Remote Sensing Recommendations for Tidal Wetland Indicators

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This document is based on the consensus advice and review of the Remote Sensing Workgroup of the Montezuma Project Technical Review Team (Appendix A). Workgroup members discussed specific comments that are the basis of this document, which the workgroup has reviewed for accuracy and completeness.

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INTRODUCTION

This document presents potential products and methods for monitoring a suite of tidal wetland habitat indicators designated for the Montezuma Wetlands Project (Project) using remote sensing technology.

This document can also serve as a starting place for the Technical Advisory Committee (TAC) of the San Francisco Estuary Regional Monitoring Program (WRMP) to develop a set of regional protocols for monitoring the same or similar habitat indicators.

As the administrator of the Technical Review Team (TRT) of the Montezuma Wetlands Restoration Project (Project), the San Francisco Estuary Institute (SFEI) developed a list of indicators that could be used to address the specific monitoring needs of the Project (Table 1), based on the Project's Mitigation, Monitoring, and Reporting Plan (MMRP) and the Master Indicator Matrix of the San Francisco Estuary Wetlands Regional Monitoring Program (WRMP). Indicators were selected to meet the particular monitoring requirements of the MMRP, while also linking the Project to the WRMP as a future collaborating source of data needed to assess the Project in a regional context.

SFEI convened a remote sensing workgroup (members are listed in Appendix A) to: (a) help identify current remotely sensed products and their derived geospatial datasets, and (b) match the indicators with the appropriate remote sensing technology and methods. This document is organized around the indicators. For a summary of the recommended technologies and how they can be applied to the proposed indicators please refer to Appendix B.

Table 1. List of tidal wetland habitat indicators for monitoring wetland change

Indicator Type	**Tidal Wetland Habitat Indicators**
Hydro-geomorphology	**1**. 3D dimension (total length, max, min and mean width; max, min and mean depth, total volume) of tidal channels, to the degree that they are dewatered at low tide, relative to NAVD88 and project-specific MHW and MHHW
	2. Intertidal landscape topography and elevation, relative to NAVD88, and project-specific MHW, and MHHW
	3. Phase and cell breach (notch) 3D shape and elevation, relative to NAVD88, and project-specific MHW, and MHHW
	4. Location and 2D size of areas of water stranded on plain and in channels during slack low tide, (not) including seasonal wetlands (seasonal - few times a year) (but not vernal pools)
	5. Boundary of maximum tidal excursion
Vegetation	**6**. Percent cover of major dominant species or assemblages
	7. Patch size-distribution for major dominant species or assemblages
	8. Vegetation mean height and mean density by major dominant species or assemblages
	9. Total vegetation percent cover
	10. Location and size of patches of invasive plant species (per Project species list)
	11. Detection of new colonies of invasive plant species (per Project species list)

Spatial resolution and accuracy are key concepts in remote sensing data analysis and interpretation. Spatial resolution refers to the size of the smallest feature that can be detected by a sensor or displayed in an image derived from remotely sensed data (e.g. pixel size of a raster). Spatial accuracy refers to how closely a measurement comes to the actual location.

A major concept integrated into the following discussions of indicators and their sources of data is that the optimal monitoring methods and frequencies depend on the rate of change in the conditions being monitored, the minimum detection limits of the methods, and the amounts of change that should be detected. This document begins to interrelate these considerations for each indicator.

Data cost information provided below stems from estimates for data acquisition at the listed resolution level. Costs may be different for different product resolutions. Costs for labor to manage, publish, and interpret the data are not included.

There are many remote sensing data sources and products that can be used to address different indicators for the Project. Each data source comes with its own trade-offs between cost, extent, spatial resolution, spatial accuracy, spectral resolution, spectral accuracy, temporal resolution, and timing flexibility. Considering these tradeoffs early is important to allow for consistency in data collection over the course of monitoring. The consistency in the time of year/seasonality of data collection is essential for change detection and monitoring over time. This document discusses a suite of remote sensing data sources and products that, when used together through an ongoing cycle of data collection and analysis, could provide an effective and efficient approach to quantify the monitoring indicators listed in Table 1 above. As remote sensing technologies and data sources advance and improve over time, new, more efficient or effective methods and approaches may become available. However, it is important that data products and metrics are comparable over time, despite the evolution of remote sensing science and technology.

REMOTE SENSING PRODUCT DESCRIPTIONS

Topographic or Topobathymetric Lidar

Topographic or topobathymetric lidar is a common data source for monitoring most Indicators. Tidal wetland monitoring surveys should be conducted via UAS, plane or helicopter during low tide. Some Remote sensing firms offer lidar that use green wavelengths, which can have increased penetration of water (if the water has very low suspended solids) and therefore might be able to capture elevations underwater to create a Bare Earth digital elevation model (DEM) that includes the subtidal channel elevations. A bare earth DEM is sometimes referred to as a Digital Terrain Model (DTM) which refers to an elevation product where the data is processed to remove elements (such as trees and built structures) which extrude above the terrain height. Digital Surface Models (DSM) are DEMs where these elements have not been removed. It is the workgroup’s experience, however, that lidar data is often problematic over water and the reliance on lidar for the structure of subtidal areas may be suspect and warrants special attention and consideration. This is particularly true in turbid waters which may be found in more recently restored sites. Please note that Indicator 2 specified intertidal landscapes and thus lidar flown at low tide should be sufficient. The use of ground control points (GCPs) could be used to improve DEM spatial accuracy.

Given the expected rates of 3D physical change for the project over its first decade of tidal action, the workgroup recommends at least a 3.0ft. (91 cm) horizontal resolution with whatever data are commercially available, and vertical accuracy of +/- 0.3ft (9.1cm). Data meeting these specifications would be adequate to monitor the hydrologic Indicators 1-3 and to support Indicator

5 (assessing the extent of tidal excursion), and are necessary to develop the baseline vegetation map for Indicators 6-11 (described below).

Different methods are needed to achieve the 0.3ft (9.1cm). vertical accuracy before and after the site is densely vegetated. After it is vegetated, the lidar-based DEM will need to be corrected for interference caused by the vegetation, including especially its water content. We recommend following the published procedures for “LEAN-corrected lidar” that have already been applied to tidal wetlands in the region of the Project[1]. Correct usage of these procedures should achieve the desired precision of the DEM, even when the marsh plain is densely vegetated.

All of the indicators rely on converting the data to tidal elevations, using targets with known elevations, relative to project-specific tidal datums, such as NOAA benchmarks. Establishing the targets may require second-order optical leveling from tidal benchmarks. Standard procedures for such leveling are readily available from state and federal governmental websites (e.g., https://www.ngs.noaa.gov/PUBS_LIB/GeodeticLeveling_Manual_NOS_NGS_3.pdf, https://dot.ca.gov/programs/right-of-way/surveys-manual-and-interim-guidelines). Special techniques can be required for high-precision leveling surveys on soft substrates such as mud or peaty soils to assure that the instrument and rod remain level and vertical, and at a constant height above the ground, for each survey turning point. The Montezuma Project will evaluate if current methods are suitable to meet internal vertical survey requirements.

For vegetation mapping, lidar data should include all the lidar returns, including the first and last return and should be paired with 4-band, high resolution aerial imagery. Finer spatial resolution DEMs could be available, but potentially more costly, and potentially not necessary. Higher resolution is not always ideal as it leads to longer processing time of lidar point clouds and results in larger and less wieldy file sizes. Required spatial resolution will be determined by the desired minimum mapping unit (MMU) determined by scientists for assessing vegetation change. It is assumed at this time that the desired MMU may be revised as the restored vegetation cover evolves, based on the data for each monitoring period.

