Incorporating the Coastal Blue Band into a Remote Sensing Toolkit for Mapping Intertidal Mudflats in South SF Bay: A White Paper

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Summary

Using 8 band multispectral imagery from Worldview-3 from April 13th, 2016, we successfully mapped the extent and distribution of mudflats within the South Bay Salt Pond Restoration Project (SBSPRP) study area (see Maps 1-4). The increased spectral resolution of the images, specifically the Near Infrared, Yellow and Coastal Blue bands, maximized the effectiveness of the various image processing techniques to map shallow water mudflats. In 2015, images were acquired for a pilot area (south of Dumbarton bridge) to test the effectiveness of a variety of image processing techniques to map mudflats. We then applied (and refined) these techniques using imagery from 2016 that covered the entire south bay salt pond restoration project area (south of the San Mateo bridge). Images were acquired close to Mean Lower Low Water (MLLW) to maximize exposure of mudflats. Our final results used a combination of (a) unsupervised classification, (b) band indices (NDWI) and (c) regression analysis (spectral matching between bathymetry and 8 image bands), to map mudflat extent and distribution.

The coefficients from the regression analysis, between the spectral band with the highest R-squared and high resolution bathymetry for Coyote Creek (Foxgrover, A.C., Finlayson, D.P., Jaffe, B.E., and Fregoso, T.A., 2015), were used to map the Mean Lower Low Water (MLLW) line. Surprisingly, the highest correlation (r2 = ~0.71) was between the bathymetry and the near infrared bands (as well as the red edge) and *not* the coastal blue band. The MLLW line was then used as a baseline for calibrating mudflat edge generated from the unsupervised classification and NDWI. For the unsupervised classification, we used the 3 band “mud flat composite” comprised of the near infrared, yellow and coastal blue bands. Although the results of this unsupervised classification were comparable to one that used all 8 bands, the mud flat composite demonstrated slightly increased ability to delineate mudflats along the edge under shallow water. The Normalized Difference Water Index (NDWI), demonstrated the most consistent ability to map mudflat under shallow water of various depths by delineating “wet soil” distinctly from sub-tidal environments.

Our final results for mapping mudflat extent and distribution were ultimately generated from a combination of: (1) obtaining images for more than one day and choosing the “best” image (closest to MLLW with minimal wind waves); (2) using the increased spectral resolution of the Worldview-3 sensor, including the Near Infrared, Red Edge, Yellow, as well as (although not exclusively) the Coastal Blue bands; to minimize the impact of tidal influence on delineating mudflats, and (3) using a series of image processing techniques, outlined in this white paper, to maximize the ability of each approach to identify mudflats under various tidal conditions.

Results

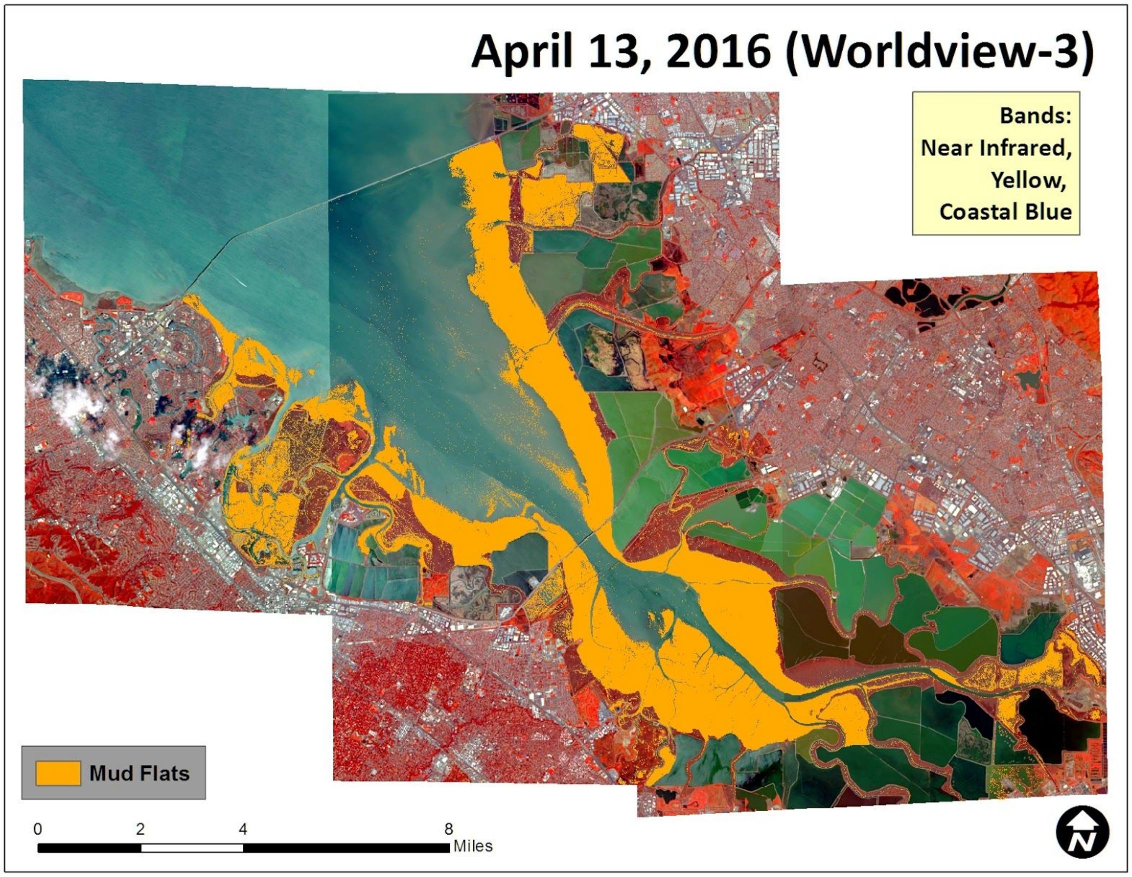
To calculate the acreage of mudflats within the study area - we divided the mapped area into two categories: (1) areas directly exposed to tidal action in the bay (“bay/slough”); and (2) areas within ponds or wetlands with a variety of tidal, muted tidal and managed connections (“pond/wetland”).

