Critical Needs for Control of Invasive Aquatic Vegetation in the Sacramento – San Joaquin Delta

Contributions by:

J. Louise Conrad[1], Dylan Chapple[1], Eva Bush[1], Edward Hard[2], Jeffrey Caudill[2], John D. Madsen[3], Wendy Pratt[4], Shawn Acuna[5], Nick Rasmussen[6], Patricia Gilbert[2], Angela Calderaro[2], Shruti Khanna[7]

[1] Delta Stewardship Council
[2] State Parks, Division of Boating and Waterways
[3] U.S. Department of Agriculture
[4] Crowe, LLP
[5] Metropolitan Water District
[6] Department of Water Resources
[7] CA Department of Fish and Wildlife

Critical Needs for Control of Invasive Aquatic Vegetation in the Sacramento-San Joaquin Delta

Table of Contents

1 EXECUTIVE SUMMARY

The growing aquatic weed crisis in the Delta is a critical threat to restoration investments, endangered species, recreation, the local economy, and water project operations (Ta et al. 2017, Jetter and Ness 2019). Success of major initiatives and mandates, including Biological Opinions for endangered species, EcoRestore, Fish Restoration Program, aspects of the Water Resilience Portfolio and the Biodiversity Initiative, and the Delta Plan, all depend on effective control of aquatic weeds in the Delta. Despite ongoing control efforts, the total area invaded by aquatic weeds has doubled between 2004 and 2018 (Ustin et al. 2019). **Recent science demonstrates that current treatment methods and monitoring for submerged aquatic vegetation (SAV) are not sufficient for reducing coverage, particularly in habitats like those targeted for restoration** (Ustin et al. 2019, Rasmussen et al. 2020). **Action is needed now to protect agency investments in restoration.**

We summarize the current status of aquatic weeds in the Delta and identify key needs for proactive adaptive management of this critical problem. We focus specifically on submerged weeds (rather than floating or emergent forms) because they are particularly costly and difficult to control. SAV has been actively spreading in recent years, particularly in Delta regions targeted for wetland restoration (e.g., North Delta).

We identify two central needs that are currently restricting advancement of the aquatic weed control program for the Delta. We recommend two actions to support proactive adaptive management.

CRITICAL NEEDS FOR AQUATIC WEED CONTROL AND ACTIONS TO ADDRESS THEM

Need: **New control tools are identified in recent Biological Opinions (NMFS 2018, USFWS 2019) but will require additional authorization to use in priority restoration areas. Implementation and evaluation of new tools may also require additional funding.**

Action: Prioritize and support regulatory authorization and identify funding to implement and evaluate new tools at two Fish Restoration Program sites (Decker Island and Prospect Island). If authorizations are in place, rapid action will allow for results in 2021 to inform management. Testing new control tools at restoration sites would be a specific implementation the Water Resilience Portfolio action to curb invasive species that are altering California waterways.

Need: **There is no consistently funded monitoring program in place for the Delta. Consistent, landscape-scale monitoring is critical for evaluating efficacy of new and existing tools at the Delta scale.**

Action: Identify funding for consistent Delta-wide monitoring of aquatic weeds based on the recently published recommendations of the Interagency Ecological Program (IEP) (Khanna et al. 2018).

1.1 AQUATIC WEEDS IN THE DELTA

Aquatic weeds are a class of noxious invasive plants that have wrought extensive damage and costs to ecosystems and human uses of those ecosystems worldwide (Gallardo et al. 2016; Keller et al. 2018). Multiple aquatic weed species are present in the Sacramento-San Joaquin Delta (Delta). The problem is costly, widespread, and continues to grow (Ta et al. 2017, Jetter and Nes 2019). The expansion of aquatic weeds started in the early 1980s. Control efforts began in 1982 for floating aquatic vegetation (FAV) and in 2001 for SAV. The Delta presents unique and difficult challenges for control because the system is hydrologically complex and invasive vegetation has multiple growth forms that rapidly occupy newly available habitat.

Aquatic weeds (including new invasive species) commonly disperse into the Delta via the Sacramento and San Joaquin watersheds, recreational boating and commercial shipping. Combined with mild environmental conditions, this makes the Delta particularly vulnerable to invasions. There are three main types of aquatic weeds that have invaded the Delta: SAV, FAV, and emergent aquatic vegetation (EAV) (Boyer and Sutula 2015). Each class has multiple species present in the Delta, including species that are widely known as noxious invaders throughout the world. SAV (e.g., Brazilian Waterweed, also known as *Egeria densa)* roots in the sediments in waterways and completes its lifecycle entirely below the water surface. In contrast, FAV (e.g., Water Hyacinth) floats on the water surface. EAV (e.g., *Arundo donax*) is generally rooted at elevations below the water surface, but the foliage is almost entirely in the air.

