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Remote sensing and mapping of floating aquatic vegetation in the Sacramento–San Joaquin River Delta

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ABSTRACT

The California Sacramento–San Joaquin River Delta (often referred to as the California Delta) is the hub for California's water supply to Northern and Southern California communities and agricultural production and supports ecosystem services in the San Francisco Bay/California Delta complex. Expansion of invasive aquatic plants and impacts of changing climate and land use, long-term drought, and fluctuations in water flow and quality are detrimental to water management and the Delta ecosystem. The Delta covers 340,200 ha (840,000 acres, 1,312.5 miles^2) land and water area in a web of sloughs, levees, rivers channels, marsh, and wetlands. The California Division of Boating and Waterways (DBW) has management responsibility for invasive aquatic plants and has partnered with the National Aeronautics and Space Administration (NASA) Ames Research Center, U.S. Department of Agriculture (USDA)–Agricultural Research Service (ARS), and University of California Davis in the Delta Region Areawide Aquatic Weed Project (DRAAWP) to develop science-based, adaptive-management strategies. Satellite-based, remote sensing methods have been developed to provide, for the first time, a comprehensive view of floating aquatic vegetation (FAV) population dynamics on a landscape scale and support operations, assessment, and strategic planning/adaptive management. An initial mapping tool utilized Landsat acquisitions, available at 14-d intervals with 30-m pixel size, and normalized difference vegetation index (NDVI) processing to map FAV. The Landsat-based tool confirmed the value of using remote sensing to inform both Delta-wide and local operations and assessment; however, significant deficiencies in spatial and temporal resolution and variability were problematic. A second mapping tool using Sentinel-2 satellites acquisitions and processing with the Acolite program provided improved performance in all areas. This effort supports operational decision making, enables assessment of management practices effectiveness, and provides new tools for planning, verification, and adaptive management. A first-ever, comprehensive, quantitative view of floating aquatic plant populations in the California Delta and linkage with operational decision making and enhanced assessment capabilities increases the efficiency of resource management efforts in the region.

Key words: adaptive management, *Eichhornia crassipes*, Landsat, *Ludwigia* spp., Sentinel-2, water hyacinth, water primrose.

INTRODUCTION

Invasive aquatic plants impact waterways throughout the world with ecological, economic, and social impacts (Thomaz et al. 2015). The California Delta, involving the San Francisco Bay and San Joaquin and Sacramento River watersheds, is seriously affected by increasing diversity and presence of aquatic invasive plants, threatening the ecological integrity of the region and water management of this critically important water distribution hub for the western United States (Anderson 1990, Cohen and Carlton 1998, Santos et al. 2009, Santos et al. 2012, DSC 2013, Boyer and Sutula 2015, Lacan and Resh 2016, Ta et al. 2017, DSC 2019a,b). Invasive aquatic plants are affecting resource management, ecosystem services, aquatic habitats and food webs, economic pursuits in the Delta region (including primary agricultural production), and water supply to 25 million people of California (Alexander et al. 2018, Sloop et al. 2018).

These invasive species impact every aspect of resource management in the Delta and as such involve a large number of stakeholders. Additional challenges include unpredictable climate and environmental variations, unknown biological response to those variations, and changing regulatory rules, stakeholder needs, and regional U.S. water resource distribution and management policy (Beller et al. 2019). In response to the situation, the U.S. Department of Agriculture–Agricultural Research Service (USDA–ARS) Areawide Program initiated a project, the Delta Region Areawide Aquatic Weed Project (DRAAWP) as a comprehensive and multidisciplinary effort to develop science-informed, adaptive management support systems (Moran et al. 2020). The DRAAWP provided for development, gap-filling science, and demonstration of how science and remote sensing-based tools can be fused to support adaptive management decisions in a complex aquatic ecosystem with a wide range of stakeholder pressures and regulatory

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oversight. DRAAWP includes the USDA–ARS, National Aeronautics and Space Administration (NASA)-Ames Research Center, University of California–Davis, and the State of California Division of Boating and Waterways (DBW).

The DBW has sole responsibility within the California Delta to manage invasive aquatic plants and address the needs of the wide array of Delta stakeholders, but also must operate in conformance with multiple Federal and State agencies having regulatory oversight authority. The project utilizes NASA remote sensing and ecosystem science expertise and tools to enable a new, adaptive-management approach to aquatic ecosystem management to inform decision making. DBW as the operational partner is the focus for developing requirements, adapting science and tools, and demonstrating the utility of new tools for operational, assessment, and management decision making.

The Delta covers 340,200 ha (840,000 acres, 1,312.5 miles^2) land and water area in a web of sloughs, levees, rivers channels, marsh, and wetlands (Lácan and Resh 2016, Hutton et al. 2019). Comprehensive monitoring of floating aquatic vegetation (FAV) across the Delta has been impossible on a regular basis. Assessment of FAV distribution has relied on public reporting of heavy populations impeding boat traffic or marina access and operations of DBW invasive aquatic plant management crews and their limited routine monitoring of historical problem areas and critical vulnerable infrastructure sites. A large portion of the Delta routinely goes without regular evaluation; as a result, there is only limited knowledge regarding the temporal and spatial dynamics of FAV population within the Delta. Occasional airborne remote sensing flights with instruments such as NASA AVIRIS (Airborne Visible Infrared Imagining Spectrometer) has provided snapshots in time of habitats across the Delta (Santos et al. 2009, Ustin et al. 2016); however, FAV has not typically been the primary focus for collections, and resulting inconsistency in timing, off-peak population collection times, inconsistent and lengthy gaps between collections, and time required for processing and analyzing imaging has limited the operational value of the collections. These collections provide important insight into the general trends of habitats across in the Delta as impacted by environmental variations experienced during that period (Ustin et al. 2016, Santos et al. 2017).