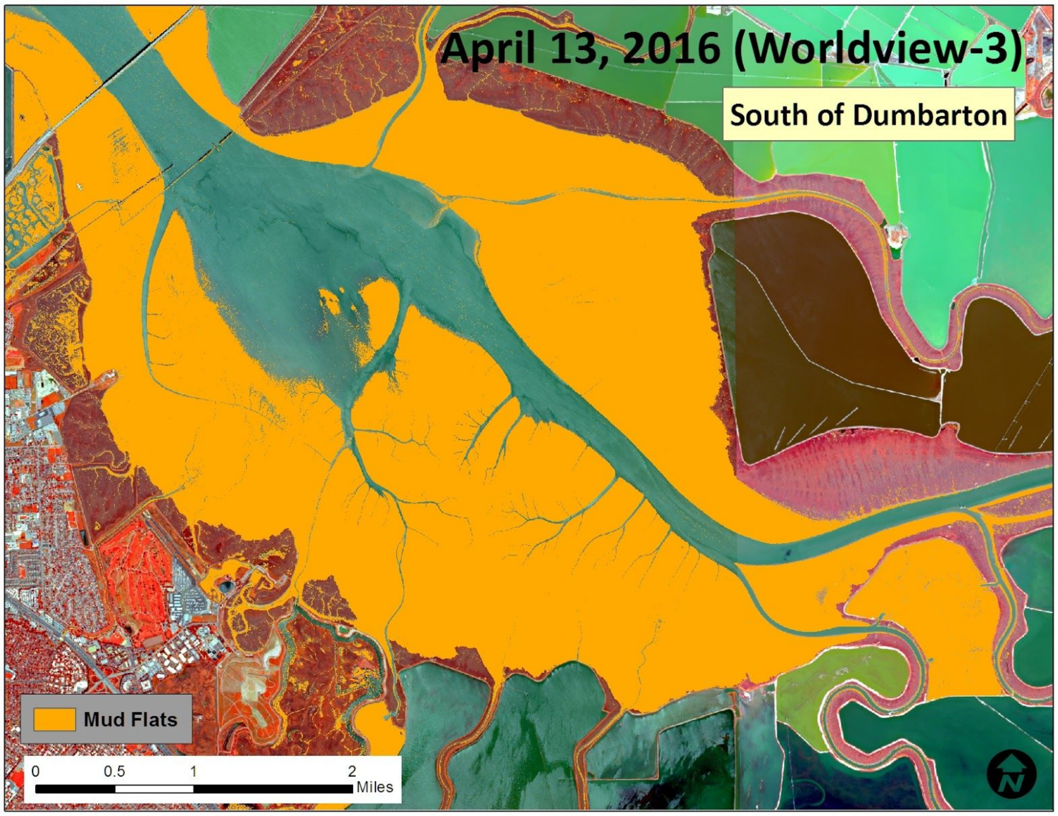
Total acreage of mudflats within the entire study areas and within the 3 SBSP management area are shown below. These tables are also included as part of the ESRI geodatabase of mudflat distribution (Mudflat_southbay.gdb) The GIS datasets provided with this report can be used to calculate mudflat acreage for other management units or geographic areas.

Mud Flat Type	**Acres of Mudflats (April 13, 2016)**
Bay/Slough	14,413.34
Pond/Wetland	4,021.71
Total	*18,435.05*