To track change over time, lidar will not be needed every year, but can be used to establish a high resolution, high accuracy baseline assessment that could be resurveyed on a repeating schedule (e.g., 3 to 5 years), determined by the rate of hydrogeomorphic and vegetation change, as evidenced during interim years through lower-cost data sources. Please refer to the *Unmanned Aerial System Imagery* section (below) for guidance on interim monitoring.

In previous wetland vegetation mapping efforts within the Bay Area, conducted by Workgroup members, Counties have collected and shared low tide lidar data. Thus it may be feasible to coordinate with Counties in order to save the Project from having to incur the costs of collecting lidar data on its own. If lidar is collected by manned aircraft then expanding the coverage area while increasing the number of partners to share the data collection cost would likely reduce costs for the Project. This may not be the case if lidar is collected by UAS. Coordination would be needed to ensure the requirements needed for Project vegetation mapping are satisfied (resolution, timing, extent, etc.).

- Initial Recommended Resolution:
    - DEM/DTM horizontal resolution of 3.0ft (91cm) with vertical accuracy of 0.3ft (9.1cm) has been used for tidal wetland surveys, although higher horizontal spatial resolution from the dense lidar point cloud (first and last returns) is possible if warranted.

  - Note: The Project currently uses a NOAA level 1 benchmarks to calibrate the surveys. Permanent GCPs referenced to local high tide datums calculated from the on-site tide gauge should be used for assessing and improving the accuracy of lidar products and making geospatial corrections.
- Current Cost Estimate:
  - NV5 Geospatial (formerly Quantum Spatial) estimate to acquire and process lidar is $39,688, for 3.0ft (91cm) spatial resolution and 0.3ft (9.1cm)vertical accuracy (for Montezuma Project ~ 2,300 acres by manned aircraft, June 2020);
  - Generally for projects over 100 sq. miles in size, airborne QL1 (Quality Level 1) lidar data costs would be approximately $550-600/sq. mile. (Kass Green personal communication); Quality Level refers to the density of points, with QL 1 being the highest density of points.
  - Processing for higher than 3-ft resolution products may increase costs.

4-band Plane Based Orthoimagery

Consisting of bands for red, blue, green and near-infrared, 4-band imagery supports detection of water and vegetation at 3-inch (7.6cm) horizontal resolution. Therefore 4-band imagery, acquired via plane, is the recommended data source for monitoring Indicator 4 (the location and 2D size of areas of water stranded on the marsh plain and in channels during slack low tide). In combination with first and last returns from a lidar survey, 4-band imagery is also recommended as the basis for the vegetation map for Indicators 6-11. The near-infrared band is important for remotely sensing water or soil moisture as well as chlorophyll content in vegetation, making it particularly useful for explaining plant distribution, abundance, and even health. From previous Bay Area regional vegetation mapping efforts, mapping professionals have found 4-band imagery sufficient, with additional spectral bands providing diminishing levels of benefit.

The high spatial resolution enables the support of smaller minimum mapping units (MMUs), allowing for the detection of smaller changes in vegetation, and potentially allowing for earlier detection of change and trends. Finer delineation of species and assemblages, enabled by higher resolution data can be rolled up to more generalized classes that do not require as small MMUs. Thus the higher resolution data provide more flexibility in the definition of plant assemblages and patches as well as generally improving mapping accuracy regardless of MMU. This flexibility will enable the TRT to adjust these metrics according to the changing complexity of the vegetation, monitoring needs, and to more easily allow for comparison with other sites. 0.5ft (15cm) or higher horizontal spatial resolution has been found to be sufficient for previous wetland vegetation mapping efforts in the Bay Area.

The schedule of remotely sensed imagery collection is important to consider, especially when tracking change over time. The remote sensing workgroup has found that imagery flown in the summer has worked best for mapping wetlands in Suisun Marsh and other areas in the San Francisco Bay Area. Summer also coincides with imagery flown to support the California Department of Fish and Wildlife's Vegetation Classification and Mapping Program (VegCAMP). Perhaps more important is a consistent schedule of imagery collection across years. This is especially important to control systematic errors in the data introduced by seasonal variations in the phenological expressions of indicator species and vegetation assemblages. The need for a standard annual schedule of data collection may limit the choice of existing data sources.

Data collection using manned aircraft has potentially lower costs per acre when surveying large areas, such as the entire Estuary. These cost saving might not exist for smaller area of interest, like the Project. Again, it may be possible to coordinate with Counties, special districts, and other local government agencies for acquisition of imagery for the Project, as part of their geographically larger data collection efforts. Such coordination has occurred in the past and can be pursued to reduce costs for local wetland monitoring efforts.

One important source of 4-band, plane-based orthoimagery that should be considered for use is the U.S. Department of Agriculture's National Agriculture Imager Program (NAIP) imagery. This imagery is generally collected during "leaf-on" periods, in late June and August, which are suitable for wetland mapping. NAIP imagery is acquired every two years, depending on funding, at a 3.2 ft (1.0 m) special resolution/ground sample distance. However, a 1.6 ft (0.5 m) resolution product may be available through vendors such as Hexagon. One challenge is that collection is timed with solar noon, rather tidal stage, and timing collection with low tide is likely not be possible. Some workgroup members have used NAIP imagery collected at mid-tide and MHHW for wetland analysis with success. However, one should be cognizant of the tidal stage during each NAIP image and the impacts that may have on comparisons between years. Given these constraints, this data source may be more suitable for interim years of monitoring between high-resolution, high-accuracy monitoring periods.

- Initial Recommended Resolution:
    - 3-inch horizontal spatial resolution;
    - 4-band spectral resolution;
    - During interim years, NAIP imagery may be suitable and at reduced costs.
- Current Cost Estimate by Vendor:
    - NV5 Geospatial (formerly Quantum Spatial) estimate: $10,046;
    - EagleView;
        - 2.7in (6.9cm) - 0.8in (2.0cm) resolution, 3-4 band. New flights - minimum cost of $25,000 for a minimum of 26,240 acres (106 km^2) (at 2.7in (6.9cm) horizontal resolution, 4 band spectral resolution) (more than 2,300 acres (9.3 km^2). Historical imagery is a mix of 4 band and 3 band (most recent is March 2019 with more going back) priced at $500/ 4 square miles (10.4km^2) or web based explorer annual subscription pricing at $1,500. They can collect both orthogonal and oblique imagery.
    - NearMap:
        - 3-band (<3" resolution), subscription based or exported 6in (15.2cm). Negotiable $15k-20k annual subscription. They already are collecting the data and have expressed interest in partnership/Case Study with a reduced price available. Can't determine timing of this imagery for low tide.
        - NearMap also does some automation of object classification including elevation classes of vegetation (i.e. short vegetation, medium height vegetation, tall vegetation) using Digital Aerial Photogrammetry (DAP) (a novel technique described in the UAS imagery section below).
    - Terravion (Closed as of September 2020):

- A standard, in-zone, single collection of (RGB, NIR, NDVI, Thermal) runs \$1.50 / acre / collection (for Phase I - 800 acres = \$1,200. For entire project - 2,287acres = \$3,430).

Unmanned Aerial System (UAS) Imagery and Digital Aerial Photogrammetry Imaging Techniques

UAS or drone-based surveys can be run at any time of year when weather conditions are appropriate. UAS can be used to produce a variety of data sets. UAS true-color imagery with GCPs might be acquired during interim years between the more resolute and expensive lidar and plane based baseline updates to monitor Indicator 1 (the 3D structure of tidal channels), and Indicator 4 (location and 2D size of areas of water stranded on plain and in channels during slack low tide). Compared to acquiring lidar for every survey year, using UAS can be a cost-effective option. However, the required and resulting accuracy levels should be carefully assessed.