An important objective of the DRAAWP is to develop a remote sensing-based tool for regular, comprehensive assessment of FAV populations Delta-wide to support near-term operational decisions as well as assess effectiveness of FAV management practices and aide in long-term strategic decision making. The paper describes the development and initial operational use of these tools.

MATERIALS AND METHODS

Requirements definition

The initial step for DRAAWP was development of requirements for a remote sensing system to meet FAV management needs. Step 2 focused on evaluation of potential remote sensing platforms.

Table 1. Landsat 8 Operation Land Imager (OLI) and Thermal Infrared Sensor (TIRS) spectral bands and spatial resolution (Landsat 8 2020).

Description[1]	Band	Spectral Resolution (nm)	Spatial Resolution (m)
Coastal/Aerosol	1	435–451	30
Blue	2	452–512	30
Green	3	533–590	30
Red	4	636–673	30
NIR	5	851–879	30
SWIR-1	6	1,567–1,651	30
SWIR-2	7	2,107–2,294	30
Pan	8	503–676	15
Cirrus	9	1,363–1,384	30
TIRS-1	10	10,600–11,190	100
TIRS-2	11	11,500–12,510	100

[1]NIR, near infrared; SWIR, shortwave infrared; Pan, panchromatic; TIRS, thermal infrared sensor.

Satellite Data Acquisition

Landsat 8 was launched on February 11, 2013 as a collaboration between NASA and the U.S. Geological Survey (USGS) with two science instruments, the Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS). These two sensors continue to provide seasonal coverage of the globe at 30-m spatial resolution (visible, near infrared [NIR], shortwave infrared [SWIR]), 100 m (thermal), and 15 m (panchromatic) (Table 1). The OLI sensor is an advanced push-broom sensor with a four-mirror telescope and 12-bit quantization and provides two new spectral bands as compared to previous Landsat missions, one for detecting cirrus clouds and the other for coastal zone observations (Landsat 8. 2020). One of the advantages of using Landsat data for analysis is that the first sensor was launched in 1972 so there is a long time series of Landsat data available.

For this study, three Landsat 8 tiles (Row/Col: 44,34; 43,34; and 44,33) were acquired for each date from April through October 2018 to cover the entire Delta region (Figure 1). The Normalized Difference Vegetation Index (NDVI) imagery used in this study were acquired from the USGS Bulk Order data download site (USGS. 2020).

Sentinel-2 was launched on Jun. 23, 2015 by the European Space Agency (ESA). Sentinel-2 is a wide-swath, high-resolution, multispectral imaging mission that includes twin satellites (Sentinel-2A and Sentinel-2B) flying in the same orbit but offset 180° in order to give a revisit frequency of 5 d at the equator (Sentinal-2 2020). The Sentinel-2 instruments sense a 290 km wide swath and 13 spectral bands: four bands at 10 m, six bands at 20 m, and three bands at 60 m spatial resolution (Table 2). Five Sentinel-2 tiles are required to cover the Delta (Figure 1b).

For this study, the acquisition period for both Sentinel-2 and Landsat-8 was March through October 2018. DBW management site polygons provide component area boundaries for summaries (Figure 2).

FAV mapping tools

The initial Delta FAV Weed Mapper tool was developed at NASA Ames to estimate FAV coverage over the Delta using Landsat derived NDVI data. The tool requires Landsat NDVI files and their associated Quality Assurance (QA) files,

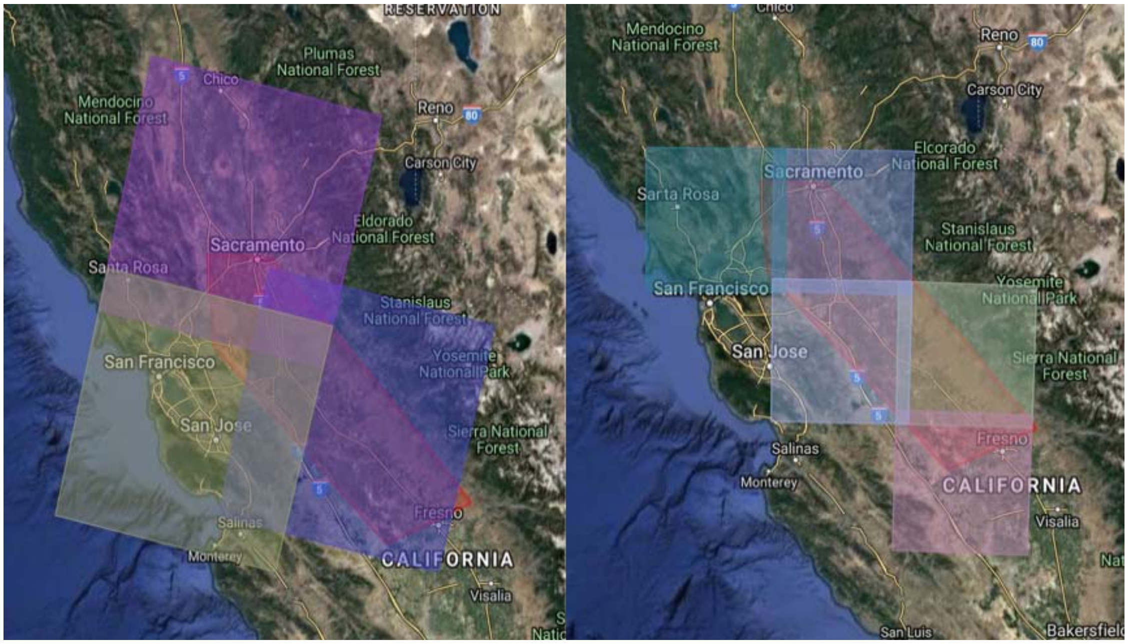


Figure 1. Remote sensing platform collection tiles necessary to view the California Delta. (A) Landsat 8: 3 tiles. (B) Sentinel-2: 5 tiles.

as well as shapefiles, which defines specific areas over which to calculate FAV area summaries. The tool uses the NDVI and QA files to filter out cloud cover and masks out the land area. Then the tool sets a predefined threshold to the Landsat NDVI data to identify vegetated pixels over the water. Finally, the tool creates a point file of all of the vegetated pixels in the waterways, as well as a polygon file with area summaries based on the input DBW polygons.