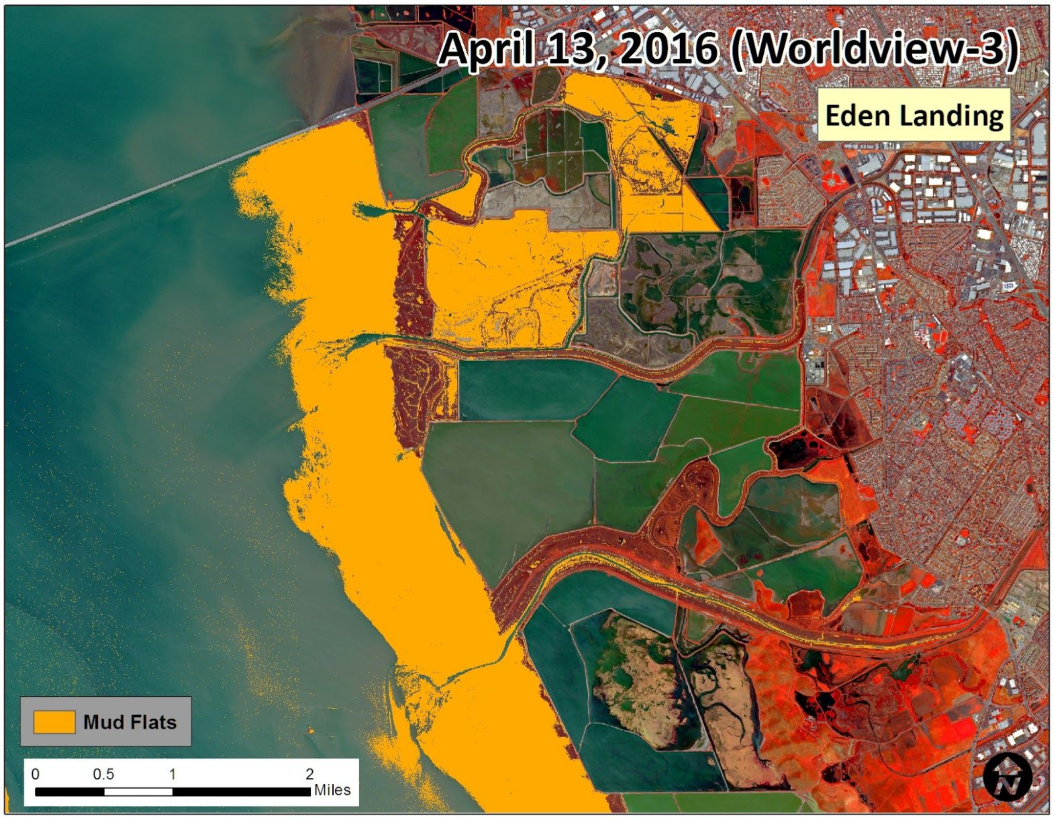
South Bay Salt Pond Unit(s)	**Acres of Mudflats (April 13, 2016)**
Alviso	863.49
Ravenswood	129.30
Eden Landing	1,122.61
Total	*2,115.39*

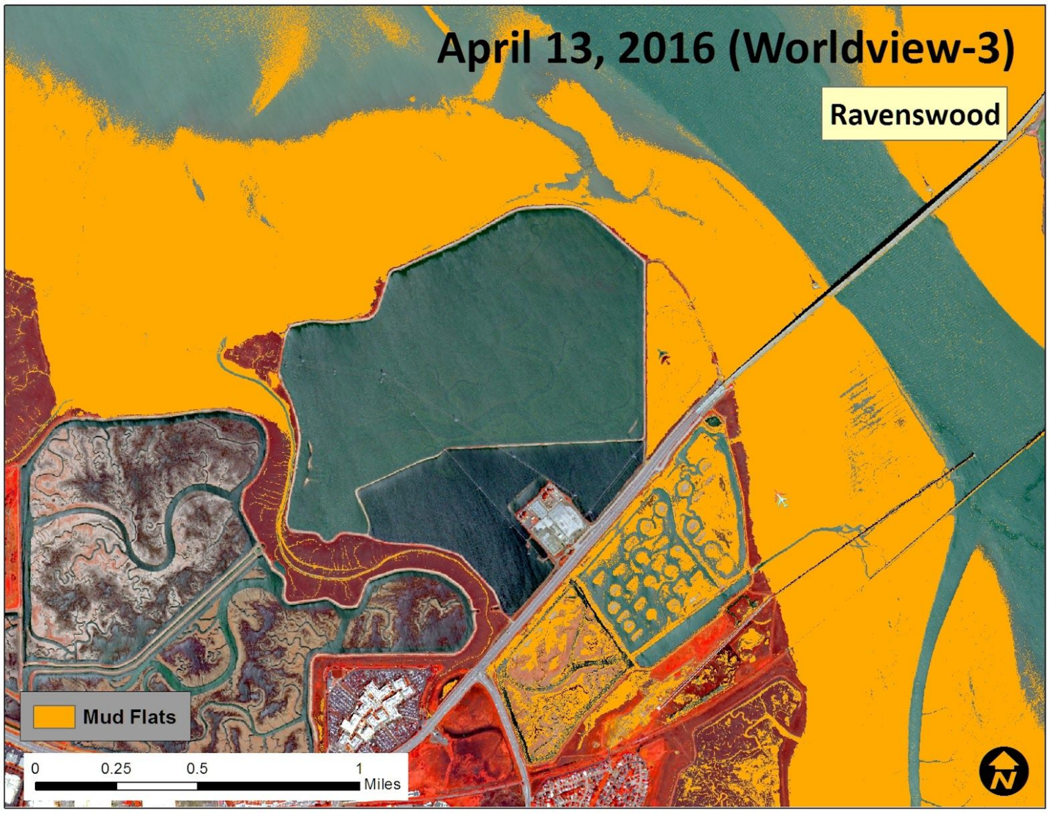
Map 1 (top) & Map 2 (bottom)





Map 3 (top) & Map 4 (bottom)