While the historic Delta had all forms of aquatic vegetation in its native communities, about half of the species in the modern plant community are non-native. These introduced species achieve unprecedented densities in today's Delta and make up most of the aquatic plant cover (Boyer and Sutula 2015). In addition, the number of invading species is expanding; for example, Alligatorweed (*Alternanthera philoxeroides*) was detected in the Delta for the first time in 2017 (DBW 2017) and is now becoming established. The California Department of Parks and Recreation Division of Boating and Waterways (DBW) Aquatic Invasive Plant Control Program (AIPCP) is tasked with controlling SAV and FAV, and is the only entity permitted to conduct these treatments in navigable waterways throughout the Delta. Between 2004 and 2018, the estimated percent cover of SAV in the consistently monitored regions of the North and Central Delta more than doubled (Ustin et al. 2019; Figure 1). **Invasive SAV, due to its high control costs, rapid spread, and limited treatment options, is the primary focus of this whitepaper.**

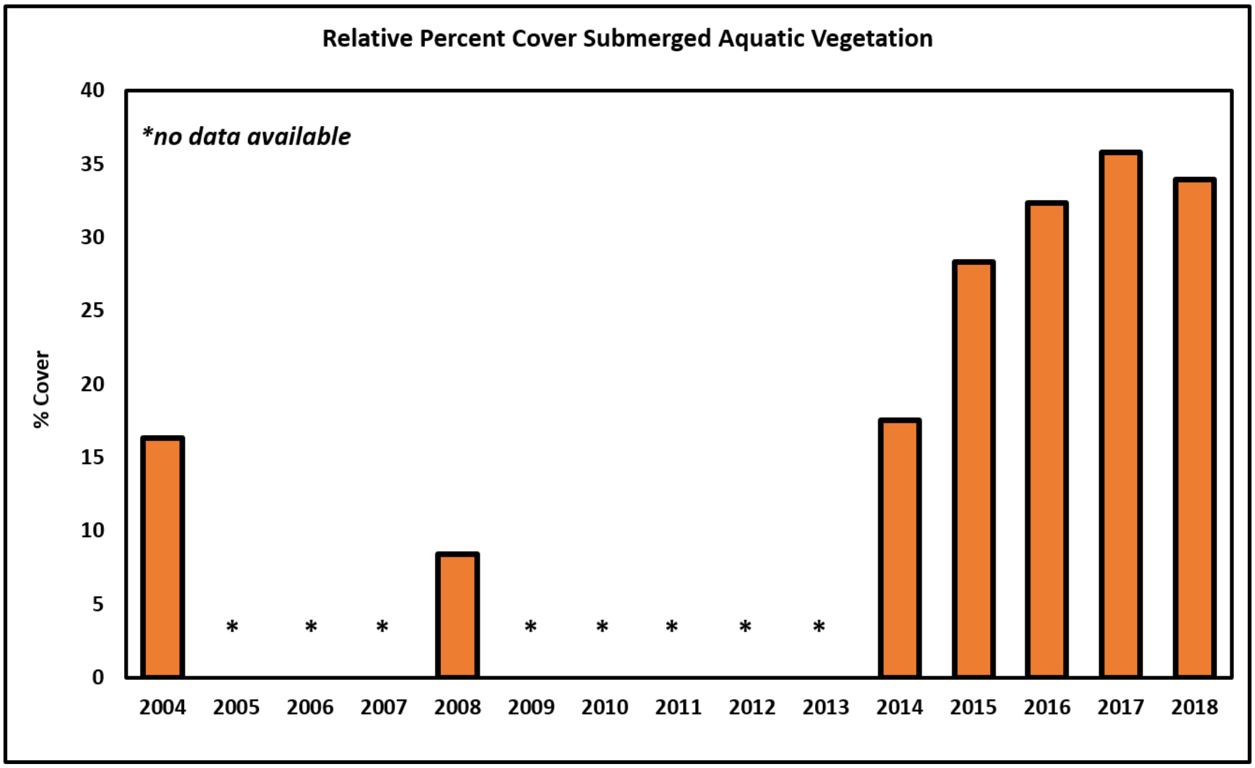

Figure 1. Percent Cover of SAV in Surveyed Areas. Percentages represent areas in the Central Delta and North Delta and are relative to the total area sampled, which differs in some years. For methods and details, see Ustin et al. 2019.