Delta FAV Weed Mapper tool Version 2 has been developed to take advantage of enhanced spectral, spatial, and temporal performance in Sentinel-2 and address inconsistency in results from Version 1 (Landsat NDVI-based). FAV Tool Version 2 incorporates a Python tool developed at the Royal Belgian Institute of Natural Sciences called Acolite (Acolite 2020), which was specifically programed to use Sentinel-2 (A/B) imagery to detect FAV in coastal and inland water applications. The program performs atmospheric correction over the water by using the "dark spectrum fitting" (Vanhellemont and Ruddick 2018, Vanhellemont 2019) and the Rayleigh Scattering approach; the Landsat NDVI data used previously is atmospherically corrected for land applications and not water. The Acolite tool was further developed by Dogliotti et. al. (2018) to estimate FAV for the Amazon Basin.

Table 2. Sentinel-2A satellite spectral bands and spatial resolution (Sentinal-2 2018).

Description[1]	Band	Spectral Resolution (nm)	Spatial Resolution (m)
Coastal Aerosol	1	421–457	60
Blue	2	439–535	10
Green	3	537–582	10
Red	4	646–685	10
Red-Edge 1	5	694–714	20
Red-Edge 2	6	731–749	20
Red-Edge 3	7	768–796	20
NIR-broad	8	767–908	10
NIR-narrow	8a	848–881	20
Water vapor	9	931–958	60
SWIR–Cirrus	10	1,338–1,414	60
SWIR–1	11	1,539–1,681	20
SWIR–2	12	2,072–2,312	20

[1]NIR, near infrared; SWIR, shortwave infrared.

FAV definition

The FAV population of the Delta is predominantly a mix of water hyacinth [*Eichhornia crassipes* (Mart.) Solms] and water primrose (*Ludwigia* spp.**).** At initiation of our work the dominant species was water hyacinth but over time a mixed population has developed with varying proportions of each species present (Khanna et al. 2012, Khanna 2018). There was no discrimination between water hyacinth and water primrose with either of the satellite-derived products tested. Product maps were unaffected by the proportion of these species occupying a pixel. The presence of other macrophytes in the Delta such as the range of Tule sedge have no impact of FAV mapping products. A patch of FAV deep within a Tule area looks no different than if the FAV patch was alone in the waterway.

On-water truthing for FAV coverage. The performance of both the Landsat-based and Sentinel-2–based tools to identify FAV-covered pixels on output maps was evaluated. The same methods were used for each tool. Acquisition dates for both Landsat and Sentinel are known in advance, making it possible to some degree to schedule on-water operations just prior to or just following an acquisition. Preacquisition, global positioning system (GPS) points were collected for specific pixel-sized areas estimated in the field to have between greater than 50% FAV coverage. Post-acquisition, specific FAV-covered pixels were selected on