Background

The distribution of mudflats play an important role in the ecological functioning of estuaries. A number of researchers have found evidence for the large role that mud fats (and biofilm) play in the diet of shorebirds (Galbraith et al 2002; Kuwae et al 2008; Drouet et al 2015). There is also an important relationship between mudflats and sediment dynamics in estuaries, and they both have been a focus of study in the south san francisco bay (Bearman, J. A., Friedrichs, C. T., Jaffe, B. E., & Foxgrover, A. C., 2010; Jaffe, B., & Foxgrover, A., 2006; Jones, C. A., & Jaffe, B. E., 2013; Townend, I., Rossington, K., Knaapen, M., & Richardson, S., 2011). In an effort to support its goals of restoring 15,000 acres of salt ponds to wetlands, the South Bay Salt Pond Restoration Project (SBSP) has identified the need for tracking changes to mudflats over their large restoration area (see Map #1). The San Francisco Bay Joint Venture (SFBJV), the California State Coastal Conservancy (SCC), the San Francisco Bay Estuary Partnership (SFEP), and the US Fish and Wildlife Service (USFWS) have also all identified the important role that mudflats play in bay conservation efforts (SFBJV 2015; SCC 2015; SFEP 2016; USWFS 2013).

A mudflat working group, led by the SBSP's lead scientist Laura Valoppi, developed criteria for mapping mudflats that would help meet the needs of the SBSP restoration project. Understanding how mudflats might be changing can help land managers better understand the role that they play as a food resource for avifauna and in the sediment dynamics of estuaries. One significant limitation of using satellite imagery to map mudflats is that the time of satellite overpass (around noon) has to be matched with the lowest tide, Mean Lower Low Water (MLLW), in order to maximize mudflat exposure across the study area. The working group evaluated a range of possible mapping methods. High resolution commercial satellite imagery, specifically the Worldview satellites(both WV-2 and WV-3) from DigitalGlobe, were identified as having great potential to meet all the mapping criteria identified by the SBSP mudflat working group . Not only could the Worldview satellites map the entire study area at high spatial resolution (~1.3 meters), the Worldview satellites also included the Coastal Blue Band (CBB), which is the least absorbed by water and as a result has the potential to increase our ability to map shallow water features (Alsubaie, N. M., 2012; Digital Globe 2010; Doxani, G., Papadopoulou, M., Lafazani, P., Pikridas, C., & Tsakiri-Strati, M., 2012; ESRI 2013; Liew, S. C., Chang, C. W., & Kwoh, L. K., 2012; Madden, C. K., 2011). We obtained Worldview-3 images of the study area (for both 2015 and 2016) from the U.S. geological Survey (USGS) via the federal government's CDIR program. This report provides an overview of the results of our two year study using Worldview-3 images to map the extent and distribution of mudflats within south San Francisco bay.

The ability to map the full extent and distribution of mudflats is mainly dependent on the quality of the satellite image and tidal exposure. We used a range of image processing techniques to derive mud flats from multispectral imagery taken by the Worldview-3 satellite on April 13, 2016. We developed methods using images from two dates in 2015 of a subset of the study area and then applied them to a nearly ideal image obtained in 2016. The image we used in our final results captures the tide level very close to MLLW (-0.1 ft MLLW), providing maximum mudflat exposure with minimal cloud cover. Worldview-3 imagery, or imagery with similar specifications (such as Landsat 8), can be successfully used to map mudflat extent and distribution under varying tidal conditions (with some limitations). Mudflat distribution mapped using these methods are a snapshot in time and the results presented here should provide a good baseline for mapping changes to mudflats into the future.

Our two year study to utilize multispectral imagery has successfully met the goals set out by the SBSP mudflat working group. The GIS dataset(s) produced and methods developed from our 2 year pilot study provide a strong baseline for tracking changes to the extent, distribution and quality of mudflats in the future.

Methods

Using 8 band multispectral imagery from Worldview-3, we mapped the extent and distribution of mud flats in south San Francisco bay. Images were acquired close to Mean Lower Low Water (MLLW) to maximize exposure of mudflats. The increased spectral resolution of the images, specifically the Near Infrared, Yellow and Coastal Blue bands, maximized the effectiveness of the various image processing techniques to map shallow water mudflats,. A combination of unsupervised classification, band indices (NDWI) and regression analysis (between each image band and high resolution bathymetry) were used to map mudflats.

Techniques used to map mudflats were first developed using Worldview-3 imagery from 2015 for a smaller subset of the study area south of the Dumbarton bridge. We attempted to minimize the impact of shallow water influence on identifying the edge of mudflats (and MLLW) by both identifying 2 or more days where MLLW was around the time of satellite overpass and by the increased spectral resolution of the sensor. Although the spectral resolution of the imagery enhances the ability to map the edge of mudflats under various tidal conditions, tide height is still likely correlated to where mud flat edge is being mapped, especially in locations with very gradual slopes. We evaluated a number of existing methods for mapping shoreline change including the water line method (Heygster, G., Dannenberg, J., & Notholt, J., 2010; Liu, Y., Li, M., Zhou, M., Yang, K., & Mao, L., 2013; Murray, N. J., Phinn, S. R., Clemens, R.S., Roelfsema, C. M., & -Fuller, R. A., 2012; Xu, Z., et al, 2016) as well as methods for mapping shallow water bathymetry using multispectral data (Baiocchi, V., Brigante, R., Dominici, D., & Radicioni, F., 2012; Dekker, A. G., et al, 2011; Lyzenga, D. R., 1985; Madden, C. K., 2011; Stumpf, R. P., Holderied, K., & Sinclair, M., 2003). Our final methods use a combination of these techniques, in an effort to maximize the various strengths and minimize the weakness of each approach. An overview of each step in our final mapping methodology is provided below.