1.1.1 Ecological Effects of SAV

The widespread growth of invasive SAV is a major stressor on aquatic ecosystems. Historically, Delta salinity was highly variable, which favored native plants. However, water project operations and Delta farming now require management for freshwater (Moyle 2010). Consistent freshwater conditions favor invasive aquatic weeds, which are generally not salinity tolerant (Borgnis and Boyer 2016). Dense invasive SAV can decrease dissolved oxygen levels, increase water temperatures, clarify the water, slow water velocities, and displace native vegetation (Yarrow et al. 2009). In the Delta, the large-scale invasion of SAV has contributed to a system-wide trend of increasing water clarity (Hestir et al. 2016). These trends negatively impact native species that rely on turbid (murky) environments to avoid predators (Ferrari et al 2014, Grossman 2016). For example, Delta Smelt require turbid, open water and do not use SAV as habitat (Ferrari et al. 2014). **Thus, areas invaded with SAV preclude the presence of Delta Smelt.**

In the Delta, beds of non-native SAV and FAV create habitat that favors non-native fishes, particularly black basses and sunfish (Toft et al 2003, Brown and Michnuk 2007, Conrad et al. 2016). These non-native fishes both compete with and predate on native fishes, including Delta Smelt (Schreier et al. 2016). Beyond the effects on the fish community, aquatic weeds may also be an important stressor on the planktonic food web: many of the SAV and FAV species present in the Delta have allelopathic properties, such that they impede growth of beneficial phytoplankton, or algae (Shanab et al. 2010, Vanderstukken 2011). This effect, if occurring in the Delta, may be a critical stressor because the Delta is already food-limited (Brown et al. 2016). Any impact on beneficial phytoplankton communities, undercuts current efforts to boost the plankton food web for native fish.

1.1.2 SAV Impacts on Restoration

If restoration sites are infested with weeds, they will be unable to provide habitat for fish species of management concern (like Delta Smelt and Chinook Salmon) and their ability to serve as food-production areas may be compromised (Toft et al. 2003, Brown et al. 2016). Through EcoRestore and other projects, California is making an unprecedented investment in restoring and creating shallow-water habitat to support native fishes. The Fish Restoration Program (FRP), initiated in 2010 based on an agreement between CDFW and DWR, is a subset of EcoRestore projects focused on restoring 8,000 acres of tidal habitat for Delta Smelt and 800 acres of low salinity habitat for Longfin Smelt as required by federal biological opinions governing water project operations (USFWS Biological Opinion 2008, NMFS Biological Opinion 2009). The full suite of EcoRestore restoration projects includes approximately 30,000 acres and is expected to cost at least $300 million in the first 4 years (CNRA EcoRestore). With current treatment options and funding levels, there is a distinct risk that these sites will be invaded by SAV and other classes of aquatic weeds, undermining their value as native fish habitat and food producers. Recent years have seen expansion of SAV in areas adjacent to planned restoration sites (Figure 2), making them highly vulnerable to infestation once levees are breached.

