demand in response to significant events)
- Can hindcast to capture historical trends (Sentinel-2 launched in 2015, Landsat 5 launched in 1985, PlanetScope launched in 2014)
- Limited data inputs necessary and low model complexity

**Cons:**

- Relatively coarse estimate of habitat area, depending on satellite dataset used. This is an important consideration when trying to quantify habitat acreage.
- Spectral signature alone does not make it possible to identify habitats according to absolute elevation or relative tidal elevation.

- Differences between years in mapped habitat extents could be due to tidal exposure or potentially lower accuracies due to data input limitations. This could be mitigated by leveraging tidal stage data to account for the tide stage differences between images for each year.

- Difficulty detecting smaller changes (sub-meter scale), such as incremental gains from restoration efforts, early and mid-stages of habitat degradation, and smaller habitat features.

- A more simplified classification system that excludes or lumps smaller habitat features is required due to the lower spatial resolutions of most satellite-based sensors.

- Limited applicability to subtidal habitats with current image and analytical technology.

- Limited control over timing of image acquisition.

- Some sources can be expensive to purchase.

**Habitat Specific Considerations:**

- ***Coastal Wetlands:*** Satellite imagery can be used to detect coastal wetlands but at a relatively coarse scale in relation to the changes of interest (annual wetland erosion, accretion, and vegetation of restoration projects). Multi spectral imagery would be useful for detecting inundated areas and vegetated areas but would not provide much high-resolution information needed to detect differences in tidal relative elevation or vegetation differences between vegetated areas. The classification system that would be possible if only using satellite imagery may be similar to the classification system that was used by the DECODE (DEtection and Characterization of cOastal tiDal wEtlands change, Yang et al. 2022) mapping effort: vegetated wetland, unvegetated wetland, open water. Related wetland features/classes such as ponds/pans, channels, fringing marsh would be lumped into more general wetland classes or may not be captured. DECODE was developed by USGS and uses Landsat time series data (30m spatial resolution) to address large-scale mapping of coastal tidal wetland changes. DECODE was noted as not working well for capturing wetlands for significant portions of the state as well as the spatial resolution mismatch between Landsat and smaller and more narrow fringing wetlands that were identified to be of interest by the OPC Mapping Expert Panel for Coastal Wetlands.

- ***Beaches and Dunes:*** Satellite-derived shoreline methods have become a routine method to determine the seaward extent of beaches at event to multi-annual time scales and across local to global spatial scales. The approach may not accurately differentiate the dune:beach boundary, which is typically based on slope change at the dune toe and requires elevation data to detect, or the limits of beaches and dunes that abut natural landscapes. Multispectral imagery is generally used to measure the shoreline at the MSL or MHW vertical datum, so there may be difficulty detecting the furthest seaward extent of the beach, as MLW is a vertical tide datum and is continuously submerged making it difficult to identify spectral-based features. It will also be more difficult to characterize seasonal dynamics, subtle changes or changes in smaller systems, depending on the amplitude of geomorphic change and satellite dataset used (i.e., higher resolution options will be able to detect smaller scale change than Sentinel-2 or Landsat).

- ***Eelgrass:*** This is a reasonable approach for detecting the intertidal portions of eelgrass beds with a relatively coarse resolution. Furthermore, platforms like PlanetScope would most likely provide a temporal frequency useful in capturing the intra-annual variability of eelgrass bed size and shape. However, based upon the limits of current technology (image capture and interpretation routines versus water column attenuation) and timing of coverage, it would be insufficient for completely mapping the deeper water, or turbid areas, of subtidal portions of eelgrass beds in coastal areas. Some sources, such as Maxar (https://www.maxar.com/maxar-intelligence/products/satellite-imagery), are sufficiently high resolution for subtidal eelgrass mapping but are unlikely to provide reliable coverage of all areas statewide in a season. This approach would also likely be unable to consistently map the subtidal portions of eelgrass beds in enclosed estuaries and embayments. Frequent and persistent coastal stratus during summer months can also complicate satellite and higher altitude remote sensing approaches for mapping coastal wetlands.

- ***Rocky Intertidal:*** This approach would only provide a single "Rocky Intertidal" class that is more general and inclusive to include exposed rocky shoreline along the coast and would be less accurate in mapping more frequently submerged portions of intertidal habitat. This approach cannot support a definition that is based on relative tidal elevation without including elevation data and tidal data. This approach would differentiate between rocky and sandy sediments but may not work as well where rocky and sandy substrates are intermixed at a small scale.

  There is another variation of this approach that would help to address some of these shortcomings while still primarily using satellite imagery. One could pair tidal models with high temporal resolution satellite imagery (such as PlanetScope or even Sentinel-2, at a reduced resolution) to create intertidal elevation data to inform lower intertidal extent of rocky intertidal habitat. Furthermore, available terrestrial coastal LiDAR (collected by occupied aircraft/planes) could be leveraged to better refine the upland boundary and relative tidal elevation extents of the habitat, while still benefiting from the more recently captured satellite imagery for rocky versus sandy substrate differentiation and sand bar extents in more dynamic portions of the coast such as at the mouths of large rivers and bar-built estuaries.

## Approach #2: Plane-based Mapping

### Detailed Habitat Mapping Using OBIA, Plane-Based Imagery and Photogrammetry, LiDAR, and Supporting Data

*Applicable to all coastal habitats.*

**Outcome:**

High resolution maps of coastal habitats that could support more detailed classes and that can be used to more accurately quantify their extent and distribution. The tradeoff for the higher resolution and more detailed mapping is a higher cost to data collection (unless reliance on existing data capture programs e.g., NAIP), which likely results in a less frequent mapping interval. Seasonal shifts and patterns could be incorporated by pairing plane-based data with satellite-based datasets that have higher temporal resolutions/return rates. By utilizing DEMs, this approach can estimate the surface area of rocky intertidal habitats to support further habitat modeling and classification. It also enables support for habitat definitions that use elevation, slope breaks, and relative tidal elevation, such as coastal wetlands.

**Addresses needs/uses**: Track acreage change over time in extent and restoration; inform permitting; support mitigation monitoring; could support basemap for estimating carbon capture; track habitat changes in natural lands; inform coastal planning and permitting; habitat mapping for sensitive species and reserve management; evaluate management actions; project-based tracking goals; status and trends. See below for more information on tradeoffs and limitations.

**Description of Mapping Approach:**

This approach is inspired by the SOP used to develop the San Francisco Estuary Wetlands Regional Monitoring Program's Baylands Habitat Map (WRMP BHM; see Appendix E for BHM hierarchical classification system). It would primarily leverage higher resolution, multispectral plane-based imagery (e.g., from the USDA National Agriculture Imagery Program, NAIP), corresponding plane-based coastal LiDAR collections, tidal datum models/observations, and OBIA with rule-based or machine learning classification to produce high-resolution maps of coastal habitats. Compared to approach #1, this approach could provide more accurate acreage measurements and support the ability to track smaller features such as tidal ponds/panes, channels, and small rocky outcroppings interspersed with sandy habitats. The level of detail supported by this approach can provide information on habitat condition and health, especially when coupled with rapid field assessment protocols.