Requirements for mapping mudflat extent and distribution were developed as part of the Mudflat Working Group of the South Bay Salt Pond Restoration Project. The workgroup developed a list of requirements for mapping mudflats based on input from avian biologists connected to the restoration. The criteria are designed to be able to track changes to habitat needs of avifauna in a cost effective manner.

The criteria included:

- Resolution of ~ 50 square feet (or better)
- Mapping mudflats in 2D is adequate (mudflat extent and distribution)
- Update every 3-5 years
- Map entire study area
- Low cost

The images and methods developed here meet all of these requirements (and more). Below is an overview of how the Worldview-3 imagery met each of the criteria.

- Resolution of ~10.7 square feet (Worldview-3)
    - Resolution is almost 5X better than needed
- Successfully maps mudflat extent and distribution (2D)
    - Imagery also provides ability to map in 3D (mudflat shape and microtopography)
- Update at least 1-2+ times a year (owing to tides and satellite overpass)
- Captures entire study area in one overpass
- Low cost (relative to Lidar)

A brief description of each step of the mapping methodology used to produce our final results, is included below.

Step #1a: Imagery Acquisition

The ability to map tidal mudflats using satellites is dependent on obtaining imagery that exposes the full extent of mudflat. In order to increase our ability to acquire an image with the maximum exposure of mudflat, our first step was to identify the days (~2-5) in which the time of satellite overpass (around noon) was closest to Mean Lower Low Water (MLLW). We obtained times when the tide in the south bay was closest to MLLW using the Redwood City and Coyote Creek tide gauges from NOAA Tides and Currents (https://tidesandcurrents.noaa.gov/). Our list of days focused on times of the year with higher likelihood of a cloud free image. If feasible, obtaining 2 or more images will not only maximize the possibility of obtaining a cloud free image close to MLLW, it will also increase the likelihood of getting one with minimal wind waves. Tidal heights above MLLW will significantly increase the amount of mud flats covered by water, decreasing our ability to identify the edge of the mudflat.

Using our review of NOAA tidal gauges in the south bay, we acquired two images south of the Dumbarton bridge in 2015 and one image south of San Mateo bridge in 2016. The Worldview-3 images for both 2015 and 2016 were provided by Dr Kristen Byrd of the United States Geological Survey (USGS). Dr Byrd acquired the imagery via the Commercial Remote Sensing Space Policy (CRSSP) program for research supporting the SBSP restoration project. We used the two Worldview-3 images from 2015 (April 24th and June 7th, 2015) to develop an image processing model for mapping mudflats. Although each image from 2015 had low cloud cover, the June 7th image was captured at a significantly lower tide with less wind waves, exposing significantly greater mudflats above the waterline. As a result, the June 7th, 2015 image was used as the primary source for developing our mapping methodology since it was more representative of the full extent of mudflats.

Date and Time of Satellite Overpass	*Predicted or Actual Water level (MLLW)*	**Redwood City Tide Gauge**	**Coyote Creek Tide Gauge**
June 7th, 2015 (12:00pm)	*Predicted*	-1.31 ft	-0.382 ft
	Actual	0.43 ft	0.328 ft
April 13th, 2015 (12:56pm)	*Predicted*	0.036 ft	-0.211 ft
	Actual	-0.157 ft	-0.043 ft

We then applied (and optimized) the mapping methods using Worldview-3 imagery from 2016 (April 13th, 2016) for the entire SBSP study area. For our final results,the image we used from April 13th, 2016, had the least cloud cover, minimal wind waves and was the closest to MLLW of all three images - providing maximum exposure of mudflats.

Step #1b: Ground Truthing

We conducted ground truthing in both 2015 and 2016 to calibrate the methods ability to identify mudflat extent under various tidal conditions (mudflats under shallow water, mudflat edge, mudflats exposed with ponding, and mudflats exposed without ponding). In 2016, we also developed a systematic (and statistically robust) sampling plan to validate our results (based on MLLW) using RTK-GPS in at least 2 locations during the time of satellite overpass. Unfortunately, due to logistical concerns, our partners at USGS did not obtain these RTK-GPS ground truthing samples. However, we did conduct a series of focused (mostly transect based) field surveys at 5 locations in 2016. The ground truthing was primarily used to qualitatively assess (i.e. calibrate) the model’s ability to capture mudflat presence, edge and shallow water mudflats. The ground truthing surveys also allowed us to better evaluate how good different image processing techniques were at identifying and/or differentiating various “types” of mudflats based on the presence of biofilm, % water coverage, water depth, % exposure, and water “sheen” (as a proxy for soil moisture). Our ground truthing surveys were collected using ocular estimates along either point based transects or locations of uncertainty in our mapping (eg mudflat “edge”). Although we conducted our calibration focused ground truthing during the time of planned satellite overpass (June 10th, 2016), we did not obtain a satellite image of the study area for that day. However, we had already obtained an image on April 13th, 2016 that had very similar tidal conditions. As a result, we used the ground truthing data collected on

June 10th to calibrate and assess our modeling results produced from the April 13th image (which was subsequently then used to produce our final results).