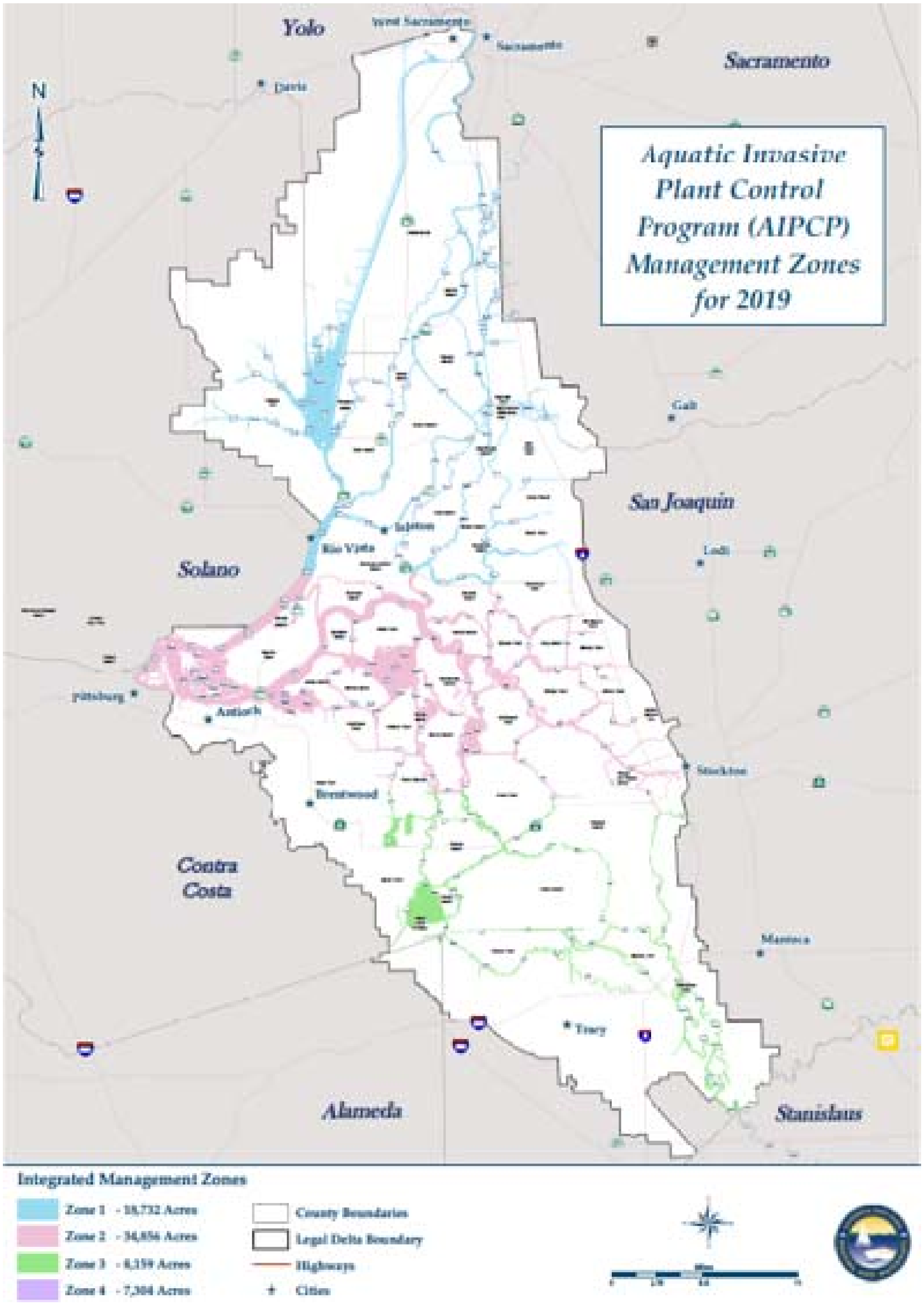


Figure 2. Delta region map of California Division of Boating and Waterways (DBW) Aquatic Invasive Plant Control Program (AIPCMP) Management Zones. (Map provided courtesy of DBW.)

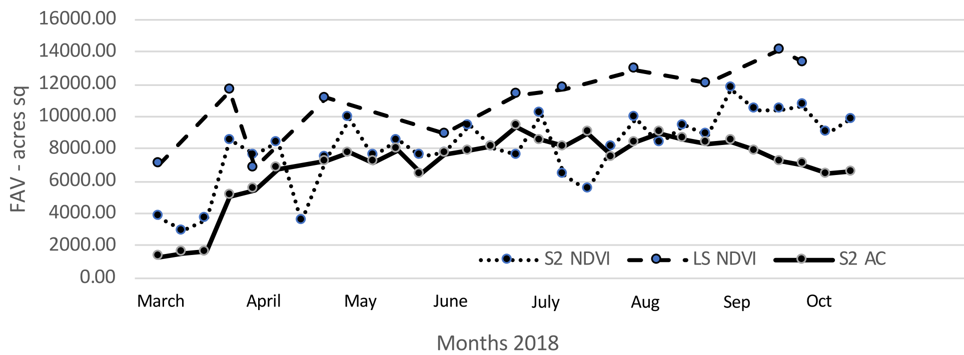


Figure 3. Delta Floating Aquatic Vegetation (FAV) coverage for period March through October 2018. FAV estimated using Landsat/NDVI (LS NDVI; FAV Mapping Tool Version 1), Sentinel-2/Acolite (S2 AC; FAV Mapping Tool Version 2), and Sentinel-2/NDVI (S2 NDVI).

the tool output maps and, at a later date, following acquisition and processing of the map product, on-water evaluations were conducted to confirm tool ability to recognize the FAV coverage of specific pixels in postacquisition maps or designated prior to acquisition. Both the Landsat- and Sentinel-2–based tools were found to be 100% consistent in the ability to identify pixels with significant FAV coverage, both when occurring in large, multipixel patches or smaller patches of a few pixels. Initial ground truthing focused on validation of significant FAV coverage (< 50%) for designated pixels. Studies including evaluation of standing biomass prediction for the FAV population are not yet complete.

Although the Landsat-based tool was found to consistently identify FAV-covered pixels, issues of large pixel size, 14-d period between acquisitions, and the frequency and data vulnerability to weather and smoke associated with Landsat have been discussed earlier. The Sentinel-2–based tool performed well but we did identify an unintended consequence resulting from the smaller pixel size—terrestrial vegetation overhang of digital levee boundary. The digital Delta map designating the boundaries for all waterways is used in both tools to mask any land vegetation. While the Sentinel-2 tool was being beta-tested by DBW field supervisors, a few areas were identified where overhanging tree or large brush canopies hung over the water's edge sufficiently to register a 10 m pixel as FAV-covered from above. The areas identified with vegetation overhang of the digital boundary by DBW represent a very minor proportion total FAV coverage and are localized. DBW has defined affected areas on levee banks and we adjusted boundaries in these areas. This is an important unintended consequence of smaller pixel size, and possible effects should be considered when appropriate.

RESULTS AND DISCUSSION

Remote sensing requirements definition

Requirements definition revealed three distinctly different applications for remote-sensing FAV mapping system: 1) Operational decisions—Directing performance of specific management practices; 2) Assessment—Monitoring operational and management plan outcomes; and 3) Adaptive management decisions—Adapt strategies and management practices to improve management and treatment effectiveness.

Operational decisions. These decisions were defined to require recurring estimates of FAV coverage in individual DBW treatment sites with frequency necessary to affect distribution of resources. Weekly frequency was determined optimal to match the standard operational management plan.

Assessment. This was defined as a critical need to quantify change in coverage over time within individual DBW treatment sites and aggregated FAV coverage across the Delta.