Having permanent GCPs that could be captured in lidar surveys, and periodically captured with ground survey grade GPS units can reduce the costs of having to set and capture new GCPs for UAS flights used to determine elevation values. True color UAS imagery could also be used for “ground truthing” in difficult-to-reach areas for vegetation mapping as well as for quickly checking for colonization by invasive vegetation species (i.e., Indicator 11).

With the aid of GCPs, UAS imagery can be processed using Digital Aerial Photogrammetry (DAP), photogrammetric range imaging techniques, to create DEMs (assuming a 20MP sensor, ~0.25 in – 2 in horizontal spatial resolution). DEMs include Digital Surface Models (DSM) and Digital Terrain Models (DTM). DSM represent the top elevation of vegetation and structures. DTM represent an estimation of the geodesic surface, or “bare earth” and are only possible to derive when sufficient bare earth is exposed (i.e. not obscured by vegetation). For example, UAS true-color imagery with GCPs could be used, in conjunction with the most recent bare earth lidar, to monitor Indicator 1 (the 3D structure of intertidal tidal channels), as well as Indicator 8 (mean vegetation heights) in the interim periods between updates of the more accurate detailed lidar dataset. It is important to note that that DEMs and DTMs derived from high resolution true-color imagery using DAP have been problematic for Bay Area vegetation mapping in the past (Kass Green, personal communication). However, as technology and processing capabilities improve, these datasets may become more affordable, accurate. Consider testing this methodology during baseline lidar collection years as a special study.

UAS-based multispectral imagery (in contrast to true-color imagery) may also be considered for the creation of the vegetation map (see below), as required for Indicators 6-11. The multispectral imagery would need to consist of at least four bands, including near-infrared. Near-infrared bands can help identify areas lacking soil moisture (i.e., very high-elevation areas) and to assess chlorophyll levels in vegetation, as a way to assess flora type as well as health or vigor. Declines in plant vigor can be an early indicator of hydrological or soil issues. However, multispectral sensors that are small enough to be carried by UAS often are more costly and produce lower resolution imagery than true color sensors, which can be problematic for accuracy and resolution of DAP-derived DEMs. These differences will likely lessen over time, however, as the technology improves. UAS compatible sensor size, resolution and capabilities continue to improve and even include hyperspectral sensors[1].

Challenges to using UAS-based imagery include an increased number of distortions or “artifacts”. This is due to processing a large number of photos that cover a relatively small area (compared to photos taken from satellite or a manned aircraft), and having to “stitch” them together into one georectified orthomosaic. These distortions could include sun glare reflected off standing water or changes in sunlight during the duration of the UAS survey, as the sun angle changes and cloud shadows move. Furthermore, the spectral values of UAS data are not always consistent across different flights, days, and images. These differences can be accounted for if ambient light is continuously evaluated (often by a second sensor on the UAS) and used to calibrate the reflectance values captured by the main sensor. This normalization of the data helps to ensure that measurements for selected, unchanging objects under different lighting conditions remain constant, which is particularly useful if comparing images taken at different dates/times.

The Moss Landing Marine Laboratory successfully applied UAS surveys to monitor changes in the channel network in Elkhorn Slough in Moss Landing, CA. The UAS data were used to create digital surface models, and surface elevation table (SET) rods served as elevation controls. The topographic data and survey data were used to make cross sectional measurements, to determine channel lengths, order, and volume measured using Potential Diurnal Tidal Prism (acre-ft.). You can find their paper on monitoring the restoration at Elkhorn Slough here: https://www.dropbox.com/s/doaabd079dt94lt/Haskins%20et%20al%202021%20UAV%20to%20inform%20restoration.pdf?dl=0.

- Initial Recommended Resolution:
    - True-color: ~1/4 - 2-in horizontal spatial resolution 3 visible (RGB) for DAP derived DEM creation;
    - Multispectral (at least 4-band) imagery useful for vegetation mapping (for example the multispectral MicaSense RedEdge MX, or Altum sensors);
    - Vertical and horizontal accuracy of DAP derived DEM and GCPS would need to be determined.
- Permanent GCPs are used in processing the data and making geospatial corrections.
- Current Cost Estimate:
    - There may be a price difference between UAS multispectral and true-color imagery, and cost estimates are needed.

WorldView 2 or 3 (operated by DigitalGlobe, a Maxar Technologies company) and comparable Satellite imagery

WorldView satellites provide roughly 1.0 ft (30 cm) horizontal spatial resolution, 8-band imagery (panchromatic at 1.0 ft (31 cm), visible and near infrared at 4.0 ft (1.24 m), shortwave infrared at 12 ft (3.7 m) and CAVIS at 98 ft (30 m)). The spectral resolution includes wavelengths in the

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[1] UAS based hyper spectral imagery https://www.sciencedirect.com/science/article/pii/S0168169917310499

visible spectrum, as well as near-infrared and infrared. WorldView 2 or 3 also provides the advantages of higher temporal resolution and spectral resolution compared to NAIP imagery or any plane-based 4-band system. While other data sources are likely better for establishing higher-resolution baselines for the Indicators, WorldView is a less costly alternative data source for interim years between baseline assessments. Unfortunately, satellite imagery is often licensed, meaning that the Project may not be able to share it with partners without significant increases in cost. For smaller areas, such as a single project AOI, satellite imagery may be less expensive per square mile than plane-based imagery. However other risks of using satellite imagery include potential cloud cover (often up to 15%) and the flyover not necessarily coinciding with low tide. The timing of the data with the tides depends on the satellite's orbital position.

During interim years, WorldView could provide data for monitoring Indicator 4, the location and 2D size of areas of water stranded on the marsh plain and in channels during slack low tide (not including seasonal wetlands), if the data happen to coincide with low tide. There would also be limitations due to the lower spatial horizontal resolution of the dataset. 1 ft horizontal spatial resolution may be too coarse for the desired vegetation or channel MMU, and higher resolution may only be achievable via airborne sensors (as recommended for baseline phases).

More likely, WorldView could be used during interim years for vegetation Indicators 9-11. This is possibly a cost-effective option, if paired with UAS derived Digital Terrain Models, compared to updating the vegetation map using lidar and 4-band imagery every monitoring year (as recommended for less frequent baseline updates). However, for the decreased costs there are concessions made in horizontal spatial resolution, reduced accuracy of elevation data, and the lack of bare earth elevation data. Methods of "pansharpening" (i.e., merging high-resolution panchromatic and lower resolution multispectral imagery to create a single high-resolution color image) can increase the spatial resolution of digital imagery, while decreasing its accuracy.

- Horizontal Spatial Resolution Options:
    - World View:
        - Panchromatic 1.0 ft (31 cm) horizontal resolution;
        - Visible & near-infrared 4.0 ft (1.24 m) horizontal resolution;
        - Short-wave infrared 12 ft (3.7 m) horizontal resolution;
        - CAVIS 98 ft (30 m) horizontal resolution.
- Current Cost Estimates:
    - NV5 Geospatial (formerly Quantum Spatial) estimate: \$3,600 for 100 km^2 (24710.5acres) (June 2020):
    - Costs may not be lower than plane based 4-band orthoimagery (Kass Green, personal communication):
    - Expect to negotiate additional costs to share licensed imagery
- Drawbacks:
    - 15cm orthoimagery (from Airborne sensors) are much better for mapping tidal wetlands than 31cm (Kass Green, personal communication, based on Elkhorn Slough experience);
    - Cannot control the timing to specifically capture a low tide image;

  - Potential cloud coverage up to 15%.