Accessing mudflats can be difficult, strenuous and dangerous due to tides and difficulty moving across a mudflat. As a result, some location were accessed from land while others (Hook's Point, Mowry Slough, and Coyote Creek) were accessed using our mud boat. Despite these limitations, we conducted ground truthing using sub meter GIS (Trimble ProXT) in both 2015 and 2016 at 7+ locations across the study area. These included:

- Eden Landing (mudflats at the mouth of Eden creek)
- Ravenswood 1 (mudflats above Pond R1)
- Ravenswood 2 (mudflats adjacent to Pond SF2)
- Faber/Laumeister (mudflats adjacent to Cooley Landing Park)
- Hook Point (mudflats adjacent to and north of Hook point)
- Mowry Slough (mudflat between Mowry slough and Newark slough)
- Coyote Creek (mudflat at mouth of coyote creek, just west of pond A6)

Step #2: Orthorectification and Atmospheric Correction

Both the 2015 and 2016 images were successfully orthrecrecified using a 2 meter combined bathymetric and topographic surface created for the entire SF bay area (USGS, 2013). We evaluated the positional accuracy of the orthorectified images, which was more than adequate to meet the needs of the project (~1-3 pixels), by comparing them to higher resolution aerial photos.

In order to be able to best compare changes to mudflats over time using satellite imagery, we remove atmospheric effects from the images so they represent true ground reflectance values. Both FLAASH and Atcor corrections were applied to the June 7th, 2015 image by the USGS. Although we do not have field spectra to calibrate against, the Atcor corrected images appeared to reduce haze overall within the study area and have generally higher reflectivity in the Coastal Blue Band (CBB). Although our final results for 2015 and 2016 use the Atcor corrected images, the mapped mudflats produced from both types of corrected imagery, produced similar results. Unfortunately, both the FLAASH and Atcor corrected images from 2015 created erroneous values in the visible (and other) spectra, including a significant number of zero and negative “reflectance” values. Although we did not correct these errors in the June 7th, 2015 image, the methods we applied to map mudflats passed qualitative review and showed a high level of correspondence with the mudflat “edge” from ground truthing.

We then used the Atcor plugin for Erdas Imagine to atmospherically correct the 2016 image. Atcor is based on the Modtran-4 radiative transfer code (see http://modtran.spectral.com/). When we were performing our QA/QC on the output of the atmospherically corrected images from 2016, we also found a large number of zero and negative values, especially in the visible spectrum. These erroneous values indicated problems with the correction. We spent significant time in an effort to identify the source of and correct the errors. After consultation with Dr Reinard Richter (who utilized the Modtran radiative transfer code to develop the Atcor software), we determined that the Worldview-3 images of the San Francisco bay area were not necessarily a good fit for the aerosol and visibility types that were modeled within Atcor for similar coastal regions. Based on recommendations from Dr Richter, we modified the visibility and gain/bias coefficients applied to each spectral band, to better meet expected outcomes. These changes almost completely removed the erroneous values, although some residual errors remained.

Step #3: Image Analysis

The image processing steps we used to derive mudflat extent and distribution from the Worldview-3 imagery are documented below. We applied these image analysis techniques to the April 13th, 2016 image to create our final results. We developed our four step “mudflat mapping methodology” after applying a range of techniques and identifying those that improved our ability to delineate mudflats. Although the June 7th, 2015 date was chosen to more representative of full mudflat extent (due to lower tides and minimal wind waves), we developed our mapping methods using both images from 2015 to best assess the ability of the WV3 imagery, including the Coastal Blue Band, to derive shallow water mud flat under non optimal tidal conditions. The model was built using these two Worldview-3 mages from 2015 that covered a subset of the study area (south of the Dumbarton bridge) and then refined and applied to the April 13th, 2016 image.

A variety of factors at time of image acquisition can influence the precision of our image analysis techniques to map the full extent of mudflat and specifically map the “edge” of mudflat, defined for this study as MLLW, under shallow water. These factors include (but are not limited to): tide level, wind waves, water turbidity, barometric pressure, mud flat slope, and water depth. We used a combination of spectral image processing techniques (unsupervised classification, band indices, and correlation/regression with bathymetry) to derive and calibrate our final mudflat extent and distribution. Once the images were orthorectified and atmospherically corrected (step #2), the final mudflat datasets (and maps) were produced using the following steps.

Step #3a: Unsupervised Classification

We ran our unsupervised classification with 50 (and 30 for comparison) classes using the 3 band “mud flat composite” (near infrared, yellow and coastal blue bands). The unsupervised classification (ISO cluster) delineated mud flats cleanly from adjacent marshes and other land cover features. Although the results of this unsupervised classification were comparable to one that used all 8 bands, the mud flats composite demonstrated slightly increased ability to differentiate very shallow water mudflat in portions of the imagery where water conditions were not as good. We selected the classes most associated with mudflats using the MLLW line (see

Step #3d below), our ground truthing, and the imagery itself, to evaluate/calibrate the presence of mudflat.