This habitat mapping approach requires semi-regular collection of LiDAR or other detailed topographic data such as Structure-from-Motion (SfM) photogrammetry at cm scale resolution. Note that LiDAR provides more relevant mapping information than a DEM produced via SfM for some habitat types (e.g., coastal wetlands). Annual collections would provide benefits for understanding habitat dynamics and ongoing processes impacting these coastal habitats, where less frequent collections (~5 years) still would capture longer term trends. This more detailed mapping approach would most likely be conducted less frequently (4-10 years). The pairing of LiDAR or SfM topographic data with tidal datum models/observations allows the use of relative tidal elevations to coarsely map habitats, which are then refined using high resolution imagery. Updated tidal datums, calculated for the state on a rolling basis, can be combined with updated LiDAR DEMs to revise maps of areas subject (or potentially subject) to tidal influence, including current tidal wetlands, muted tidal wetlands behind partial barriers, and non-tidal wetlands behind complete barriers. This will provide an efficient approach to tracking changes due to sea level rise. Oblique coastal imagery could also help enhance classification and potentially habitat boundary delineation when paired with photogrammetry techniques. The California Coastal Records Project is an example of where coastal oblique imagery is freely available and collected every 4 years. It has even been used by USGS scientists to derive three dimensional structures using photogrammetry (Warrick et al. 2017). However, this product is produced by private citizens and may need additional financial and logistical support if it is to serve as a long-term data source for habitat mapping. Recent work by the USGS shows that small aircraft with combined photographic equipment and survey-grade GPS sensors can be used to map the topography large swaths of the California coast at similar resolutions and uncertainties as LiDAR (Sherwood et al., 2018; Warrick et al., 2019).

Geoscience Australia is augmenting this general approach by incorporating Sentinel-2 data (or other relatively high spatial resolution satellite datasets that also have high temporal resolutions) with tidal models to provide more accurate intertidal elevation data. Traditional LiDAR provides less accurate elevation data in submerged regions (intertidal areas). Blue-green bathymetric LiDAR has proved valuable to overcome this limitation but is less useful in more turbid and disturbed waters. This pairing of higher temporal resolution imagery with tidal models can help fill this gap in intertidal elevation data. This could be particularly useful for mapping rocky intertidal, beach, and unvegetated coastal wetland (mudflat, sandflat) habitats.

Additional work could be done to further support mapping of additional habitat types through the incorporation of higher temporal resolution data by characterizing the phenological signature of habitats/classes of interest. The use of Principal Components Analysis (PCA) has been useful to accomplish this in the past, although other approaches could be explored.

**Classification Need/Limitations:**

- A much higher spatial resolution product, with a minimum mapping unit of up to 5m$^2$, could be produced to allow for a much finer scale tracking of habitat features.
- Classification definitions could include relative tidal height, as well as changes and differences in elevation and vegetation height.
- Seasonal or inter-annual dynamic aspects to mapped classes of features could be supported, but only if they can be characterized based on using supplemental satellite or other high temporal resolution data in addition to the plane-based imagery and LiDAR data.

**Data Inputs:**

- Primary data inputs:
    - Plane-based multispectral public imagery (NAIP)
    - Plane-based coastal LiDAR topography (Q1 or better ideally with an RSME of around 10cm (4in) or better). Note that sensors are becoming more accurate with denser point clouds generally as technology advances.
    - Plane-based SfM photogrammetry topography
    - Tidal models and local tide gauge data. Consider NOAA's VDatum. Models can be locally adjusted based on local gauge data as well as how well tidal relative elevations match observed habitat patterns in imagery.

- Secondary data inputs:
    - High Temporal Resolution Satellite Imagery – Options similar to PlanetScope or Sentinel-2. An option with a higher spatial resolution would be preferred. Useful for intertidal elevations and phenological signatures.
    - Oblique imagery (e.g., The California Coastal Records Project).

**Pros:**

- Higher resolution and accuracy can detect changes in habitat health and/or incremental changes/gains over time in restoration areas or seasonal variation (when paired with satellite data with a higher temporal resolution than most plane-based sensor/datasets).
- Can capture smaller habitat features and include more classes in the classification system.
- The DEMs used for this approach can provide critical information to differentiate between more nuanced habitat classifications and can support elevation or slope-based habitat definitions and boundaries.
- LiDAR or SfM topographic data can also be used to create complex three-dimensional structures of some habitats (e.g., rocky intertidal) which are important for determining surface area in addition to habitat area.
- Can compensate for inaccuracies of intertidal LiDAR data with a complementary method of high temporal resolution satellite imagery with tidal datum models (Similar to Geoscience Australia's Digital Earth Australia Intertidal product).
- Able to produce habitat area and habitat surface area metrics.
- Can do limited hindcasting of historical trends if not relying on more recently initiated data sources
- Ability to be nimble with flight schedules to time image acquisition for optimal data collection over conditions with low tide, low sun angle, low wind, and low turbidity and maximum seasonal biomass. This is an advantage over satellite acquisitions.
- Can be done with public datasets.

**Cons:**

- Relies on the availability of LiDAR or SfM photogrammery data collected, which can be costly, especially if not coordinated across agencies. Can also be expensive if existing free sources do not meet project needs.
- A more complicated mapping effort.

- Does not map the dynamic nature of the habitat boundaries due to the lower mapping frequency.
- This mapping approach still has challenges, even though it has advantages over satellite imagery in this respect, in lining up data collection flights with low tide, low sun angle, and low winds to avoid surface chop and sediment resuspension when mapping subtidal habitats, such as eelgrass. Regarding LiDAR, blue-green bathometric LiDAR can be useful for additional water penetration, but still poses some logistical challenges and has depth limitations.

**Habitat Specific Considerations:**

- ***Coastal Wetlands:*** This approach supports a much more detailed and specialized classification system than can be supported by Mapping Approach #1. The classification might be similar to the one used to support the WRMP Baylands Habitat Map, developed by the San Francisco Estuary Institute (SFEI), modified to consider the unique landscape positions of bar-built estuaries. It is important to balance adding additional more specific classes with having higher accuracy of more general habitat classes (e.g., mapping "low marsh" and "high marsh" likely results in a lower accuracy that lumping classes together as "tidal marsh"). Other strategies can include using hierarchical classifications so that more detailed classes can roll up to more general classification levels. If mudflats and lower intertidal habitat types are of interest to map, leveraging the higher temporal resolution imagery, such as satellite imagery with tidal models, is of particular benefit. However, obtaining imagery with sufficient temporal resolution may be prohibitively expensive.
- ***Beaches and Dunes:*** This approach requires meter to sub-meter resolution imagery (likely from occupied aircraft to map due to the practicality of mapping an area as large as California). If only larger features are of interest, such as larger dune fields (i.e., Pismo Beach) would not require sub-meter imagery to track extent change over time. Intertidal extents of beaches could be mapped more accurately by leveraging the higher temporal resolution imagery with tidal models. Plane-based LiDAR or SfM photogrammetry surveying are likely the best techniques for mapping the seaward extent of the beach, which is marked by MLW elevation. Derivative elevation products, such as slope or surface roughness maps, could also be used to detect the location of the dune toe, marking the transition between the beach and dune habitats.
- ***Eelgrass:*** This LiDAR-focused approach would not be applicable to subtidal eelgrass beds given the requirements to distinguish between vegetated and unvegetated sediments. Low tide imagery would likely be required for intertidal eelgrass detection and is challenging to collect across the state at the same time. Higher resolution imagery from aircraft or UAV platforms have had some success in identifying subtidal eelgrass in shallow water, low turbidity systems when paired with detailed bathymetry information and ideal light/tide conditions. Multispectral aerial imagery is commonly used for seagrass delineation on the east coast using that approach, although some states do this on regionally rotating basis to keep costs down and limit the

geographic scope to something that can be flown, delineated and ground-truthed within eighteen months.