Adaptive management decisions. These critical needs were defined as informing 1) understanding of short-term response to management practices in a specific site with defined constraints, and 2) improve future, comprehensive Delta management through balanced application of management practices in appropriate situations to affect overall desired outcome.

Remote sensing platform and FAV mapping tool performance

At the time of initial requirements review, Landsat represented the only practical satellite platform providing regular, comprehensive view of the Delta. Landsat acquisitions are accessible but only minimally addressed requirements for remote sensing data collections.

The Landsat/NDVI-based FAV Weed Mapper Tool was developed in ArcMap and provided an estimate for FAV coverage across the Delta and locally with 30-m spatial resolution (Figure 3). The tool provided the first comprehensive mapping of FAV across the Delta and could be run on a regular 14-d schedule or when Landsat acquisitions were available. The method provided estimates of FAV that followed expected seasonal trends and provided reasonable estimates for area coverage and biomass density (within limits); however, the deficiencies in spatial, temporal, and spectral performance were obstacles to satisfying performance requirements.

There was considerable data variability; Delta areas with narrow waterways were missed due to the 30-m pixel size, frequency of pervasive cloud cover in spring months (i.e., March, April, May) and dense smoke from wildfires in California in summer and fall resulted in long periods (up to 6 wk) without clear sky Landsat acquisition (Figure 3). Further, the bimonthly sensing of Landsat does not provide acceptable operational location data during periods of rapid change such as water hyacinth mat breakup. Deficiencies were evident regarding lack of sensing numerous water hyacinth small mats observed on the water. Even with identified shortcomings, the tool did provide insight and confirmation of the value of using remote sensing to inform both Delta-wide and local operations and assessment. One of the clear values in using Landsat data for analysis if appropriate is that the first sensor was launched in 1972 with several satellite updates providing continuity over four decades of archived images and data (Landsat 2020).

The launch of Sentinel-2 in 2015 and the promise of enhanced temporal and spatial resolution prompted us to initiate review and testing as Sentinel acquisition data became available. We were able to improve performance of FAV mapping by switching to the Sentinel-2, coupled with the Acolite processing tool. Increased spatial resolution with Sentinel-2 and the customization of Acolite for over-water acquisitions reduced data variability and improved satisfaction of remote sensing requirements. With 10-m pixels compared with 30 m for Landsat smaller waterways with FAV are characterized and smaller patches of FAV are included in acquisitions. With regular 5-d intervals, sensitivity to viewing rapidly changing positions of FAV is enhanced and duration of weather or smoke impeded imaging periods is diminished. Improved spatial resolution and utilization of processing specifically designed for over-water application provide the FAV Mapping Tool Version 2 with improved ability to estimate FAV coverage area compared with Landsat NDVI approach.

The influence of spatial resolution on estimating the coverage and distribution of vegetation is dependent on specific features of the subject material (Liu et al. 2020). The variability in patch size for water hyacinth is likely an important feature in determining appropriate spatial resolution. Pixel size less than 20 m has been identified as important to coverage area estimation for small patches (Ponzoni et al. 2002, Roth et al. 2015, Liu et al. 2020). The Delta is a network of many channels with predominantly small patches of FAV present throughout the year, the seasonal expansion of patch size in spring, and larger patch breakup in late summer and fall. Spatial resolution and interaction with FAV patch dynamics is an ongoing subject of study for us. Increased resolution with Sentinel-2 (10 m) compared with that of Landsat (30 m) resulted in improved stability of coverage area estimates (Figure 3). Use of NDVI appears to be a source of significant variability in FAV coverage estimates, regardless of remote sensing platform. When the NDVI program was applied to the Sentinel-2 acquisition, the magnitude of coverage estimates remained in-line with that produced with Sentinel-2 and Acolite; however, use of NDVI resulted in a dramatic increase in variability compared with Acolite processing (Figure 3).

FAV mapping tool utilization

The remote sensing tools presented here represent a developmental process to address FAV management needs in the California Delta, beginning with definition of requirements to support management needs, testing initial methods, and advancing as limitations of initial methods and equipment become evident and other options become available. In this process, the Landsat-based tool was found to have several significant deficiencies. It was very effective in revealing to DBW managers during beta testing that significant improvements in operations and assessment could be achieved. The Landsat tool enabled identification of hyacinth nursery populations that provided early-season propagules, and focus on managing and treating these areas early had a positive impact on suppressing early season hyacinth distribution. Similarly, the Landsat tool provided beta testing managers with a new source of information regarding the status of FAV populations across the Delta. The issues of scale, timeliness, and vulnerability to weather and smoke already discussed did not discourage DBW; rather, they supported development of a new tool to fill critical gaps in Landsat tool performance. That new tool was the Sentinel-2/Acolite tool.

Each Sentinel acquisition, processed using Acolite, produces a map of FAV-occupied pixels across the Delta for that day (Figure 4), or individual pixels can be displayed to provide the specific location of FAV-occupied pixels and an estimation of the scale of FAV patch presence and canopy characteristics at those locations. The water area of the Delta covered with FAV can be summed for the entire Delta or each map and used to consider temporal development as shown in Figure 3. The maps provide new information to making short-term resource utilization deployment to potentially problematic areas. However, the temporal value of assessing the effectiveness of management practices and using that information to modify practices, quantify ability to achieve intended goals, and make adaptive changes in management strategy in response to new understanding is a novel approach in the Delta. Table 3 provides a general but comprehensive description of the decision paths associated with addressing the operational, assessment, and adaptive needs of DBW in support of FAV management. The full impact of the temporal and quantitative analysis aspects is just beginning to impact management, particularly as the Delta Plan is evolving along with standards as to how to set performance objectives and measure them.