Stationary Camera

One or more stationary cameras are recommended for monitoring Indicator 5, the boundary of maximum tidal excursion. If placed strategically to capture the extent of the high tide water line, the images acquired can be used in combination with the baseline topographic lidar survey DEM to extrapolate elevation of the observed inundation to estimate the extent of Mean Higher High Water (MHHW) for each Phase of the Project. Ideally, cameras would be adjusted initially to cover this MHHW boundary and other areas of interest and then remain stationary until the boundary leaves the camera frame, which might happen due to sea level rise. Stationary cameras are also used for monitoring vegetation in many different natural environments. These cameras are sometimes referred to as "phenocams". There is a wide range of stationary cameras that could be deployed. Some are true color cameras and some also include infrared bands. There may be additional benefits from being able to monitor over time and compare data collected from these cameras to other sites around the Bay Area and beyond. An example of a network of stationary cameras used in this way is operated by the National Ecological Observatory Network (NEON) (https://www.neonscience.org/data-collection/phenocams). NEON uses Stardot NetCam CS CAM-SEC5IR-B to collect RGB and IR images every 15 minutes.

- Current Cost Estimate:
  - Stardot NetCam CS CAM-SEC5IR-B: $892.50 (4-band), not including camera pole and installation. There are additional potential costs with remote sensing data associated with data acquisition, transmission and processing.
    - In many cases this may be overkill. And may not be necessary for detection inundation extent.
  - There may be other less expensive true color (RGB) cameras that are still weather resistant and meet monitoring needs.

Multibeam and Side-scan Sonar

Multibeam or side-scan sonars can be deployed with manned or unmanned water vehicles to map the structure and bathymetry of larger channels that do not dewater at low tide to address monitoring Indicator 1. Side-scan sonar has a wider spatial swath of data collection than multibeam sonar and is less costly. Some combination of side-scan or multibeam sonar might be used to characterize structure/bathymetry in the larger channels that do not dewater. The Project has used an over-the-side mounted Reson SeaBat T50-R Multibeam Echosounder (MBES) on a 24ft boat. This multibeam echosounder is designed to operate nominally between water depts. Of 0 to 265 ft and was used to collect bathymetric data from 0 to 45 ft of water depth on the Project site. After acquisition, position and navigation data were post-processed to achieve position accuracy of < 0.3 ft (0.1m). The Project has reported that different sensors might have been used for some surveys. Depending on boat accessibility, using autonomous floating vehicles may allow for access to smaller and shallower channels, if deemed necessary.

The following link from the U.S. National Parks Service describes several mapping technologies for shallow water mapping including Side-scan and Multibeam sonar:

https://www.nps.gov/caco/learn/nature/upload/Copy-of-Matrix-of-mapping-technologies-for-shallow-water-mapping.pdf.

- Initial Recommended Resolution:
    - 24 ft (7.3m) long survey vessels have been used at the Montezuma Restoration Project using an over-the-side mounted Reson SeaBat T50-R Multibeam Echosounder (MBES);
    - For shallow areas where manned one potential option would be the HYCAT Autonomous Surface Vehicle (ASV) (https://www.ysi.com/hycat). These vehicles with required sensors may be available to rent.
- Cost information:
    - At the Project a boat survey using the multibeam echosounder for the initial breach was roughly $5,000, included data download and transfer.

On-ground Surveys

On-ground surveys may be needed for validation of remotely assessed indicators. Such surveys may be necessary to detect new colonies of invasive plant species, as well as ground-truthing for the development of the vegetation map (in support of Indicators 6-11). As previously mentioned, locations that are inaccessible on foot could be virtually “ground-truthed” using UAS, ideally in coordination with suitable field scientists to direct UAS activities.

DEVELOPING THE VEGETATION MAP

Vegetation maps will be essential for monitoring Indicators 6-11. Key to the creation of the vegetation map will be decisions regarding the vegetation classification scheme and the MMU, as these specifications will significantly affect both the cost and the usefulness of the map.

A vegetation classification scheme defines the vegetation classes to be mapped and includes rules that distinguish classes from one another. As opposed to developing site-specific customized classes, the workgroup recommends using the standard vegetation alliance/association classes and rules established in the Manual of California Vegetation (MCV) created by the California Department of Fish and Wildlife (CDFW) and the California Native Plant Society (CNPS) as a base classification scheme. However, please note, as of the initial publication of this document, there are additional efforts ongoing with CNPS to make classification rules more robust in tidal wetlands. Adoption of MCV classes will enable comparison with other vegetation mapping projects across the entire San Francisco Bay Estuary and the state. However, it will be critical for the TRT to determine whether or not Indicators 6 (% cover of major dominant species or assemblages) and 8 (vegetation mean height and mean density by major dominant species or assemblages) are sufficiently represented by the MVC classes, or if more detail is required.

It is common for MMUs to vary within a map depending on the needs of map users, with critical and/or rare vegetation classes often mapped with smaller MMUs than less important classes. A constant trade-off in vegetation mapping is the desire for detail (i.e. very small MMUs) contrasted with the need for the map data to be affordable, manageable and comprehensible on a landscape scale. Recent MMUs for tidal wetland mapping include 540 to 1075 sq ft (50 to 100 sq. m) in the

South Bay South Bay Salt Ponds (Fulfrost and Associates, 2012) and 0.25 acre (10,090 sq ft or 1,011 sq m) in the ongoing NOAA tidal wetland vegetation mapping of Marin, San Mateo, Santa Clara, and Santa Cruz Counties. A common combined approach is to use larger MMUs for resource management and planning projects of 1000 acres or larger, with the hierarchical implementation of smaller MMUs and more detailed classification schemes for site specific, large-scale projects set within the landscape map area.

Vegetation mapping efforts can result in either raster or vector products. A vector based vegetation map is recommended as it allows for much more robust analysis. A myriad of approaches can be taken to map vegetation. Traditionally, wetland maps have been created through the manual interpretation of imagery captured from manned aircraft or satellites. With the advent of machine learning, automated image segmentation, and robust GIS software has come the adoption of cost-effective, semi-automated approaches that rely on multiple data sets (e.g. imagery, lidar products, management history, field samples, etc.) and computer generated algorithms to map the easily discernible classes, reserving manual interpretation by experts for the harder to distinguish classes. As a result, mapping costs have decreased while map accuracy, detail, and consistency have increased.

For this project, the workgroup recommends employing Object Based Image Analysis Classification, utilizing machine learning to cost effectively map larger areas and efficiently replicate mapping efforts over multiple years of collected datasets for monitoring changes in vegetation over time. The process involves image segmentation, field data collection, QA/QC, machine learning (such as Random Forest) model training, model testing, accuracy assessment, and manual editing to produce the final vegetation map. To support the addition of new vegetation classes discovered during the fieldwork, but not in the MCV, field data collection procedures should be rigorous enough to support the creation of new MCV alliances or associations. Field data collection may be supplemented with UAS in locations that are inaccessible on-foot.

Different remote sensing imagery data types can be used to support large area (>1000acres) vegetation mapping efforts. Each dataset has its own strengths and weaknesses, which are summarized in Table 2 below.

Table 2. Strengths and weaknesses of different remote sensing imagery data that support monitoring of large areas.