- ***Rocky Intertidal:*** This mapping approach would allow for surface area mapping of rocky intertidal which could be particularly important to support biological zone modeling on the 3D surface and to assess the distribution of more detailed classes of intertidal rocky habitat areas. Biological habitats modeling could be conducted using the coastal DEM and rocky intertidal habitat extent generated from this approach. This approach can compensate for limitations of intertidal LiDAR or SfM photogrammetry collection with a complementary use of high temporal resolution satellite imagery and tidal models. This may not need to be done all that frequently as the physical structure of the rocky intertidal habitat may not change at this scale frequently. This approach could be more useful for determining the impacts of sea level rise and mapping more narrow habitat patches. LiDAR intensity and rugosity could be used to help differentiate rocky and sandy habitats. SfM orthoimagery could be used to help define habitat types and characteristics. Some investigation could determine if topographic complexity needs to be characterized to distinguish rocky versus sandy habitats. The approach could extract either or both surface extent/area or surface area.

## Approach #3: Field-based Remote Sensing and Surveys

**Combine GPS Delineations of Habitat with Locally Remotely Sensing Data to Create Intertidal and Subtidal Habitat Extent Maps**

*Tailored to eelgrass but applicable to all coastal habitats.*

**Outcome:**

Map of intertidal and subtidal habitat extent. While this approach is tailored to mapping eelgrass, it could be applicable to other coastal habitats.

**Addresses needs/uses**: track acreage change over time in extent and restoration (eelgrass); inform permitting; support mitigation monitoring; could support basemap for estimating carbon capture (eelgrass); track habitat changes in natural lands (eelgrass); inform coastal planning and permitting; habitat mapping for sensitive species and reserve management; evaluate management actions; project-based tracking goals. See below for more information on tradeoffs and limitations.

**Description of Mapping Approach:**

Both intertidal and subtidal habitat features could initially be mapped by local remote sensing platforms, with accessible portions manually mapped by field crews tracing habitat boundaries with GPS units. Some small areas may be covered sufficiently solely by field surveys.

For intertidal habitat components, UAS vehicles can capture imagery that could be processed with a variety of the different classification methods detailed above (e.g., manual mapping and machine learning). For eelgrass in specific, imagery or sensors capable of specifically identifying Chlorophyll *a* and other phytopigments could also be used to aid in delineating vegetated and unvegetated sediments since eelgrass is photosynthetic plant. However, separation of eelgrass from macroalgae using UAS imagery, often requires additional considerations such as texture analysis as well.

For subtidal habitat components and within intertidal environments surveyed at high tide, side scan sonar with integrated GPS tracking deployed from piloted vessels can be used to capture the acoustic reflectance of the subtidal environments. This creates a detailed sonogram image of the seafloor. Individual sonar paths/swaths can be integrated in a single mosaic (e.g., geoTiff files) for a given location. Eelgrass and other bottom features can then be identified and boundaries delineated at a high resolution by interpretation of the mosaics using manual mapping, image processing and/or AI software. Because interpretation of side-scan sonar utilizes multiple aspects of the sonar data to identify the features being characterized, such as pixel intensity, spatial context, shadowing, and scour effects, to distinguish eelgrass from other features, mapping often relies on a combination of manual and automated processes coupled with ground-truthing in complex environments where errors are potentially made. One particular benefit of side-scan sonar is a tremendous capacity to distinguish eelgrass from macroalgae, as a result of differences in acoustic reflectance properties. Using interferometric side-scan sonar or other advanced sonar systems, it is possible to obtain bathymetric data from the sonar surveys in addition to seafloor habitat and structure.

Intertidal habitats inaccessible to UAS vehicles can be traced on foot by field crews GPS units, ideally with units capable of recording continuous paths (versus those that can only record points). Similarly, in subtidal habitat components inaccessible to vessels with the side-scan or multi-beam sonar (typically too shallow), low-draft vessels (e.g. kayaks, paddle boards, and jet skis), SCUBA divers, or snorkelers equipped with GPS units can trace the boundaries of the habitat feature by navigating along its edges.

Field based monitoring and local scale UAS surveys are useful for validation and potentially training of Mapping Approaches #1 and #2.

**Classification Needs/Limitations:**

- A much higher spatial resolution product could be produced with a minimum mapping unit of 2x2m down to 0.5x0.5m scale. This could allow for a much finer scale tracking of year-to-year fluctuation of eelgrass beds and higher accuracy mapping of patchy eelgrass beds.
- Both the application local remote sensing and manual GPS tracing require specialized training and equipment. However, certain locations deemed unsafe or inaccessible to field crews and equipment could not be accounted for.
- Many coastal areas of interest will be off limits to UAS surveying due to FAA airspace regulations.

**Data Inputs:**

- GPS records for manual tracing efforts

- Georeferenced side-scan or multi-beam sonar data
- UAS imagery

**Pros:**

- Ability to accurately measure the extent of both intertidal and subtidal habitats, even in waters in excess of 30m.
- Ability to distinguish non-eelgrass types of SAV from eelgrass when they are comingled or adjacent to each other. However, ground truthing of side-scan and multibeam sonar is still recommended via direct observation, especially at the upper end of the subtidal zone/intertidal zone where niche overlap with other forms of SAV or macroalgae is common.
- Can be done in conjunction with other types of eelgrass monitoring programs.
- High degree of spatial resolution and accuracy of extent. UAS can acquire imagery at cm-scale resolution, depending on camera specifications and flight altitude.
- UAS imagery can be used to create elevation products using Structure-from-Motion photogrammetry for detection of the dune toe, MLW, and other important habitat boundaries.
- Specialized side-scan sonar systems such as interferometric sonar or computed angle-of-arrival transient imaging sonar can be used to produce high resolution swath elevation data similar to multi-beam sonar systems.
- UAS and side-scan sonar can be efficiently used in combination to map large areas more accurately and efficiently than either system alone (e.g., San Diego Bay, Humboldt Bay, Morro Bay, San Francisco Bay).

**Cons:**

- Labor and time intensive when conducted across the entire state, but efficient at the site level due to portability, easy mobilization, and capacity to plan around unsuitable climatic or tidal conditions.
- Not conducive to unsupervised automated mapping due to differences between conditions when surveying small areas and stitching together (especially if using spectral signatures). That said, automated processing of UAS imagery is possible to produce orthomosaics, DEMs, etc.
- Typically mapping would be done at small spatial increments – ranging from individual features to a single embayment/portion of the coastline – depending upon the size of the feature, local conditions, etc.
- Assuming the work at a statewide scale would be done by multiple parties, intercalibration of personnel and equipment would be strongly encouraged.

- Many coastal areas of interest will be off limits to UAS surveying due to FAA airspace regulations.

**Habitat Specific Considerations:**

***Coastal Wetlands:*** Site specific and field-based measurements and surveys are very valuable for training and validating mapping models/approaches that rely on more remotely sensed data (e.g., Mapping Approaches #1 and #2).

***Beaches and Dunes:*** DEM created using Structure-from-Motion of UAS imagery can detect the habitat boundaries requiring elevation data: MLW, dune toe, and the landward boundary of the dune. UAS imagery can also provide valuable validation data for machine learning classification results of satellite data.

***Eelgrass:*** This approach is particularly important to consider for the mapping of eelgrass, as a significant portion of the habitat is subtidal where satellite and plane-based remote sensing datasets are less reliable in capturing their full (i.e., depth and turbidity) extent.

***Rocky Intertidal:*** Site specific and field-based measurements and surveys are very valuable for training and validating mapping models/approaches that rely on more remotely sensed data (e.g., Mapping Approaches #1 and #2).