The increased spectral resolution of the WorldView-3 imagery (over the Ikonos imagery acquired from 2009-2011) appeared to improve the ability of unsupervised classifications to map shallow water mudflat. The unsupervised classification (on all 8 bands as well as on the "mudflat composite") included 2-3 image classes along the "edge" that indicate possible submerged mudflat at the time of image acquisition. As a result, we utilized the unsupervised classifications, an easily reproducible technique on a variety of platforms, as the foundation for mapping mudflat extent. Although the focus of our work was on mudflat extent, the unsupervised classification also appears to do a good job at differentiating a variety of mudflat "types" that likely relate to geomorphology, moisture or ponding water, and the presence of biofilm.

Step #3b: Normalized Difference Water Index (NDWI)

In addition to the unsupervised classifications, we applied a variety of band indices to evaluate, and potentially improve, their ability to map mudflat under various tidal conditions. The Normalized Difference Water Index (NDWI), which is a ratio of the Green to Near Infrared bands, has shown to be very good at differentiating the land/water interface (Baiocchi, V., et al, 2012; Ji, L., Zhang, L., & Wylie, B., 2009; Ho, L. T. K., Umitsu, M., & Yamaguchi, Y., 2010; McFeeters, S. K., 1996). Index values between -1 to 0 depict land while values between 0 and 1 depict water. The NDWI demonstrated the best ability to identify the possible presence of "shallow water" mudflat from exposed mudflat, especially in areas with very shallow slopes (e.g. Eden Landing). We also experimented with an alternative version that uses Green to Shortwave Infrared (MNDWI) but this reduced our ability to differentiate both exposed mudflats and shallow water mudflats from adjacent marshes. We utilized thresholds based on previous research that explored the use of NDWI (and MNDWI) to delineate open water and coastal water features (Ji, L., et al, 2009). We used the index (index values are in parenthesis) to differentiate four types of features:

- "land" (< -0.3) - which directly adjacent to mudflats was marsh;
- "mudflat" (-0.3 to 0) - which seemed to delineate exposed mudflat
- "shallow water" (0 to 0.3) - which might indicate possible shallow water mudflat
- "water" (> 0.3) - which indicates deeper water

We also applied a range of other band indices to the images some of which did a good job of delineating mudflat, but not as cleanly or as consistently to differentiate the land/water interface as NDWI. These include NDVI, EVI, SAVI, and MSAVI. The Modified Soil and Vegetation Index (MSAVI), and NDVI to some degree, also demonstrated the ability to improve the mapping of the edge of mudflat under shallow water (specifically where MSAVI/NDVI values were equal or slightly under zero and likely corresponded to the "true" mud flat edge that was slightly submerged). Although we used NDWI in our final results, these other indices also demonstrate the potential to be used to improve the precision of mudflat mapping efforts under various tidal conditions.

Step #3c: Mean Lower Low Water (MLLW)

We generated 10 Mean Lower Low Water (MLLW) lines from high resolution bathymetric data collected between 2005 and 2015 (Foxgrover, A.C., et al, 2015). The 2005 MLLW line, which was created from high resolution bathymetry that covered the entire south bay (Foxgrover, A.C., et al, 2007), was used to represent the edge of the full extent of mudflat and served as the baseline reference for the study. The remaining 9 MLLW lines were generated from bathymetry of coyote creek collected between 2010 and 2015 by the USGS. These bathymetric datasets were as a means of calibrating the mapped results of mudflat extent *within coyote creek.*

The bathymetric dataset of Coyote Creek from October 2015 was also used to generate correlation matrices with each of the eight WorldView-3 bands. We ran a OLS regression between the spectral bands (that had the highest R-squared) and the bathymetry and used the resulting coefficients to generate the MLLW line throughout the study area (Balakrishnan, P., & Halimi, A. A., 2015). Surprisingly, the Coastal Blue Band had *less* power to predict MLLW (and therefore the edge of the mudflat) than other bands, including the Near Infrared-2, Near Infrared-1, Red Edge and Red bands. This MLLW line identified mudflat edge under certain types of shallow water. Ths was evident in the April 24th, 2015 image, which had significantly higher tide and more wind waves than either the June 7th, 2015 or April 13th, 2016 image. Ultimately, we used the coefficients produced from the Near Infrared-2 band and the October 2015 bathymetry of Coyote Creek (R2 = 0.71), to derive an elevation surface relative to MLLW and map the MLLW line *for the entire study area*. This surface also provides the potential to predict topographic variability (e.g. concave/convex) including identifying areas of ponded water. The MLLW line was subsequently used for evaluating and calibrating the bayward edge of mudflat that was derived using both the unsupervised classification and band indices described above (Step 3b & Step 3c).