Provider***	**Spectral Resolution**	**Cost/ sq. mile**	**Can be Confounded by Cloud Cover**	**License restriction**	**Can be coordinated with the tidal phase or stage**
New Airborne 15cm	Red (R),Green (G), Blue (B), Near Infra-Red (NIR)	$250-275*	No	No	Yes
New Airborne 30cm	R,G,B,NIR	$175-215*	No	No	Yes

Provider***	Spectral Resolution	Cost/ sq. mile	Can be Confounded by Cloud Cover	License restriction	Can be coordinated with the tidal phase or stage
Upgraded NAIP 2020 30cm	R,G,B,NIR	$10.59**	No	Yes	No. Hit-or-miss depending on the date and time-of-day of image collection.
Upgraded NAIP 2020 15cm	R,G,B,NIR	$21.18**	No	Yes	No. Hit-or-miss depending on the date and time-of-day of image collection..
Satellite 30cm	R,G,B,NIR + 4-8 more frequencies	$89.36**	Yes up to 15% cloud cover	Yes	No. depending on the date and time-of-day of image collection.

* Assumes an area of 100 square miles or more for new airborne data collection.

** Assumes single use license.

*** UAS collected imagery is not considered useful for large area vegetation mapping because current UAS capacity is too small, and FAA regulations are too restrictive to cost effectively use UAS data to map large areas.

Costs per square mile for new aerial image collections are highly dependent on the size of the area being imaged. The fixed high cost of manned aircraft mobilization (fuel, maintenance, pilot) decrease as survey area increase, although very large areas can require multiple flights. For a small area the size of the Montezuma Project (3.57 sq. miles), costs for new airborne imagery have been estimated to be $2,814/sq. mile. Neither satellite imagery nor upgraded NAIP imagery require mobilization costs, and as a result their costs per square mile are not affected by the size of the area. However, both satellite and upgraded NAIP imagery are license-restricted (e.g. the imagery cannot be shared universally) and tidal coordination is hit-or-miss depending on the tidal stage when the imagery are collected. Licenses for multiple agencies or other entities can be purchased, but at escalating costs relative to a single license (20% more for 2-5 entities, 45% more for each group license of 5 or more entities). Upgraded NAIP imagery licenses can also be purchased for multiple entities at additional cost. Finally, both new airborne collects and upgraded NAIP imagery are cloud free. Satellite imagery can contain up to a maximum 15% cloud cover. Requests for lower maximum cloud cover cost $10 per sq. km (~$26 per sq. mile) for less than 10% clouds and $20/sq. km (~$52 per sq. mile) for < 5% clouds.

The South Bay Salt Ponds project used DigitalGlobe Worldview 2 and 3 satellite imagery. This imagery was of fairly low spatial resolution 1.0 ft (30cm) but provides greater optical spectral width (8 bands). For the Salt Bay Salt Ponds project an approach called panchromatic sharpening (or “pan sharpening”) was applied to approximate a higher spatial resolution, however, trades off increasing resolution with decreasing accuracy. This approach would be relatively affordable, but would have benefited from having fewer images stitched together for the mapping and higher spectral spatial resolution. The drawbacks would be relatively lower resolution, potentially higher levels of uncertainty, perhaps limiting the ability to distinguish some classes from others.

Wetland vegetation can be mapped with either airborne or satellite imagery, however the accuracy of either approach is greatly improved with the incorporation of lidar data. Lidar data can provide highly detailed and accurate measures of vegetation height and density (Indicators 8 & 9), as well as a broad suite of topographic products. Lidar data would be required for mapping vegetation height (Indicator 8), as heights cannot be obtained from imagery alone. Elevation data (DEMs) derived from DAP, using stereo imagery, were tested in 2018 and proved unusable due to errors. A special study would be needed to test if subsequent improvements to sensor and software processing has addressed these shortcomings, making it more suitable for vegetation mapping. While vegetation density (Indicators 8 & 9) can be mapped from imagery, they are far more accurately mapped from lidar data. There are no high spatial resolution lidar sensors on satellites which would meet the requirements of the Montezuma project. For projects over 100 sq. miles in size, airborne Q1 lidar data costs would be approximately $550-600/sq. mile.

In the Bay Area, a common approach to mapping both upland and wetland vegetation is to use a combination of high resolution imagery with lidar data. The Golden Gate National Parks Conservancy, the County of Sonoma, NOAA, and the Santa Cruz Mountain Stewardship Network all used or are using a combined imagery, lidar and machine learning approach to map the fine scale vegetation of Sonoma, Marin, San Mateo, Santa Clara, and Santa Cruz Counties. All of these projects relied on the broader based requirements of a consortium of organizations who needed imagery and lidar data for more expansive applications than only tidal wetland vegetation mapping. For example, in 2018, Santa Clara County committed to funding imagery collections annually and lidar data collections every three years. Through collaboration, the Santa Cruz Mountain Stewardship Network and others were able to persuade the County to require that their lidar and imagery collections be conducted at low tide to better support tidal wetland vegetation mapping, thereby eliminating any lidar or imagery collection costs incurred by the vegetation mapping project. The workgroup recommends that collaboration opportunities be actively pursued as a way to lower project imagery and data acquisition costs.

MONITORING SCHEDULE

A monitoring schedule for each indicator lays out the timeline for collecting data to track change over time. The schedule starts with an initial baseline survey of foundational data that can be used as a reference for other remotely sensed data collected during the subsequent interim monitoring phase, before the baseline is updated. The baseline update, or baseline phases, will provide the highest resolution and most accurate data for tracking change over time, although they may also be the most expensive. Data collected during the interim phases between baseline updates generally will be less resolute and accurate, but can be a cost-effective way to detect or track changes (especially large ones) at a shorter timescale, to help explain the baseline changes, and to provide early warnings that trigger changes in Project management, future Project Phases, and monitoring methods. The TRT will need to recommend the suites of baseline and interim indicators, data sources, the schedule of their uses, and duration of indicator monitoring, all of which could change as the restored landscape evolves.

It is possible that data such as lidar that are acquired by federal, state, or local agencies could be used to support monitoring and vegetation mapping needs with cost savings to the Project. However, collaboration and coordination on data acquisition can impact the monitoring cycle.

The following tables can be used as a guide for developing a customized data collection schedule depending on the Indicator, amount of area to be assessed, monitoring accuracy, and desired frequency of monitoring, balanced against costs. Table 3 lists the remotely sensed products and/or datasets needed to assess initial baseline conditions and interim conditions that help track change over time for all tidal indicators listed in Table 1 above. Tables 4 and 5 present an example 5-year annual monitoring schedule for the hydro-geomorphology and vegetation Indicators, with short descriptions of the products and datasets to use (either separately or together).The Baseline year would start with a site survey at the time that construction is completed. Interim annual surveys in years 1 through 4 support tracking initial changes over time and help the project evaluate and address any developing issues as needed. The 5-year baseline reassessment will employ the same products as before (or more accurate products) in order to more accurately compare changes in baseline conditions every 5-years. The monitoring schedule could be adjusted based on the rate of observed or expected change within the tidal wetland project area compared to remote sensing detection accuracies and/or change in monitoring priorities.

Table 3. Summary of remotely sensed products and datasets needed during the baseline and interim monitoring phases.

Product/Dataset	**Baseline Phase**	**Interim Phase**
Vegetation Map	🟦	🟦
Lidar	🟩	
4 band plane based Imagery	🟩	
Multibeam side-scan sonar	🟩	
UAS targeted inspections	🟩	🟨
NAIP 4 band Imagery		🟨
WorldView 2 or 3		🟨
UAS orthomosaic		🟨
UAS photogrammetry based 3D model/DAP*		🟨

* May require a special study to assess accuracy of DAP derived DEMs

Table 4. Example monitoring schedule for hydro-geomorphic Indicators.