# Summary of Data Suitability by Mapping Approach and Habitat Type

This section summarizes the discussion above in a series of matrix tables. Availability metrics of the data sources, including public availability, cost, ease of data processing, logistics of implementing, and availability of historical information are evaluated for its utility (high, medium, low) in Table 3. The suitability of the data sources by mapping approach for each habitat type are assessed in Tables 4. Each combination is evaluated for its utility (high, medium, low) and ability to meet the following requirements:

- S: meets only the **spatial** scale requirements
- T: meets only the **temporal** scale requirements
- P: meets only the **spectral** scale requirements
- ST, SP, or PT: meets **combinations of S, P, and T** scale requirements
- SPT: meets the **spatial, spectral, and temporal** scale requirements
- NS: **not suitable** for the habitat type

**Table 3:** Summary of **availability metrics of data sources** by habitat type.
Availability metrics of data sources are available in this spreadsheet: Table 3 - OPC Scoring Matrix_All Habitats_v5_Availability Metrics.xlsx

**Table 4:** Summary of **data suitability by mapping approach by habitat type.**
Habitat specific matrix tables by Mapping Approach are available in this spreadsheet: Table 4 - OPC Scoring Matrix_All Habitats_v5_By Mapping Approach.xlsx

Refer to Appendix H for the *Summary of Data Suitability by Boundary Attribute and Habitat Type*, and to Appendix I for *Detailed Matrix for Mapping Approaches for Coastal Wetlands.*

# Topics for Potential Future Investigation

Implementation of statewide mapping programs provides opportunities for advancing the science and practice of statewide mapping. Below are several considerations for future investigation:

**Advancing the Science and Practice of Statewide Mapping**

- Determine if intertidal elevation derived by pairing tidal models with high temporal resolution satellite imagery is useful for refining habitat classes at this scale and habitat classification detail (Mapping Approach #1).

- Expand work to explore how Sentinel-2 or other higher resolution imagery (current or may be developed in the future) could be used to capture phenological and seasonal signatures of specific habitat types (Mapping Approach #2) to improve classification and characterization of coastal habitats.

- Expand efforts to use Synthetic Aperture Radar (SAR) to map coastal habitats. Current research has used Sentinel 1 SAR datasets for spatial inundation mapping, however other potential datasets include "Radarsat, Radarsat-2 and JERS-1 missions, ENVISAT ASAR, and ALOS PALSAR" (Dronova 2015). TCarta also has produced some promising preliminary work on this front using their SAR data (https://tcarta.com/synthetic-aperture-radar-sar/).

- Consider tidal bias issues when using sun-synchronous sensors for coastal earth observation monitoring applications - Combining SAR and a sun-synchronous sensor is very beneficial in capturing a better spread of the tidal range according to preliminary investigations by Geoscience Australia. However, work has yet to be done to combine SAR data with imagery datasets for a scalable mapping workflow.

- Identify how mapping could be leveraged to approximate carbon storage within habitats. Carbon flux estimates require information on the habitat extent and composition, surface and sub-surface biomass and carbon flux rates between habitats and the atmosphere. Future efforts could pair eddy covariance or gradient flux towers with mapping products to begin developing regional and statewide estimates of carbon flux associated with coastal habitats.

**Coastal Wetlands Considerations**

- Investigate methods for remote sensing and analysis of hydrologic connectivity and flow barriers with the ocean and watershed. In particular, high temporal resolution estimates of estuary mouth opening and closing, and the size and position of mouth bars can support model development to better characterize mouth dynamics. This information is vital for understanding habitat condition, potential SLR vulnerability and impacts, landward migration opportunities for coastal habitats, and restoration/mitigation opportunities.

**Rocky Intertidal Specific Considerations**

- Determine what scale is appropriate to characterize changes between one habitat type to another (e.g. beaches and rocky intertidal). For example, the Environmental Sensitivity Index (ESI), a map produced by NOAA that provides a concise summary of coastal resources at risk if an oil or chemical spill occurs nearby, requires a change in habitat to persist for 10 meters of shoreline or more for it to be distinguished from the habitat types on either side of it. This of course relates to the need for a class specific minimum mapping unit for polygonal habitat mapping, where a linear limit for when to break from one habitat to another relates to linear shoreline mapping.

- Determine if topographic complexity information needs to be characterized to distinguish between rock and sand habitat breaks.

- Determine whether detecting whitewater that is consistently observed over time could be used to infer the extent of rocky intertidal habitat. It is unclear what frequency of imagery we would need and if this approach could distinguish general waves breaking at the shore versus waves breaking over rocky intertidal.

- Determine a standard for minimum mapping units and grouping/lumping when sand is intermixed with rocky intertidal habitats (Mapping Approach #2 and #3).

**Eelgrass Specific Considerations**

- Analyze eelgrass mapping data to determine where annual versus perennial eelgrass populations occur and where continuous versus patchy eelgrass beds occur.

- Experiment with pairing of eelgrass mapping data with environmental data (temperature, salinity, etc.) to improve or generate eelgrass habitat suitability models, which in turn can be used to inform location of eelgrass restoration and future mapping efforts.

- Analyze depth ranges at which eelgrass is observed to refine mapping boundaries recommended herein.

# Considerations for Implementation

The choice of a mapping approach and associated data types will depend on the desired outcome (i.e., general mapping versus detailed mapping that captures spatial and temporal dynamics) and the resources available to obtain the necessary data and process/analyze the data to produce maps.

Once a mapping approach is chosen, a more detailed matrix and combination of approaches for each habitat type should be developed prior to implementation. This whitepaper partially demonstrated this for coastal wetlands (Appendix I).

Continued coordination with the expert panelists convened for this effort would offer a platform for ongoing technical guidance as method selection and mapping proceed (e.g., through quarterly meetings). As a community of practice, this group would additionally help maintain connections, enable sharing of products, identify co-funding opportunities, explore new ways to collaborate, support diverse perspectives nationwide, and enhance the visibility of products to better understand our coastal habitats.

The following additional aspects (data sources, habitat classification, mapping methods, and maintenance of data) should be considered when selecting a mapping approach or hybrid of approaches.

## Data Sources

- The desire or need to capture annual changes and changes due to large episodic events should be weighed.
- Data choice and mapping frequency will be affected by dynamism, which will vary by habitat type (e.g., rocky intertidal may be less dynamic, eelgrass may be more dynamic).
- The selection of a private or a public dataset should be considered. Options such as Planet provide a number of benefits as it has high spatial resolution, high temporal resolution, and is multispectral. However, it is not a public dataset, which poses a challenge related to cost and ensured access to support long term monitoring.
- C-CAP land cover and impervious data can be helpful to help establish boundaries.
- LiDAR (from either aircraft or UAS) can be helpful for providing elevation data.
- NAIP imagery is good for vegetation but is only available every other year.

## Habitat Classification

- Maintain a consistent habitat class definition to enable comparison and change detection analysis, even as methods and input data specifications change over time.

- The inclusion of non-target habitats will need to be determined. The historical, jurisdictional, and future extent (i.e., under sea-level rise) will need to be considered to inform the integration of process-based, input variables, such as elevation, tidal datums, projected sea level rise, salinity, and hydrologic connectivity.

- The approach for reporting on habitat change will need to be determined (Braud et al. 2025). Considerations of habitat classes and changes of interest (either gains/losses) should be evaluated in terms of:

    - Changes in habitat class or overall extent
    - Classes are dictated by agency needs and accuracy will vary
    - Episodic versus gradual/incremental change from climate change, degradation or restoration.
    - Other approaches

## Mapping Methods

- Past approaches have focused on heads-up digitization with some modeling. This manual approach is prone to interpretation error. Therefore, automated and supervised methods should be considered over the long term to improve consistency.