Operational utilization. Operationally, maps showing individual DBW treatment sites provide an easy-to-use visualization of FAV infestation (Figure 5). These regularly produced maps are utilized to augment traditional operational planning. Historically, limited on-the-water reporting by DBW as well as public provided reporting were the only basis for modification of weekly standard practices. Maps now provide a comprehensive view of the Delta at a spatial resolution relevant to specific Area Managers. Figure 5 provides a snapshot example of a portion of the Delta with single-pixel resolution at level showing a few DBW treatment areas. Specific site managers utilize this informa-

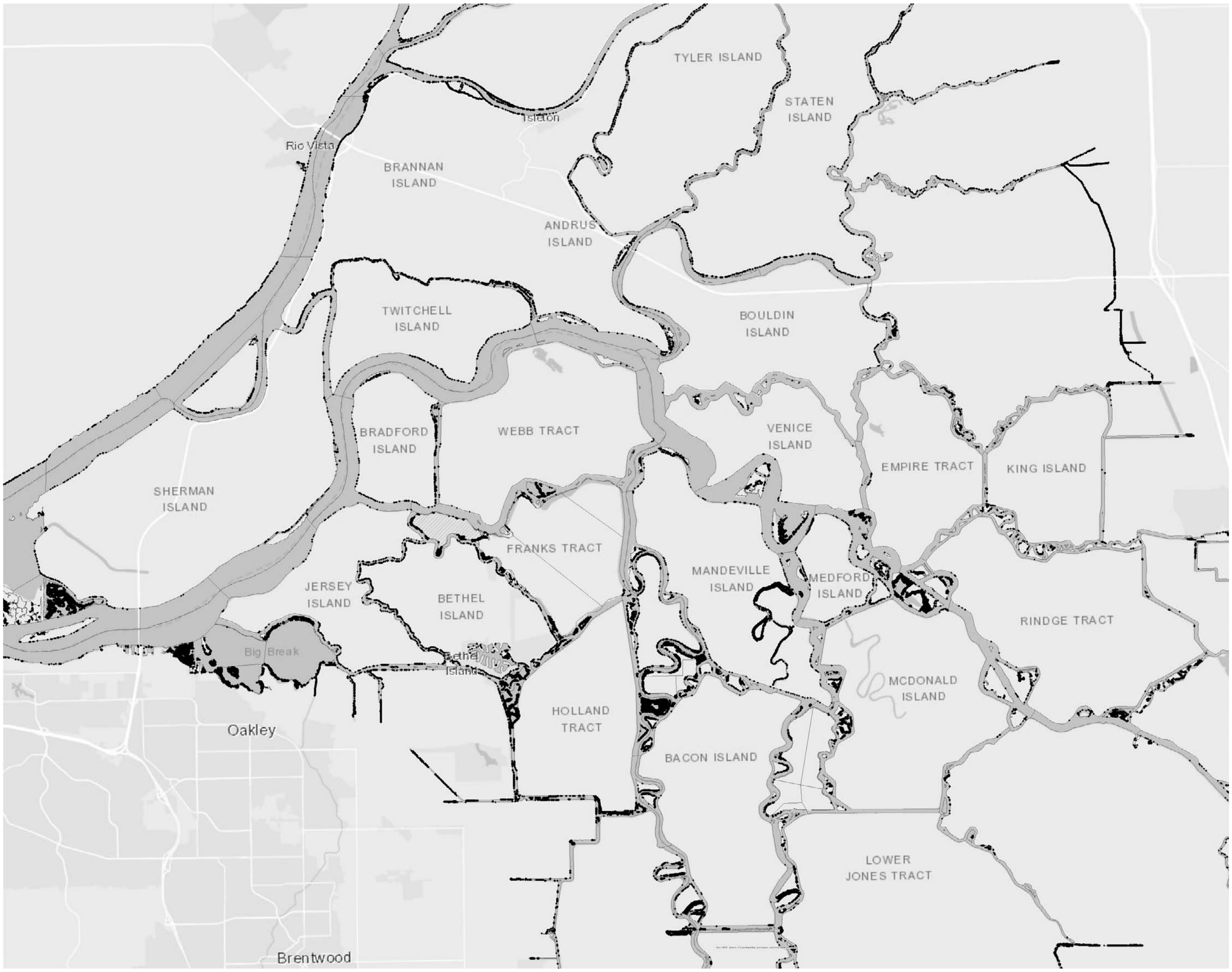


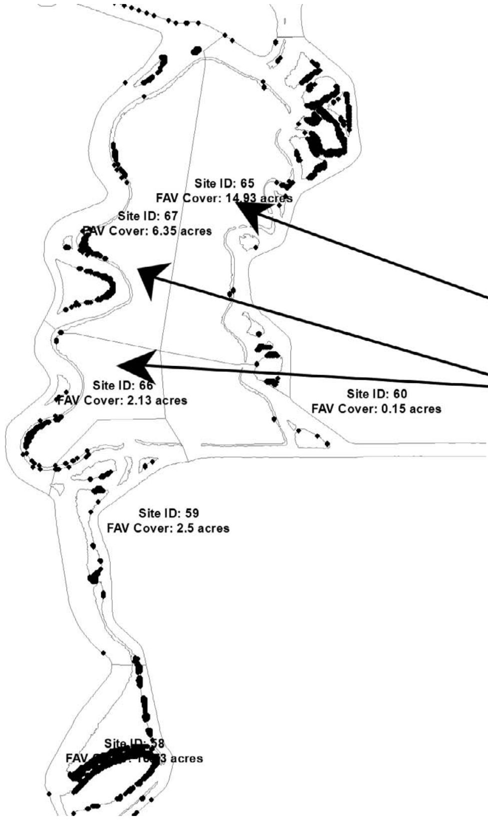
Figure 4. Sentinel-2 FAV Map DBW FAV Management Zone 2. Black dots designate individual 10 m pixels occupied by FAV.

tion to inform the specific actions of work crews in the area in their weekly plans.