Hydro-geomorphic Indicators	Baseline Year & Year 5	Interim Year 1	Interim Years 2-4
1. 3D dimension (total length, max, min and mean width; max, min and mean depth, total volume) of tidal channels, relative to NAVD88, MHW, and MHHW	LiDAR (topographic/topobathymetric)	UAS low tide survey - DEM using DAP with ground control points, in non-vegetated, exposed channels.	UAS low tide survey - DEM using DAP with ground control points, in non-vegetated, exposed channels.
2. Intertidal landscape topography and elevation, relative to NAVD88, MHHW, and MHW	LiDAR (topographic/ topobathymetric)	UAS low tide survey - DEM using DAP with ground control points, in non-vegetated, exposed areas.	UAS low tide survey - DEM using DAP with ground control points, in non-vegetated, exposed areas.
3. Phase and cell breach (notch) 3D shape and elevation, relative to NAVD88, MHHW, and MHW	LiDAR (topographic/ topobathymetric)	Traditional ground survey methodology may be most appropriate UAS low tide survey - DEM using DAP with ground control points, if non-vegetated and exposed.	Traditional ground survey methodology may be most appropriate UAS low tide survey - DEM using DAP with ground control points, if non-vegetated and exposed.
4. Location and 2D size of areas of water stranded on plain and in channels during slack low tide, (not) including seasonal wetlands (seasonal - few times a year) (but not vernal pools)	4 band plane based imagery	UAS orthomosaic (4+ band if available) Worldview 2 or 3 or NAIP (if taken at low tide)	UAS orthomosaic (4+ band if available) Worldview 2 or 3 or NAIP (if taken at low tide)
5. Boundary of maximum tidal excursion	LiDAR derived DEM and stationary cameras	UAS low tide survey - DEM using DAP with ground control points, if non-vegetated and exposed. paired with stationary cameras	UAS low tide survey - DEM using DAP with ground control points, if non-vegetated and exposed. paired with stationary cameras

Table 5. Proposed monitoring schedule for remote data collection to develop the vegetation map and other vegetation Indicators.

Vegetation Map & Indicators	**Baseline Year**	**Interim Year 1**	**Interim Year 2-4**
Vegetation Map	LiDAR and 4 band plane based imagery. UAS and site visits for ground truthing	Use Worldview 2 or 3 (8 band) imagery (consider Pan sharpening) or NAIP with baseline year bare earth LiDAR data (unless large change), and UAS based DAP for DSM and DTM. UAS and site visits for ground truthing	Use Worldview 2 or 3 (8 band) imagery (consider Pan sharpening) or NAIP with UAS based DAP for DSM and DTM. UAS and site visits for ground truthing
6. Percent cover of major dominant species or assemblages	Veg Map	Veg Map	Veg Map
7. Patch size-distribution for major dominant species or assemblages	Veg Map	Veg Map	Veg Map
8. Vegetation mean height and mean density by major dominant species or assemblages	Veg Map paired with LiDAR first return and bare earth products	Veg Map paired with UAS based DAP DSM and baseline LiDAR bare earth products, post processing clean up	Veg Map paired with UAS based DAP DSM and DTM, post processing clean up
9. Total vegetation percent cover	Veg Map	Veg Map	Veg Map
10. Location and size of patches of invasive plant species (per Project species list)	Veg Map	Veg Map	Veg Map
11. Detection of new colonies of invasive plant species (per Project species list)	UAS and onsite targeted inspections (UAS technician and ecologist directing inspections)	UAS and onsite targeted inspections (UAS technician and ecologist directing inspections)	UAS and onsite targeted inspections (UAS technician and ecologist directing inspections)

Example Monitoring Schedule

This example assumes that the monitoring schedule calls for a baseline assessment of all the hydro-geology Indicators 1-5 (listed in Table 1 above) and vegetation monitoring (Indicators 6-11) with interim monitoring between baseline reassessments that are scheduled at 5-year intervals.

During the first baseline assessment, lidar and high resolution, plane-based, 4-band imagery would be collected at the completion of project/phase construction to establish a detailed and highly resolute dataset to (1) establish the baseline topographic status of the hydro-geomorphic Indicators, and (2) develop the vegetation map needed to assess relatively long-term trends in the vegetation Indicators. The baseline data will be used to verify the less detailed and less resolute imagery and products collected during the previous and subsequent interim years (e.g. UAS low tide and on the ground surveys, DigitalGlobe Worldview 2 or 3 imagery, NAIP imagery, UAS-based DEMs, and other imagery).

The MMUs and other analytical specifications for all interim products would be decided by the TRT (or Project contractors with TRT review), based on review of the baseline data. This would lead to analysis of Indicator status and trends, relative to the Project performance criteria, and recommendations for any changes in the monitoring program. The monitoring schedule, the suite of indicators used during either baseline or interim monitoring phases, and the data sources could be adjusted based on program monitoring needs, significant environmental events, new science or technology, and available funding.

INDICATOR SPECIFICATIONS

This section presents an initial description of the monitoring specifications for each Indicator listed in Table 1 (above) and lists the preferred remote sensing methods and products for quantifying each Indicator. The tables in Appendix B summarize this information and Table B2 lists candidate products with the most spatially resolute and accurate method listed first. The first method listed in Table B2 is also usually the most expensive method. These methods might only be employed when the more accurate measurements are needed (e.g. during the initial baseline survey and during subsequent baseline updates). The other methods listed are more appropriate for interim monitoring years, or when lower accuracy or resolution are sufficient to characterize, detect and track change in the Indicator.

Indicator 1 (3D dimensions of tidal channels, relative to a local or more distant geodetic benchmark), Indicator 2 (Intertidal landscape topography and elevation), and Indicator 3 (phase and cell breach (notch) 3D shape and elevation, relative to NAVD88, MHHW, and MHW).

The vertical dimensions of the as-built and subsequent evolving tidal channels and marsh plains within the Project should be characterized and tracked relative to the local Mean High Water (MHW) and Mean Higher High Water (MHHW) tidal datums.

It should be noted that, for Indicators 1 and 2 (and 3-5), it is not necessary to tie the project measures to NAVD88, even if the project elects to monitor land motion. Doing so may incur additional systematic error. Assessment of land motion only requires a site-specific geodetic datum based on local upland benchmarks. Their motion can be detected by periodically tying them to each other, and to one or more distant benchmarks that are unlikely to move with the local benchmarks. The distant benchmarks can be tied to NAVD88 if some comparison to other, distant projects in the Estuary is needed.

The specific channel metrics to be calculated for each channel include: total length; maximum, minimum and mean width; maximum, minimum and mean depth; and total volume. Large and small channels will likely be monitored differently, however. Large channels are the constructed channels that tend not to completely dewater during ebb and flow, and therefore tend to retain water at low tide. Small channels form by incising the marsh plain and tend to dewater during ebb flow, and to retain very little water at low tide. The TRT should provide additional guidance about how many channels and which channel sizes to characterize.

Additionally, it should be noted that newly formed channels may not be large enough to measure all their dimensions. As these channels evolve, they can be mapped and characterized in more detail. Each reach between confluences in each channel system should be mapped and given a unique name or code, such that its change in size can be individually tracked. This will be important for identifying places in the channel systems that warrant management, due to detrimental erosion, for example. Care should be taken to track changes in the locations of the headward ends of channels on the marsh plains, such that any risk of headward erosion into non-cover sediment can be addressed. In general, however, we recommend tracking and reporting changes in overall channel system length and volume.

Furthermore, it is important to note that collecting lidar data that detects actual channels is different than manually mapping or developing and applying algorithms that will map the channels. We recommend working with GIS professionals to standardize assessment methods applied to the data collected.

Recommended data source for baseline assessments:

- Topographic/topobathymetric lidar, Bare Earth, for dewatered intertidal channels;
- For large channels that don’t dewater, multibeam sidescan sonar may be need to characterize and track channel depth.