- Initial, lower cost options include pixel-based classification, although object-based image analysis may result in more accurate and/or detailed maps.

- Rule-based classification requires a strong understanding of breaks/boundaries between habitats in relation to available data which may limit its long-term application.

- Machine learning can be useful for classification and detecting less understood or subtle differences in data signatures but requires more expertise and training data to implement.

- A method that is able to capture gradual or diffuse boundaries between habitat types should be developed and tested.

- A decision should be made as to whether artificial substrate/habitat should be included/distinguished.

- The availability and capability of data to capture the near subtidal/low-tide boundary should be explored.

- Implementation of the mapping program should consider whether to focus on sentinel sites that are mapped at higher resolution with the results extrapolated regionally.

- Intercalibration exercises among data collectors will need to be conducted, if field-based and/or locally remote sensed data (e.g., UAS) data is used

- Robust QA/QC accuracy plans, e.g., agreement on the frequency of ground-truthing that are developed and used should be routinely used.

- One can generalize more detailed mapping to compare it to other lower resolution mapping products, both at a classification or spatial level, to assess change over time.

## Maintenance of Data

It is critical to develop and support the data infrastructure necessary to manage the mapping products and analyses over the long-term. Ongoing funding to maintain these datasets, provide updates when possible, and respond to inquiries are important for keeping data up-to-date and lay the groundwork for efficient, regular mapping updates to track these habitats through time.

Below are some considerations for the long-term maintenance and implementation of the mapping:

- Consider ease of implementation and approaches that can be implemented quickly if funding becomes available.
- Collaborate on funding the routine production of LiDAR for California's coastline.
- Coordinate annual reflying of the California Coastal Records Act oblique photos. This would be a relatively low cost with a high return investment (e.g., California Coastal Records Project), since these data would be helpful with the classification of habitat types and investigation of areas of potential change. However, the data would not be as useful for delineating width or determining the area of habitats.
- Integrate data into online visualization tools, such as EcoAtlas (ecoatlas.org), to provide more dynamic ways to visualize, query and summarize habitat data for managers and the public.
- Consider the opportunity of using on-the-ground implementation and monitoring projects as a source of ground observation to support the mapping. This would be greatly facilitated by integrating with tracking systems like EcoAtlas.
- Support the development of GIS models for mapping and developing the data sets necessary to support, validate, and train the algorithms and models.
- Include sufficient documentation of methods, standard operating procedures (SOPs), map specification, habitat class definitions, and metadata standards so that mapping can be consistently applied and updated over time as methods and technology change.
- Identify an entity to be responsible for performing updates and responding to user requests and inquiries.
- Make maps and datasets available to the public to further monitoring efforts, increase opportunities for collaboration and research, and lend greater credibility to reported numbers and analysis.
- Produce dynamic dashboards to show change over time and create summaries of habitat distributions. Displaying the data in a dynamic way will increase access and help the public and

decision-makers understand the distribution and importance of this work, instead of producing static reports.

- Consider technological advancements over time. New approaches and data sources will become available in the future and replace existing ones.
- Create and/or maintain foundational datasets needed for mapping, such as water-level tide gauge, elevation, salinity, and typography.
- Continue to engage with an Advisory Group, similar to the expert panels used to develop this whitepaper, to guide and interpret monitoring and mapping efforts and apply them to decision-making.

# Conclusions

To support coastal habitat conservation and management, the state of California needs to develop and maintain current, comprehensive and cohesive mapping of coastal habitats. Maps should be updated at least annually, and in some cases seasonal updates may be appropriate. These maps are critical to better track acreage over time, quantify ongoing changes in habitat extent, and inform management actions.

This report summarizes available data and geospatial analysis approaches and presents three mapping approaches that could be used to support OPC's Strategic Plan goals on coastal habitat acreage targets and to support other State agencies in their mandates to track habitat acreages. The applicability of the three approaches varies by habitat type, difficulty and intensity, resolution and accuracy, input data needs, and cost. The pros and cons of each method should be considered alongside the spatial and temporal mapping needs to select an appropriate approach, define the specific mapping methods, and data sources for each of the four focal habitats. For any mapping approach or specific methodology, map product specification and habitat classification need to be consistent and comparable to accurately map habitats statewide and track acreage changes over time. Given that habitat mapping and remote sensing is an evolving field, mapping approaches must be sufficiently flexible to integrate new methods, techniques, and data sources as they arise while maintaining continuity and comparability.

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# Appendix A: OPC Expert Panels and Project Team

Below is a list of contributors who participated in the habitat expert panels. Also listed are the members of the SFEI, SCCWRP, and OPC Project Teams.

## Coastal Wetlands Expert Panel

Christina Toms - *San Francisco Bay Regional Water Quality Control Board*
Dan Friess - *Tulane University*
John Callaway - *University of California, San Francisco (retired)*
Kyle Cavanaugh - *University of California, Los Angeles*
Laura Brophy - *Oregon State University*
Liana Heberer, Bret Folger, Nate Herold - *NOAA Office of Coastal Managemen*t
Lisa Beers - *San Francisco Estuary Institute*

## Beaches and Dunes Expert Panel

Jean Ellis - *University of South Carolina*
Jon Warrick - *US Geological Survey*
Joshua Kelly - *California State University, Los Angeles (CalState)*
Karina Johnston - *University of California, Santa Barbara (UCSB)*
Kyle Emery - *University of California, Santa Barbara (UCSB)*
Timothy Baxter - *University of California, Santa Barbara (UCSB)*

## Eelgrass Expert Panel

Andrea Dell'Apa - *NOAA National Marine Fisheries Service*
Cayla Sullivan - *US Environmental Protection Agency, Region 1*
Chris Patrick - *Virginia Institute of Marine Science (VIMS)*
Keith Merkel – *Merkel & Associates, Inc.*
Kelly Luis - *Jet Propulsion Laboratory (JPL)/California Institute of Technology (Caltech)*
Liz Allen - *WRA, Inc.*
Matt Dornback - *NOAA National Marine Fisheries Service*

## Rocky Intertidal Expert Panel

Bryant Chesney - *NOAA National Marine Fisheries Service*
Chris Patrick - *Virginia Institute of Marine Science (VIMS)*
Corey Garza - *University of Washington*
Jon Warrick - *US Geological Survey*
Justin Ridge - *North Carolina National Estuarine Research Reserve (NERR)*
Pete Raimondi - *University of California, Santa Cruz*
Steve Sagar - *Geoscience Australia*

## Ocean Protection Council (OPC) Project Team

Sreeja Gopal, *Coastal Habitats Program Manager*

## San Francisco Estuary Institute (SFEI) Project Team

Cristina Grosso, *Managing Director for Environmental Informatics Program*
Alex Braud, *GIS Specialist/Environmental Scientist*
Donna Ball, *Senior Scientist*
Lydia Vaughn, *Senior Scientist*
Pete Kauhanen, *Senior GIS Manager*
Jennifer Symonds, *Graphic Designer*

## Southern California Coastal Water Research Project (SCCWRP) Project Team

Eric Stein, *Department Head, Biology Department*
David Gillett, *Ecologist*
Jan Walker, *Ecologist*
Jill Tupitza, *Scientist*

# Appendix B: Definition of Mapping Terms

Definitions for mapping terms used in this report.