Assessment utilization. FAV mapping provides assessment capabilities at immediate, seasonal, annual, and multiyear scales. Assessment of waterways critical for commerce or recreational pursuits are viewed for potential FAV threats, and treatment crews can be dispatched as needed to head off a local problem. Within a season, the tool provides an

Table 3. Decision map for remote sensing products to support operations, assessment, and adaptive management in the California Delta.

Operations	Management	Adaptive Management
Enabling Information: **What and Where** –Local Areas and Delta Wide	Enabling Information: **What, Where, and How Much** –Local Areas and Delta Wide	Enabling Information: **What, Where, How Much, and When** –Local Areas and Delta Wide
Decision Path: • Priority Areas • Permit Regulations • Management Practice Options	Decision Path: • Management Practice Performance • Iterative Learning / Reduce Uncertainty • Temporal / Spatial Variations	Decision Path: • Evaluate action sets based on estimated and observed performance • Temporal / Spatial Objectives
• Resource Allocation	• Performance Objectives • Management Plans • Knowledge Gaps	• Delta Plan Conformance • Restoration Goals • Management Plan Revisions



Treatment Zone ID	Pixels in Site	Site Area (m^2)	FAV Pixels	FAV Area (m^2)	FAV Area (Acre)
65	22,747	2,274,700	604	60,400	14.93
66	8,628	862,800	86	8.600	2.13
67	19,136	1,913,600	257	25,700	6.35

Figure 5. Example of FAV mapping at DBW Treatment Zone level. Black dots designate individual 10 m pixels occupied by FAV. Data characterizing physical features of the site and FAV coverage for that site on specific date are include.

assessment of the effectiveness of the level of management applied to specific areas and indicate need for enhanced efforts or, when treatment has surpassed expectation, the possibility to redirect resources to other areas in need of enhanced management. Annually, the cumulative data archived from the FAV-mapping tool provides quantitative evaluation of FAV phenological development across the Delta and assessment of management practice effectiveness in achieving objectives for specific treatment areas and Delta-wide, particularly as related to the Delta Plan.

Adaptive Management Utilization. The quantitative assessment of FAV population dynamics in the Delta and the effectiveness of management provides new and novel insight to enable adaptation of management in the Delta. Remote sensing-based FAV mapping is a strategic tool in planning and assessing management practices in response to the variable range of multiple environmental pressures on the Delta, and specific FAV management practices (herbicide, mechanical, biological, no treatment) to achieve objectives and maximize effectiveness. In addition to contributing to the invasive plant management strategy and operations of DBW, the remote sensing FAV mapping tool should enable evaluation and refinement of Delta ecosystem planning and overall management objectives set forth in the Delta Plan.

CONCLUSIONS

Through DRAAWP we have shown the utility of remote sensing with appropriate spatial and temporal frequency to large-scale resource management and to understanding the dynamic nature of the Delta FAV ecosystem. The Delta is a complex assemblage of waterways, from rivers with deep channels to sloughs that flow to various degrees, and some which are dead ended. The geographic size, input from multiple watersheds, and complex routing of water, lead to variability in water qualities, both physical and chemical, within the Delta. Remote sensing on a regular basis provides an assessment and quantifies the local and comprehensive situation regarding floating aquatic vegetation presence and health, both as it is now, and when archived to evaluate trends. The remote sensing capability significantly enhances DBWs' decision-making process and provides a unique characterization and measure of comprehensive functional outcomes for the Delta that are not available via other means but are recognized as essential for effective adaptive management in the future for DBW and stakeholders in the Sacramento–San Joaquin River Delta.

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LITERATURE CITED

Acolite. 2018. Acolite.https://odnature.naturalsciences.be/remsem/software-and-data/acolite. Accessed October 1, 2018.

Alexander CAD, Poulsen F, Robinson DCE, Ma BO, Luster RA. 2018. Improving multi-objective ecological flow management with flexible priorities and turn-taking: A case study from the Sacramento River and Sacramento-San Joaquin Delta. San Francisco Estuary Watershed Sci. 16 (1), art. no. 2. doi: 10.15447/sfews. 2018v16iss1/art2.

Anderson LWJ. 1990. Aquatic weed problems and management in the Western United States and Canada, pp 371–391. In: AH Pieterse, KJ Murphy (*eds*.). Aquatic weeds: The ecology and management of nuisance aquatic vegetation. Oxford University Press, New York. 616 pp.

Beller ES, Spotswood EN, Robinson AH, Anderson MG, Higgs ES, Hobbs RJ, Suding KN, Zavaleta ES, Grenier JL, Grossinger RM. 2019. Building ecological resilience in highly modified landscapes. Bioscience 69:80–92.

Boyer K, Sutula M. 2015. Factors controlling submersed and floating macrophytes in the Sacramento–San Joaquin Delta. Technical Report No. 870, Southern California Coastal Water Research Project. Costa Mesa, CA. 86 pp.

Cohen AN, Carlton JT. 1998. Accelerating invasion rate in a highly invaded estuary. Science 279: 555–558.

[DSC] Delta Stewardship Council. 2013. The Delta Plan. Delta Stewardship Council, Sacramento, CA. 322 pp. http://deltacouncil.ca.gov/delta-plan-0. Accessed October 1, 2018.