Recommended data sources and related considerations for interim assessments:

- GCP and UAS to get topographic changes at low tide for lower cost and accuracy unless area of interest is heavily vegetated.

Notes from Remote Sensing Workgroup:

- Commercially available high vertical accuracy data are needed.
- Project could inquire about the possibility of finer horizontal resolution than 3 feet.
- LEAN correction methods will be useful for filtering out vegetation to estimate elevation of marsh plain.
- Initial survey could be timed when existing vegetation has died back, exposing more bare earth, but before the cover of tidal marsh vegetation becomes dense.
- Contour lines for the marsh plains could potentially be drawn at 0.5-foot intervals (custom interval easily derived from lidar based DEM).

Indicator 4. Location and 2D size of areas of water stranded on plain and in channels during slack low tide, (not) including seasonal wetlands (seasonal - few times a year) (but not vernal pools)

Recommended data source for baseline assessments

- Baseline 4 band imagery

Recommended data source for interim assessments

- UAS true color to allow regular monitoring, potentially lower cost
- NAIP imagery

Notes from Remote Sensing Workgroup

- WorldView satellite imagery- may not correlate with low tide and may be too coarse of resolution
- Image acquisition must be timed for slack low tide (all lower reaches of the main channel should be dewatered).
- Could fly one cell at a time with UAS.
    - UAS spectral accuracy and normalization is challenging.
    - True color may be all that is needed, but 4 band would also be helpful for water detection.
    - One can more easily coordinate image acquisition with low tide.
- Plane-based sensors have higher spectral accuracy and can coordinate image acquisition with low tide.
- This indicator can help support investigation into support of waterfowl, impacts of vegetation, impacts on mosquitoes and impacts of stranding fish.

Indicator 5. Boundary of maximum tidal excursion

Recommended data source for baseline assessments

- Stationary camera paired with topobathymetric lidar surveys (baselines). One would have a highly accurate bare earth DEM from the lidar survey and be able to both model the maximum tidal excursion, based on local tidal datum, and directly monitor this indicator in a channel or along the backshore (marsh-upland interface), using stationary cameras, and then extrapolate that elevation across the DEM.
- A UAS flight taken at high tide could help refine modeled maximum tidal excursion.
- Extrapolate this indicator from vegetation type and extent.

Notes from Remote Sensing Workgroup

- To directly observe, timing of image acquisition must coincide with Higher High Tide of each spring tide series.

- Spatial resolution of aerial imagery must be greater than 3 ft (1m). Higher resolution would be better.
- Could potentially estimate this indicator using high-resolution (small MMU) vegetation mapping.
- Could potentially use high temporal resolution time lapse cameras, with visible benchmarks in view, then extrapolate across site using elevation data.
    - Location of image acquisition must coincide with Higher High Tide of spring tide series.
    - UC Davis is using automated cameras to get high temporal resolution of tidal excursion.
    - Cameras in the transition zone (marsh-upland interface) would suport monitoring of associated vegetation.
    - PhenoCams are a collection of stationary cameras to monitor vegetation over time in a wide range of locations. The Project could participate in this program. https://www.neonscience.org/data-collection/phenocams

Indicator 6. Percent cover of major dominant vegetation species or assemblages

Recommended data source for baseline assessments

- Veg Map with standardized classes from MCV (joint publication from DFW and CNPS). As of initial publication of this memo, there are efforts ongoing from Kass Green and CNPS to make classification rules more robust in tidal wetlands. Requires lidar (first and last returns) paired with at least 4-band high resolution imagery.

Recommended data source for interim assessments

- WorldView 2 or 3, or NAIP imagery paired with most recent bare earth and first return elevation data (lidar or lidar and potentially UAS derived DAP elevation data)

Notes from Remote Sensing Workgroup

- For vegetation classification, use the MCV for ease of comparison across sites or between project and reference sites.
- Mapping each segment to "percent cover for major dominant species or assemblages" will be very expensive and highly inaccurate. Mapping to alliances will be more accurate and significantly less expensive (See vegetation map section).
- At Rush Ranch, an historical reference site in the North Bay, annual transects are used for vegetation monitoring, and remote sensing is paired with ground-truthing. In addition, different transects are surveyed in each different habitat type (e.g. upland transition zone, marsh plain, etc.). Some areas can be accessed on foot for on-ground surveys, and UAS is used to fill-in inaccessible areas.

Indicator 7. Patch size-distribution for major dominant vegetation species or assemblages

Recommended data source for baseline and interim assessments

- Most recent Vegetation Map, with standardized classes from MCV (from DFW and CNPS), can be used for analysis (using LiDAR and 4-band imagery from manned aircraft for baseline measures, and a combination of Worldview or NAIP and recent elevation data in interim years).

Notes from Remote Sensing Workgroup

- TRT must determine a minimum mapping unit (MMU) for the vegetation patches.
- The MMU should tie directly to habitat significance for a specific MMRP performance measures/success criteria es (e.g., Black rail).
- MMUs will likely change over time as the vegetation cover becomes increasingly species-rich, especially along the backshore (marsh-upland boundary).
  - Low marsh tends to have monocot patches.
  - High marsh tends to be more complicated in the transition zone and marsh plain/channel.
- Spatial resolution of 3ft (1m) is stated in the MMRP, which is adequate for early detection of plants and their rapid response to the initial breach.
- Regarding plant classifications, achieving species-level identification is far less important compared to being able to assess sea level rise impacts on revegetation, using CNPS standardized classes. See vegetation map section above.

Indicator 8. Vegetation mean height and mean density by major dominant species or assemblages

Recommended data source for baseline assessments

- Sample lidar data and imagery used to map the major dominant species or assemblages.

Recommended data source for interim assessments

- UAS with GCP to develop DAP generated DSMs compared to bare earth imagery from the most recent Lidar could be a viable approach to estimating vegetation height and density. However, as mentioned in the UAS section above, additional study of DAP techniques to improve its accuracy is warranted.

Notes from Remote Sensing Workgroup

- The *LiDAR Elevation Adjustment with NDVI* (LEAN) method from Karen Thorn group (Buffington et al., 2018) can be used to discern the marsh plain once vegetation starts to get established. The LEAN method uses the vegetation index from multispectral plane-based imagery to correct lidar digital elevation models. The method uses available imagery such as NAIP and minimal field surveys to achieve greater accuracy while maintaining high 3ft (1m) spatial resolution. This approach may require a special study. To do so, must also recommend methods for both reference sites and project sites.

Indicator 9. Total vegetation percent cover

Recommended data source for baseline assessments

- Most recent Vegetation Map, with standardized classes from MCV (from DFW and CNPS), can be used for analysis (using LiDAR and 4-band imagery from manned aircraft for baseline measures, and a combination of Worldview or NAIP and recent elevation data in interim years).

Recommended data source for interim assessments

- A simpler Vegetation map could be used (i.e., without using Lidar) if other indicators are not needed to be assessed.

Notes from Remote Sensing Workgroup

- Near-infrared data are critical. It’s not worth flying manned aircraft without these data.
- TRT needs to recommend how much change or the rate of change that should be detected.
- Lidar is better than optical data for relative height of vegetation.
- China Camp sites have Q1 Lidar. Could test approach for getting vegetation structural information through this dataset. But, the China camp effort could only detect early colonization.

Indicator 10. Location and size of patches of invasive plant species (per Project species list)

Recommended data source for baseline and interim assessments

- Most recent Vegetation Map, with standardized classes from MCV (from DFW and CNPS), can be used for analysis (using LiDAR and 4-band imagery from manned aircraft for baseline measures, and a combination of Worldview or NAIP and recent elevation data in interim years).
- UAS imagery may be needed for smaller or less dense vegetation patches.