| Term | Definition |
|---|---|
| Digitization | The process of converting analog information into a digital format so it is computer readable. |
| Environmental Sensitivity Index | Maps and data produced by NOAA researchers provide a concise summary of coastal resources that are at risk if an oil or chemical spill occurs nearby; https://response.restoration.noaa.gov/resources/environmental-sensitivity-index-esi-maps |
| Extent | The geographic area or region for which mapping is occurring. |
| Minimum mapping unit | The smallest size of a feature that is reliably represented and mapped for a mapping product. |
| Remote sensing | The science of acquiring information without contacting it. In this context it refers to using sensors such as cameras, LiDAR sensors, sonar etc. to collect data that can be used to help characterize the landscape and habitat types. |
| Return time | The time elapsed between observations of the same point on earth by a satellite or remote sensing sensor. Also referred to as "revisit period". |
| Spatial scale | The description or categorization (e.g., into orders of magnitude) of the size of a space or the extent at which a process or subject is studied or mapping occurs. |
| Spectral signature | The unique pattern of reflected electromagnetic radiation across different wave lengths, characteristic of a particular material or object. |
| Structure from motion (SfM) | Software that uses photogrammetric analysis to derive three-dimensional information (often elevation information) from photos taken at different locations. |

# Appendix C: Agency Needs and Potential Uses of Mapping Products

| Agency Name | Agency Type | Needs/Uses |
|---|---|---|
| **OPC** | State | Track acreage change over time in extent and restoration, MPA monitoring |
| **BCDC** | State | Inform permitting, support mitigation monitoring |
| **CARB** | State | Map for quantifying GHG flux and carbon stock change over the longest possible time period (at least from 2001) |
| **CCC** | State | Inform coastal planning and permitting, support mitigation monitoring |
| **CDFW** | State | Habitat mapping for sensitive species, reserve management and MPAs |
| **CNRA** | State | Track habitat changes resulting from conservation, restoration and management activities in relation to State targets; effectiveness and outcome assessment of management activities |
| **CSP** | State | Habitat mapping, evaluating management actions, inform restoration and climate adaptation |
| **SCC** | State | Prioritize grant funding, performance monitoring, project-based tracking goals |
| **Water Boards** | State | Integrated reporting, basin planning, inform permitting and regulatory compliance |
| **NOAA** | Federal | Inform permitting and consultation process, habitat mapping for sensitive species, EFH monitoring, SAV mitigation, planning for nature-based solutions, aligning mapping with State goals |
| **USACE** | Federal | Inform permitting, support mitigation monitoring |
| **USEPA** | Federal | Permit coordination, assist partners in restoration implementation, status and trends |
| **USFWS** | Federal | Reserve management and MPAs, habitat mapping for sensitive species |
| **Local agencies and conservancies** | Local | Monitoring and management of local reserves |

# Appendix D: Coastal Wetland Definitions

- **Wetlands with fully tidal connections.** This category includes fully tidal marshes, such as those found in Humboldt Bay, Tomales Bay, the San Francisco Estuary, Elkhorn Slough, Morro Bay, San Diego Bay, and other tidal embayments (including permanently open river mouths such as the Garcia River and Big River). It also includes tidal forested and scrub-shrub wetlands, such as those found in the upper San Francisco Estuary (Sacramento-San Joaquin Delta). Tidal wetlands often include sub-habitats that may be unvegetated such as mudflats, channels, and pannes/ponds. These wetlands are generally found below the Highest Astronomical Tide (HAT) elevation.

- **Wetlands with limited to no tidal connections.** This category includes coastal wetlands below HAT that have limited connections to tidal sources due to culverts, tide gates, or other artificial water control structures (e.g., duck clubs in Suisun Marsh, diked wetlands throughout Elkhorn Slough, Moro Cojo Slough, and San Diego Bay Salt Ponds, etc.). When these wetlands have some amount of tidal connection, they are often referred to as managed or muted tidal wetlands.

- **Bar-built estuarine wetlands, including coastal lakes and lagoons.** Bar-built estuaries, also known as coastal lagoons, perched wetlands, or (natural) salt ponds, are unique estuarine environments that exist where coastal rivers and streams meet the Pacific Ocean. They are generally open to marine influence via tidal and wave action through an open inlet across a beach berm during the wet season and become less subject to marine influence during the dry season as watershed runoff subsides, the beach berm grows, and the inlet closes. Bar-built estuaries in California exist along a broad spectrum of hydrology and morphology driven by landscape position, the relative influences of watershed (precipitation and runoff), marine (tides and waves) processes, and climate (cooler, wetter northern California versus warmer, drier southern California; Jacobs et al. 2011, Heady et al. 2014). This category includes coastal lakes and lagoons with minimal contributing watersheds, such as Lake Earl, Stone Lagoon, and Abbott's Lagoon, as well as dune slack wetlands such as those found at Manchester State Beach and Pismo State Beach. This category also includes bar-built estuaries where the inlet is managed for flood control, water quality, or other purposes (e.g., Russian River, San Elijo Lagoon, etc.). Many bar-built estuaries and related systems have wetlands at elevations well above HAT, due to the influence of inlet closure and beach/dune dynamics on estuarine hydrology.

- **Coastal river/stream valleys.** Coastal river/stream valley wetlands include riparian and floodplain habitats within the influence of coastal fog belts that support base flows through the dry season. They typically occur in the geologically defined coastal plain. This coastal wetland type overlaps with bar-built estuarine habitat in the downstream reaches of rivers and streams and generally extends farther upstream. Differentiating between the two habitat types generally requires information other than remote sensing data.

- **Other coastal wetlands.** This category includes a wide variety of other wetland types within coastal areas, such as agricultural wetlands (e.g., rice fields or riparian areas on agricultural lands), wastewater ponds, seasonal wetlands, and vernal pools.

# Appendix E: Baylands Habitat Map Hierarchical Classification System

*Classification system used to map the Baylands Habitat Map (BHM).*

Note that classes in red were not originally included in the BHM2020 mapping effort. Blue cells were mapped in the first iteration of the BHM2020, while purple cells (Estuarine-Terrestrial Transition Zone) were not mapped. Some red classes were added in subsequent updates to BHM2020 (Muted Open Water, Managed Open Water, Salt Pond, Wastewater Pond, Undetermined Other Open Water, and added Storage/Treatment Basin under Other Open Water).

| Level 1: Geography | Level 2: Landscape Complex | Level 3: Hydrogeomorphic Setting | Level 4: Ecosystem Complex/Habitat Type | Level 5: Functional Habitat | MMU (Modified) |
|---|---|---|---|---|---|
| Subregion | Estuarine (Derived) | Subtidal | **Shallow Subtidal** | SAV/FAV Beds | $50m^2$ |
| | | | | Shallow Subtidal Without SAV | $50m^2$ |
| | | | **Deep Subtidal** | | $50m^2$ |
| | | Intertidal, Full Tidal Connection | **Tidal Flat** | | $5m^2$ |
| | | | **Tidal Pond/Panne** | | $5m^2$ |
| | | | **Intertidal Channel** | Intertidal Channel | $5m^2$ |
| | | | | Intertidal Borrow Ditch | $5m^2$ |
| | | | Tidal Marsh | **High Marsh** | $5m^2$ |
| | | | | **Low Marsh** | $5m^2$ |
| | | | Beach | | $50m^2$ |
| | | Intertidal, Limited to No Tidal Connection | Other Marsh | **Muted Tidal Marsh** | $50m^2$ |
| | | | | **Managed Marsh** | $50m^2$ |
| | | | | **Undetermined Other Marsh** | $50m^2$ |
| | | | **Other Open Water** | Muted Open Water | $50m^2$ |
| | | | | Managed Open Water | $50m^2$ |
| | | | | Salt Pond | $50m^2$ |
| | | | | Playa | $50m^2$ |
| | | | | Wastewater Pond | $50m^2$ |
| | | | | Undetermined Other Open Water | $50m^2$ |