Both the Near Infrared (NIR) and red edge bands had higher statistical correlation with the bathymetry of Coyote Creek (and therefore ability to map MLLW) than did the Coastal Blue Band (CBB). The NIR has been associated with suspended sediment and not necessarily bathymetric depth. The higher correlation between bathymetric depth and the NIR bands (and red edge) likely indicates suspended sediment from the underlying but *very* shallow mud flats. As a result, we think that the NIR band(s) still serve as a good proxy for identifying mud flat edge at sharper boundaries (e.g. at mouth of coyote creek) but perhaps less well in locations with very shallow mud flats that are nearly flat (e.g. off of Eden Landing) where the MLLW “line” can actually extend for quite some distance (e.g. kilometers).

Step #3d: Final Results

We calculated the final mudflat extent and distribution using a combination of our unsupervised classification and NDWI. After the results of both of these techniques (Step 3b & Step 3c) had both been evaluated and calibrated to the MLLW lines (Step 3c), they were combined so to maximize the usefulness of each approach. Locations were considered to be “mudflat” if they met either one of the following two criteria:

1. identified as “mudflat” in *both* the (a) unsupervised classification *and* (b) the NDWI; or

2. identified as both (a) “shallow water” in the NDWI *and* identified as (b) “mudflats” in the unsupervised classification.

After reviewing locations that were identified from the NDWI as “shallow water”, it wasn’t clear that all of these areas were actually shallow water *mudflats*. As a result, we only included areas of “shallow water” that were *also* identified as mudflats by the unsupervised classification.

Areas outside of the baylands were then removed using a mask that was derived from SFEI’s Bay Area Aquatic Resource Inventory (BAARI). The mask was also used to calculate acreages of mudflats that were directly exposed to the bay (“bay/sloughs”) and those within natural or man-made features (“pond/wetland”).

Limitations and Next Steps

The maps and methods described in this white paper provide a strong foundation for monitoring and managing intertidal mudflats in SF, San Pablo and Suisun Bays. The methods serve as a cost effective means for mapping and tracking to changes to mudflats, with some limitations. We have provided a series of “next steps” below that begin to address some of these limitations

Quantify Variability and Uncertainty

Although we have developed a relatively robust mechanism to map mudflat extent and distribution, we have not yet quantified the degree of spatial or temporal variability corresponding to the mapped presence of mud flats at a given location or quantified the degree of uncertainty in our modeling approach. Quantifying the range of “normal” variability of seasonal and interannual variability of mudflat extent (and “type”) would improve our understanding of changes to those mudflats.

Mean Lower Low Water (MLLW) serves as a convenient and documented method for delineating the edge of mud flats (Jaffee, B. & Foxgrover, A., 2006).. However, using MLLW can introduce mitigating factors when calculating changes to mudflats due to possible spatial and temporal variability that are inherent in tidal datums and uncertainties in various method used to map the MLLW line (Jaffee, B. & Foxgrover, A., 2006). The largest uncertainties appear to occur in areas of very gradual slopes with very shallow water, where there is not as distinct boundary (e.g.Eden Landing). Consensus should be obtained whether extremely shallow water mudflats are intertidal or subtidal (or perhaps somewhere shifting between the two).

Map Mudflat 'Type'

The tidal influence on the presence of water, microtopography, shape, presence (and type) of biofilm, and sediment type have a direct impact on various ecological functions that mudflats play, including as food resources for foraging birds, sediment repositories, and links to estuarine habitats. These relationships might be used to help create a typologies of mudflat that could be used for monitoring and conservation valuation.

Map Mudflats in 3D (and RTK GPS for validation)

As part of our model we developed a combined bathymetric/topographic surface as a means of calculating the MLLW line. Highly accurate surveys of MLLW along with improvements to the inputs (using study area wide bathymetry) and type of regression (multiple linear regression, CART) used could improve our calculations of MLLW (even under shallow water). These surfaces can provide increased ability to map MLLW using spectral bands but also provide improvements to calculations of mudflat shape (concave/convex) and microtopography.

Map Biofilm and Bird Use

We did not map biofilm distribution or type. Certain tasks, dominantly the time spent doing the atmospheric correction, took much more time than anticipated. However, both the images (seen using visible, false color, or mud flat composite band combos), image processing techniques outlined here (the unsupervised classification and MSAVI) and in previous studies (Fulfrost, B., Thomson, D., et al, 2012) , demonstrate the ability to identify the presence and possibly even the type/density of biofilm across the mudflats. Maps of biofilm distribution can be coupled with research on bird use of mudflats to better inform overall estuary conservation.

Observed Changes between 2015 and 2016 Images

Since the errors produced from the atmospheric correction of the 2015 mages were not fixed,we did not use them to assess changes to mud flats between years. Despite these errors, the edge of the mud flats derived from the 2015 imagery demonstrated a high level of visual correlation with ground truthing points acquired on days with similar tides. Some locations within the study area indicate some differences in the extent of mudflats between years. The MLLW lines (between 2005 - 2015) we derived from the bathymetric datasets developed by the USGS (2015) appear to show interannual (and interseasonal) variability at at least one location at the mouth of Coyote Creek. It's possible the trend line might indicate possible accretion or erosion at this location, since the longitudinal depth of bathymetric change in Coyote Creek is significant. The causes of these differences can include (1) tidal differences; (2) wind waves; (3) differences connected to source imagery or analysis; (3) mudflat accretion or erosion.

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