Indicator 11. Detection of new colonies of invasive plant species (per Project species list)

The Project should have a project-specific list of invasive plants that should be monitored and tracked. The workgroup recommends a high monitoring frequency for early detection and suggests that UAS flights are a good way to frequently monitor relatively small project areas for plant invasions.

Recommended data source for baseline assessments

- Vegetation Map with Lidar and high resolution 4-band imagery. NAIP and WorldView probably will not pick up small plant colonies.

Recommended data source for interim assessments

- Targeted UAS surveys.
- Alternatively, use a UAS orthomosaic survey (multispectral sensor, if it's helpful to differentiate that specific species, while likely making a lower resolution tradeoff, or with a true color sensor for higher resolution imagery)

Notes from Remote Sensing Workgroup

- TRT should estimate the monitoring frequency for early detection and rapid. response; minimum mapping unit and required spatial resolution
- Must use high monitoring frequency for colonization as vegetation arrives and changes quickly. China Camp sites have Q1 Lidar, but these data only detect early colonization from drone imagery. It took a year before they could detect them in DEMs derived from Lidar.

APPENDIX A. LIST OF REMOTE SENSING WORKGROUP MEMBERS

Members	Affiliation
Josh Collins (TRT Chair)	San Francisco Estuary Institute
Pete Kauhanen (WRSW Chair)	San Francisco Estuary Institute
Sarah Lowe (WRSW Support)	San Francisco Estuary Institute
Roger Leventhal (Montezuma Lead Engineer)	FarWest Restoration Engineering
Cassie Pinnell (Montezuma Lead Biologist)	Vollmar Natural Lands Consulting
Doug Lipton (Montezuma Manager)	Montezuma Wetlands, LLC
Kass Green	Kass Green & Associates
Danny Franco	Golden Gate National Parks Conservancy
Miguel Barretto and/or Eric Hass-Staplleton	Alameda County Mosquito Abatement District
Mike Vasey (TRT member)	SF Bay National Estuarine Research Reserve
Dylan Chappel	RIC & Delta Stewardship Council
Jerry Davis	SFSU – Institute for Geographic Information Science
Andy Lyons or Sean Hogan	UC Berkeley & UCANR
Iryna Dronova	UC Berkeley
Brandon Udelhofen	Terravion
Charlie Endris	Moss Landing Marine Labs
John Haskins	Elkhorn Slough - UAS pilot
Fuller Gerble	Data Processing for John and Charlie

APPENDIX B. TABLES OF RECOMMENDED REMOTE SENSING PRODUCTS BY INDICATOR

Table B.1 List of tidal wetland monitoring Indicators and recommended remote sensing Products.

Indicators	**Topo- Lidar**	**4 band plane based imagery**	**UAS (at least 4 band) imagery**	**UAS true-color imagery**	**Multibeam side-scan sonar**	**Worldview 2 or 3** (produced by DigitalGlobe)	**NAIP imagery**	**Stationary camera**	**On ground survey**	**Vegetation map**
	3-ft (91cm) spatial resolution	3in (7.6cm) spatial resolution 4 band imagery (RGB + NIR)	0.25ft (8 cm) spatial resolution (RGB + NIR)	~0.25in to 2.0in (0.6cm -5cm) spatial resolution 3 band imagery (RGB)		1ft (30cm) spatial resolution 8-band imagery	3ft – 4ft (1m – 1.2m) spatial resolution, 4 band imagery (RGB + NIR)			
1. 3D dimension (total length, max, min and mean width; max, min and mean depth, total volume) of tidal channels, relative to NAVD88, MHW, and MHHW	**X**			**X***	**X**					
2. Intertidal landscape topography and elevation, relative to NAVD88, MHHW, and MHW	**X**			**X***	**X**					
3. Phase and cell breach (notch) 3D shape and elevation, relative to NAVD88, MHHW, and MHW	**X**								**X**	
4. Location and 2D size of areas of stranded tidal water during slack low tide.		**X**	**X**	**X**			**X**			
5. Boundary of maximum tidal excursion	**X**			**X**				**X**		**X**
6. Percent cover of major dominant species or assemblages	**X**	**X**	**X**	**X/X***		**X**	**X**			**X**
7. Patch size-distribution for major dominant species or assemblages	**X**	**X**	**X**	**X/X***		**X**	**X**			**X**
8. Vegetation mean height and mean density by major dominant species or assemblages	**X**			**X***						**X**
9. Total vegetation percent cover	**X**	**X**	**X**	**X**		**X**	**X**			**X**
10. Location and size of patches of invasive plant species	**X**	**X**	**X**	**X***		**X**	**X**			**X**
11. Detection of new colonies of invasive plant species	**X**	**X**	**X**	**X***			**X**		**X**	**X**

*Accuracy of UAS based DAP may need to be assessed via special study.

Table B2. List of Indicators and their recommended remote sensing product with the most spatially resolute and accurate Indicator listed first. The first method listed is usually the most expensive method and is therefore more appropriate for baseline monitoring.

Indicator	Recommendation
1 & 2	1. Topographic/topobathymetric lidar - Bare Earth, at low tide 2. Multibeam sidescan sonar for channel depth where too deep/turbid for lidar penetration 3. Interim years, DAP derived DEMs using ground control points (GCP) and UAS at low tide for lower cost and accuracy (*may require special study)
3	1. Initial baseline Topographic/topobathymetric lidar (Bare Earth) survey timed in relation to cell breach 2. Interim years, use traditional surveyor methodology (not remote sensing)
4	1. Baseline 4 band aerial imagery 2. Interim years, use UAS true color to allow regular monitoring, potentially lower cost 3. Interim years, if 4 band UAS imagery is gathered at low tide, use. 4. Interim years, if NAIP is collected at low tide, use
5	1. Stationary camera paired with Topographic/topobathymetric surveys (baselines) 2. UAS flights taken at high tide could help refine modeled maximum tidal excursion 3. Extrapolate from vegetation type and extent
6&7	1. Baseline Veg Map, developed with standardized classes from MCV (from DFW and CNPS) based on LiDAR and 4 band plane based high resolution imagery. The project must determine the MMU for vegetation patches. 2. 2. Interim years, use WorldView 2 or 3 or NAIP imagery, paired with most recent bare earth and first return elevation data (lidar or lidar and potentially UAS DAP derived DEMs) 3. UAS imagery (4 band or true color) can help ground truth or provide additional mapping layers and resolution.
8	1. Veg Map (baseline). Sample lidar statistics for the major dominant species or assemblages. 2. Interim years, DAP derived DEMs using GCP and UAS for lower cost and accuracy (*may require special study) and compare to bare earth from most recent lidar. Note that one couldn't sample density without recent lidar data collection
9	1. Veg Map (baseline). 2. Interim years, use WorldView 2 or 3 or NAIP imagery (could supplement with available UAS for ground truthing)

Indicator	Recommendation
10	1. Veg Map (baseline) 2. Interim years, use WorldView 2 or 3 or NAIP imagery for cost-savings and pair it with most recent lidar or potentially UAS DAP derived DEMs (*may require special study). 3. UAS multispectral survey may provide path for mapping during certain times of year (when phonologically distinct) and may be needed for smaller or less dense patches
11	1. Veg Map (baseline) 2. Interim years, targeted UAS surveys 3. Interim years, alternatively use UAS orthomosaic survey (multispectral or true color - depending on species phenology and reflectance - *may require special study) 4. Interim years, NAIP imagery may catch new patches at 1-1/2 m resolution.