| | | | | | |
|---|---|---|---|---|---|
| | | | Non-Aquatic Diked Baylands | **Low Intensity Agriculture** | $50m^2$ |
| | | | | **High Intensity Agriculture** | $50m^2$ |
| | | | | **Developed/Urban** | $50m^2$ |
| | | | | **Undetermined Non-Aquatic Diked Bayland** | $50m^2$ |
| | | Supratidal | **Levee** | | $50m^2$ |
| | | | Estuarine-Terrestrial Transition Zone | | |
| | | | **Dune** | | $50m^2$ |
| | Riverine (Acquired) | Fluvial Channel | River/Stream | River/Stream | |
| | | | Flood Control Channel | Flood Control Channel | |
| | | Floodplain | Floodplain | Low Intensity Agriculture | |
| | | | | High Intensity Agriculture | |
| | | | | Woody Riparian | |
| | | | | Point Bars/Unvegetated Flats | |
| | | | | Floodplain Marsh | |
| | Terrestrial (Acquired) | Depressional Wetland | Depressional Wetland | Seasonal Wetlands | |
| | | | | Vernal Pools | |
| | | Hillslopes | Hillslopes - Natural | Grassland | |
| | | | | Shrubland | |
| | | | | Woodland | |
| | | | Hillslopes - Developed | Low Intensity Agriculture | |
| | | | | High Intensity Agriculture | |
| | | | | Parks/Open Spaces | |

# Appendix F: Status of Current Mapping Efforts

## Habitat: Coastal Wetlands

The San Francisco Estuary Wetlands Regional Monitoring Program (WRMP) is funding the monitoring of the San Francisco bayland habitats through a similar effort resulting in the Baylands Habitat Map (BHM) that is remapped every five years by the San Francisco Estuary Institute (SFEI). BHM has been completed for the baylands status in the year 2020 and is being repeated to represent the baylands in the year 2025. Given that the San Francisco estuary is California's largest estuary and a large portion of the Coastal Wetlands of interest, aligning methods to be comparable to the BHM could be an efficient approach while providing high quality and detailed habitat mapping of coastal wetlands. San Francisco Bay also represents one of the more complicated areas in relation to tidal connectivity of coastal wetlands due to the network of levees and water control structures that necessary to incorporate into the model to account for muted and managed tidal influence.

Other proposed coastal habitat approaches also leverage coastal LiDAR. Coordination between mapping habitat types may make the regular collection of coastal LiDAR more appealing and justify the cost of collection.

- DECODE (DEtection and Characterization of cOastal tiDal wEtlands change)
    - UConn/USGS Tidal Wetlands
- **NOAA Coastal Change Analysis Program (C-CAP):** https://coast.noaa.gov/digitalcoast/data/ccapregional.html
- Other past efforts have been regionally focused, and many current efforts are focused on methods development, such as:
    - **Baylands Habitat Map (BHM)** is developed on behalf of the WRMP by the SFEI. This approach relates closely to the proposed Mapping Approach # 2.
    - **California Aquatic Resource Inventory (CARI)** is developed and maintained by SFEI. It is a compilation of the most recent and highest quality wetland and aquatic feature mapping that is available across California. This, however, means that it doesn't represent a single point in time and thus is not suitable for conducting change detection alone. There are regional intensifications of CARI being developed by SFEI (including the BHM) that focus on automated or semiautomated methods at a regional scale to provide more detailed and up-to-date mapping, where needed and funded, that can be incorporated into CARI as well as often in the National Wetland Inventory.
    - **National Wetland Inventory (NWI)** developed and maintained by the U.S. Fish and Wildlife Service (USFWS).
        - NWI has historically used traditional heads-up digitization paired with field verification. Due to higher cost and longer development times, much of the

dataset is out of date across the country and this model is likely not suitable for regular statewide mapping and detecting changes in habitat acreage.

- **Pacific Marine and Estuarine Fish Habitat Partnership (PMEP)** – CMECS elevation-based mapping of estuary extent for >400 estuaries on the U.S. West Coast. This map establishes an elevational estuary boundary based on annual high tide, important for many aspects of this project (https://www.pacificfishhabitat.org/data/estuary-extents).
- **PMEP Biotic Component map** classifies wetland habitat types within the elevational estuary extent for >400 estuaries on the U.S. West Coast. The classification for emergent, shrub and forested wetlands was derived from NWI and C-CAP (https://www.pacificfishhabitat.org/data/estuarine-biotic-habitat).

- **NOAA high tide flood layer** – This is not a wetland map per se, but it is similar to the PMEP estuary extent layer. This layer maps areas within the range of high tide flooding which occurs once to several times a year. It is very helpful for determining which wetlands are (or were historically) tidal wetlands (https://coast.noaa.gov/htdata/Inundation/NOS_Mapping/NOS_Mapping_2021.zip),

## Habitat: Beaches and Dunes

**Current Mapping Status**

- Early efforts to map coastal dunes in California by William S. Cooper in 1967.
- Timothy Baxter's efforts to create a historical and current (2016) geospatial layer representing the spatial extent of dunes in California.
- USGS Coastal Hazards Portal – historical shoreline position
- California Coastal Dune Science Network – dune inventory and vulnerability assessment - https://www.resilientcoastlines.com/about-3
- Past efforts have been regionally focused, and many current efforts are focused on methods development
  - Current study to map dune change within the Greater Farallones National Marine Sanctuary and across the state of California to inform the addition of a dune evolution model into CoSMoS-COAST. The physical beach and dune modeling will also enable modeling of ecological responses to sediment management interventions such as sediment augmentation and help to answer key questions about the ecological benefits of adaptation. https://coastalscience.noaa.gov/news/developing-coastal-dune-models-specific-to-californias-coast/
  - Eco-Adapt Northern California dune vulnerability assessment
  - Beyond the tide dune mapping - https://eos-gnss.com/successes/kyle-emery-sea-level-rise-research

### Dune Mapping Efforts in Other Regions

- Maine Geological Survey Coastal Sand Dune Mapping - https://www.maine.gov/dacf/mgs/pubs/digital/dunes.htm
- Michigan Department of Environment, Great Lakes and Energy Mapping of Critical Dune Areas - https://www.michigan.gov/egle/about/organization/water-resources/sand-dunes/critical-dunes/maps

## Habitat: Eelgrass

### Current Mapping Status

- There has been episodic mapping of eelgrass beds in individual enclosed estuaries and embayments, as well as portions of the open coast across California since 1994. A considerable portion of these data resides within EcoAtlas (www. ecoatlas.org).
- Considerable project-based mapping of individual embayments or specific eelgrass beds driven by restoration or mitigation efforts. The availability of these data is highly variable, depending upon the funding source. These efforts are often funded by municipalities or companies and driven by NOAA's California Eelgrass Monitoring Policy (CEMP).

### Eelgrass Mapping Efforts in Other Regions

- Long Island Sound eelgrass mapping and restoration efforts
- Virginia Institute of Marine Science eelgrass mapping and restoration efforts (https://www.vims.edu/research/units/programs/sav/)
- Texas Statewide Seagrass Monitoring Program (https://www.texasseagrass.org/)

## Habitat: Rocky Intertidal

Past efforts have been regionally focused, and many current efforts are focused on methods development.

- Environmental Sensitivity Index classification of linear shoreline features.
- Current CARI modeled extent based on relative tidal elevation.
- UAS-based surveys compiled to create a DEM for California rocky intertidal habitats paired with modeling of the current and predicted future distribution of intertidal organism community extents (Peter Raimondi, UCSC).