[DSC] Delta Stewardship Council. 2019a. Delta Stewardship Council. http://delta.ca.gov/. Accessed October 1, 2018.

[DSC] Delta Stewardship Council. 2019b. The Delta Science Plan. Accessed October 1, 2018. http://deltacouncil.ca.gov/science-program/delta-science-plan-2.

Dogliotti AI, Gossn JI, Vanhellemont Q, Ruddick, K. 2018. Detecting and quantifying a massive invasion of floating aquatic plants in the Río de la Plata turbid waters using high spatial resolution ocean color imagery. Remote Sens. 10(7):1140. https://doi.org/10.3390/rs10071140.

Hutton PH, Chen L, Rath JS, Roy SB. 2019. Tidally-averaged flows in the interior Sacramento–San Joaquin River Delta: Trends and change attribution. Hydrolog. Process. 33:230–243.

Khanna S, Santos MJ, Boyer JD, Shapiro KD, Bellvert J, Ustin SL. 2018. Water primrose invasion changes successional pathways in the estuarine ecosystem. Ecosphere 9 (9), e02418.

Khanna S, Santos MJ, Hestir EL, Ustin SL. 2012. Plant community dynamics relative to the changing distribution of a highly invasive species, *Eichhornia crassipes*: A remote sensing perspective. Biol. Invasions14:717–733.

Lácan I, Resh WH. 2016. A case study in integrated management: Sacramento–San Joaquin rivers and Delta of California, USA. Ecohydrol. Hydrobiol. 16:215–228.

Landsat. 2020. Landsat: Four decades of images and data. https://www.space.com/19665-landsat.html. Accessed 2020.

Landsat 8. 2020. Title of website. https://landsat.gsfc.nasa.gov/landsat-8/. Accessed 2020.

Liu M, Yu T, Gu X, Sun Z, Yang J, Zhang Z, Mi X, Cao W, Li J. 2020. The impact of spatial resolution on the classification of vegetation types in highly fragmented planting areas based on unmanned aerial vehicle hyperspectral images. Remote Sens. 12:146. doi:10.3390/rs12010146.

Moran PJ, Madsen JD, Pratt PD, Bubenheim DL, Hard E, Jabusch T, Carruthers RI. 2021. An overview of the Delta Region Areawide Aquatic Weed Project for improved control of invasive aquatic weeds in the Sacramento–San Joaquin Delta. J. Aquat. Plant Manage. 59(01s)2–15.

Ponzoni FJ, Galvao LS, Epiphanio JCN. 2002. Spatial resolution influence on the identification of land cover classes in the Amazon environment. An. Acad. Bras. Ciênc. 74(4):717–725.

Roth KL, Roberts DA, Dennison PE, Peterson SH, Alonzo M. 2015. The impact of spatial resolution on the classification of plant species and functional types within imaging spectrometer data. Remote Sens. Environ. 171:45–57.

Santos MJ, Hestir E, Khanna S, Ustin SL. 2017. Using remote sensing to monitor past changes and assess future scenarios of the Sacramento–San Joaquin River Delta waterways, California USA. EGUGA, 3182.

Santos MJ, Hestir ES, Khanna S, Ustin SL. 2012. Image spectroscopy and stable isotopes elucidate functional dissimilarity between native and nonnative plant species in the aquatic environment. New Phytol. 193:683–695.

Santos MJ, Khanna S, Hestir ES, Andrew ME, Rajapakse SS, Greenberg JA, Anderson LWJ, Ustin SL. 2009. Use of hyperspectral remote sensing to evaluate efficacy of aquatic plant management in the Sacramento–San Joaquin River Delta, California. Invasive Plant Sci. Manage. 2:216–229.

Sentinal-2. 2018. Sentinal 2 Overview. https://sentinel.esa.int/web/sentinel/missions/sentinel-2/overview. Accessed October 1, 2018.

Sloop C, Jacobs B, Logsdon R, Wilcox C. 2018. Delta Conservation Framework—A Delta in Common. California Department of Fish and Wildlife, Sacramento, CA. 194 pp. http://wildlife.ca.gov/DeltaConservation Framework. Accessed October 1, 2018.

Ta J, Anderson LWJ, Christman MA, Khanna S, Kratville D, Madsen JD, Moran PJ, Viers JH. 2017. Invasive aquatic vegetation management in the Sacramento–San Joaquin River Delta: Status and recommendations. San Francisco Estuary Water Sci. 15:4, Art. 5:1–19. doi: 10.15447/sfews. 2017v15iss4art5.

Thomaz SM, Kovalenko KE, Havel JE. 2015. Aquatic invasive species: general trends in the literature and introduction to the special issue. Hydrobiologia 746:1–12. https://doi.org/10.1007/s10750-014-2150-8.

USGS. 2020. Bulk order download. https://espa.cr.usgs.gov/ordering/new/. Accessed June 1, 2020.

Ustin S, Khanna S, Bellvert J, Ustin JD, Shapiro K. 2016. Mapping changes in the distribution of aquatic plant species in the Sacramento–San Joaquin Delta from airborne AVIRIS-ng data. American Geophysical Union Fall Meeting 2016, GC53C-1301.

Vanhellemont Q. 2019. Adaptation of the dark spectrum fitting atmospheric correction for aquatic applications of the Landsat and Sentinel-2 archives. Remote Sens. Environ. 225:175–192. https://doi.org/10.1016/j.rse. 2019.03.010.

Vanhellemont Q, Ruddick, K. 2018. Atmospheric correction of meter-scale optical satellite data for inland and coastal water applications. Remote Sens. Environ. https://doi.org/10.1016/j.rse.2018.07.015.