### Rocky Intertidal Mapping Efforts in Other Regions

- National Park Service Rocky Intertidal Communities Monitoring: https://www.nps.gov/im/medn/rocky-intertidal-habitat.htm.

# Appendix G: Using Mapping Approaches in Concert

## Habitat: Coastal Wetlands

### Monitoring Program – Multi-tiered Approach

One could envision mapping using Mapping Approach #1 more frequently to get a good synoptic view of the extent of tidal wetlands in California, but it would not provide detail regarding if those wetlands are starting to degrade across their marsh plane (additional ponds/pannes and mudflat interspersed with vegetation) and thus understanding if there is a real impact and threat of drowning from SLR or other effects to California's tidal habitats. Furthermore, it would be difficult to monitor the smaller scale progress and changes that occur in restoration projects in order to understand how well they are progressing over time. However, that approach is relatively low cost, provides coverage for the entire state and relies on freely available data sources, and could be repeated at low cost.

Mapping Approach #1 could be paired with a costlier but more detailed mapping approach, such as Mapping Approach #2, but restricted to known areas with tidal marsh to manage costs and perhaps just the largest areas and at a lower frequency than a statewide mapping. This is already being done on a five-year interval for one of the largest estuaries (the lower San Francisco Bay Estuary) through the efforts of the WRMP. This would provide more detailed habitat information as well as enable a host of metrics to detect the quality of habitat that coastal wetlands are providing over time and how restoration projects are progressing and the impacts of sea level rise, etc. Being able to do this higher resolution mapping across different latitudes to better understand patterns happening at the regional scale and variability across Northern and Southern California's coastal wetlands.

A Project Tracker (https://ptrack.ecoatlas.org/) approach where coastal wetland project managers submit information about their progress to a central location, allows for statewide summaries of coastal wetland project impacts. This approach would help specifically with tracking change from restoration efforts, but not larger system impacts to wetlands such as sea level rise and temperature trends. However, without remote sensing approaches information on completion may be limited to "breach dates" and other course measures of completion rather than habitat generation and stability over time. Incorporating California Rapid Assessment Method (CRAM; https://www.cramwetlands.org/) assessments for specific coastal wetlands across subregions can help characterize the condition of coastal wetlands across the state, as well as allow for tracking impacts and performance of restoration efforts. Greater benefits to understanding and tracking habitat acreage, and quality come from using these levels of monitoring in concert.

### Mapping Subregions

Most of California's tidal wetland acreage occur in a limited number of larger embayments and estuaries that could be used to focus more detailed mapping (e.g., Mapping Approach #2) mapping:

- San Francisco Bay Estuary

- San Diego Bay
- Elkhorn Slough
- Tijuana Estuary
- Sacramento–San Joaquin River Delta
- Drakes Estero
- Bolinas Lagoon
- Bodega Bay
- Humboldt Bay
- Arcata Bay
- Morro Bay
- Santa Monica Creek
- Mugu
- Ballona Wetlands Ecological Reserve
- Seal Beach National Wildlife Refuge
- Bolsa Chica
- Upper Newport Bay
- Kendall-Frost Mission Bay Marsh

These estuaries could be mapped at less frequent intervals than statewide lower resolution mapping. Note that some of the largest already being mapped (San Francisco Bay through the WRMP) at a regular interval (e.g., 5 years).

### Bar-built Estuaries

Bar-built estuaries occur in a more distributed way along the coast of California and have a more dynamic nature of seasonal breaching and extent due to wave action on fronting sand bars/beaches than most other tidally influenced wetlands. These features may need an adjusted approach to mapping them than other tidally influenced wetlands for Approach #2 level mapping, but likely would rely on the same type of data sources.

## Habitat: Rocky Intertidal

### Monitoring Program – Multi-tiered Approach

For a more wholistic monitoring approach of Rocky Intertidal, one could consider using a mapping approach such as Mapping Approach #3 that creates a Coastal DEM that would support the modeling and forecasting of how different more detailed and ecologically based rocky intertidal habitats are distributed. Furthermore, one could consider dividing the California coast into ecologically distinct regions to direct more detailed site based and biological monitoring which could be extrapolated across the habitat delineated in the more synoptic rocky intertidal area mapping effort. This approach might consider establishing sentinel sites across each subregion where consistent site-based and biological monitoring could occur. The OPC expert panel mentioned that for rocky intertidal, UAS surveys that include LiDAR and imagery provide most of the data needed for biological monitoring at the site level. That level of monitoring exceeds the level of detail desired at this time by OPC.

Coastal LiDAR data collection poses a significant cost, but also provides increased mapping accuracy, specificity, and modeling opportunities. If regularly collected LiDAR data provides benefits for mapping multiple habitat types and desired efforts, it may become more apparent that it is worth the additional investment.

## Other Mapping and Monitoring Approaches

Two other types of mapping or monitoring that were discussed by the OPC Habitat Mapping Expert Panel for Rocky Intertidal: 1) Biological Habitat Suitability / Ecological Predictive Model and 2) Site Based Biological Monitoring. Neither of these efforts are suitable for estimating general area acreage of “Rocky Intertidal” but rather focus on habitat definitions with stronger biological/ecological based definitions and investigating organism’s range within Rocky Intertidal as well as ecology community health. However, a Rocky Intertidal area mapping approach could be chosen with the added benefit of being able to support these additional desired efforts.

### Biological Habitat Suitability / Ecological Predictive Model

This effort builds off work that is already being conducted by Pete Raimondi and others where they have taken a detailed rocky intertidal DEM and modeled the inundation patterns to determine ecological habitat suitability and predict how it might change with predicted sea level rise over time. This effort might pair nicely with the Mapping approach #3 as it would create a detailed DEM of coastal habitats that could be used for this effort. This effort would model the amount of surface area of biologically defined habitats and is a more detailed habitat modeling effort than just looking at area of “Rocky Intertidal” habitat. It would model and map available and predicted future habitat available for specific groups of organisms based on inundation frequency and potentially other ecological factors.

### Site-Based Biological Monitoring

The Expert Panel also discussed how site based biological monitoring or mapping of the impacts of heat stress and other biological events are important for understanding the health and quality of these ecological communities that exist within Rocky Intertidal habitats. These efforts go beyond estimating the area of Rocky Intertidal habitat and require onsite monitoring by specialists. Site-based biological monitoring could also include more detailed local mapping using Unoccupied Aerial Systems (UAS).

# Appendix H: Summary of Data Suitability by Boundary Attribute and Habitat Type

This appendix provides a series of matrix tables that assess the suitability of the data sources by boundary attribute for each habitat type. This higher-level summary is useful for a more general overview of the potential data sources. Each combination is evaluated for its utility (high, medium, low) and ability to meet the following requirements:

- S: meets only the **spatial** scale requirements
- T: meets only the **temporal** scale requirements
- P: meets only the **spectral** scale requirements
- ST, SP, or PT: meets **combinations of S, P, and T** scale requirements
- SPT: meets the **spatial, spectral, and temporal** scale requirements
- NS: **not suitable** for the habitat type

The matrix tables by habitat boundary attribute are available in this spreadsheet. Please note that there is a different tab for each habitat type:
Appendix H - OPC Scoring Matrix_All Habitats_v5_By Boundary Attribute.xlsx

# Appendix I: Detailed Matrix for Mapping Approaches for Coastal Wetlands

This appendix illustrates the rationale regarding why certain datasets are more appropriate for certain coastal wetlands mapping approaches than others. Please note that there is a different tab for each mapping approach:

Appendix I - OPC Scoring Matrix_Coastal Wetlands_v5 Detailed Mapping Approaches.xlsx