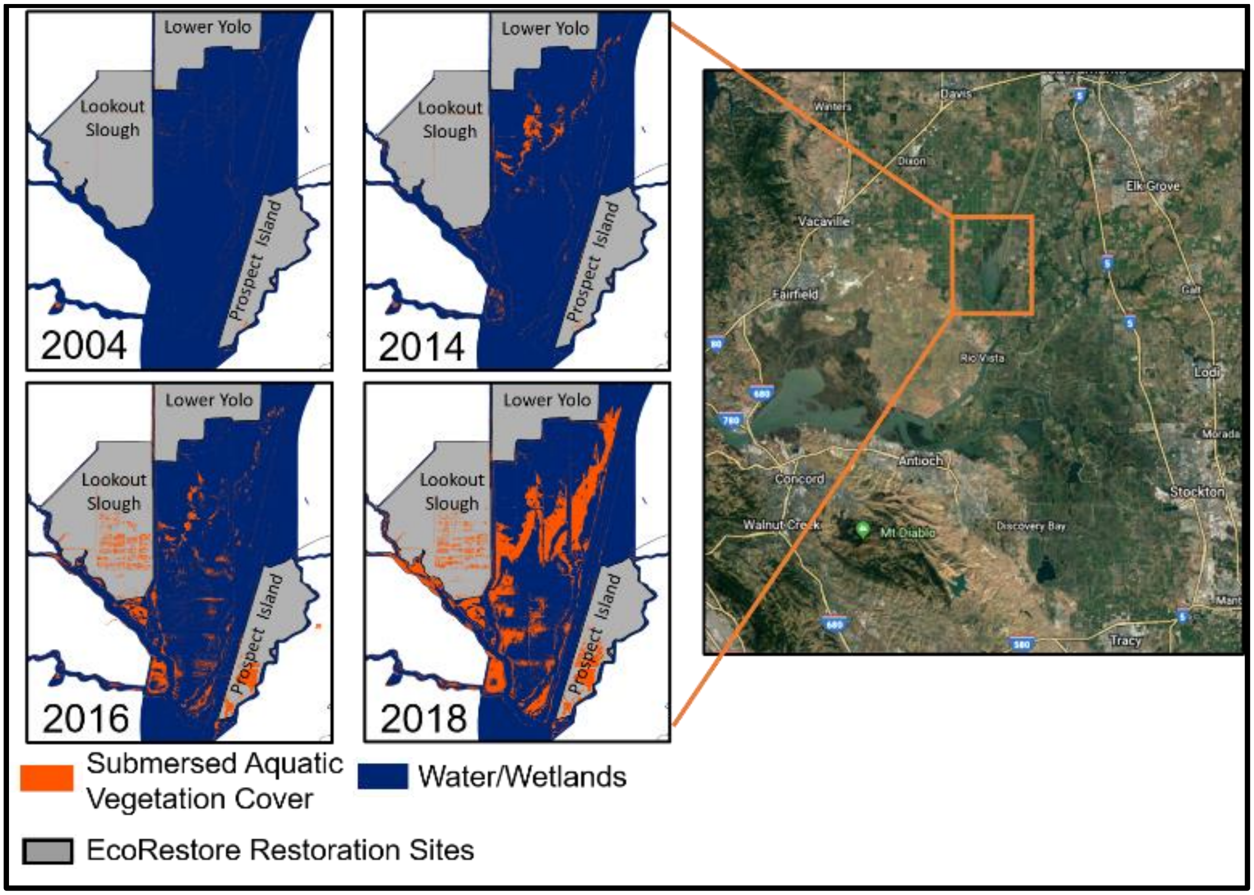

Figure 2. SAV Cover Adjacent to Future EcoRestore Sites. See Ustin et al. 2019 for methods and details.

1.1.3 Marinas and Shipping

Weeds impact recreational and commercial shipping traffic in the Delta. There are more than 88 active marinas in the Delta, providing recreational opportunities, including tournaments for trophy bass fishing (Jetter and Nes 2019). These are generally small, private businesses that are sensitive to closures and access limitations caused by weeds. Collectively, these marinas and public boat launches support 14.4 million person-days of recreational boating and 11.8 million person-days of recreational fishing (Ustin et al. 2019). This activity is vital to the economy of the rural towns in the Delta. Marinas lose revenue when slips become inaccessible due to infestations and incur costs when they have to manually remove weeds on their own (Table 1). Floating aquatic weeds also affect commercial traffic to the Port of Stockton, causing delays in ship arrivals until weed mats (particularly FAV in this area) are no longer present (Jetter and Nes 2019).

1.1.4 Water Project Operations

Aquatic weeds can limit water exports and fish salvage operations for the State and Federal Water Projects. When weeds are entrained at the Tracy Fish Collection Facility and the Skinner Delta Fish Protective Facility, they must be removed to allow normal operation. Fish salvaged at the Skinner Delta Fish Protection Facility are periodically counted to detect protected species.

High weed volume interferes with fish count operations, leading to reduced precision in counts (Khanna et al. 2019). When vegetation volume is high, it can clog the screening components and increase the potential for equipment failure. These failures often result in an interruption to salvage operations.

Interruptions can also affect water exports at the Jones Pumping Plant (CVP), usually leading to a reduction in pumping. When exports increase, more weeds are drawn into the facilities. In periods of high weed volume, this can lead to exporting less than the planned amount of water (Khanna et al. 2019). For instance, the Banks pumping plant (SWP) requires a full-day closure after chemical treatment of aquatic weeds in Clifton Court Forebay (USFWS Biological Opinion 2008, NMFS Biological Opinion 2009).

1.2 Division of Boating and Waterways Aquatic Invasive Plant Control Program

The DBW AIPCP is tasked with the control of invasive aquatic vegetation in the Delta. The DBW AIPCP started in 1982, with a mandate to control Water Hyacinth in the Delta and Suisun Marsh (DBW 2017). As the aquatic weed problem continued to expand and SAV became increasingly problematic, further legislation authorized DBW to treat additional aquatic weeds, including SAV species. The AIPCP is now permitted to treat nine aquatic invasive weeds across approximately 418 sites in the primary Delta (DBW 2017). Chemical control with herbicides is the predominant approach, with limited use of mechanical and biological control tools.

1.2.1 AIPCP Program Costs

Approximately 70 – 95% of AIPCP control costs are devoted to chemical treatment of SAV. The annual cost of the program is approximately $12.5 million. From 2013 to 2017, the AIPCP spent approximately $52.7M on aquatic weed control, with other state, federal, and local entities spending an estimated $7.4M (Table 1).

Table 1. Aquatic Invasive Weed Control Costs (SAV and FAV; in thousands of dollars), 2013-2017 (adapted from Jetter and Ness 2019)

Entity	2013	2014	2015	2016	2017	Total
State Investments (DBW/DWR)	7,124	7,625	13,718	12,545	13,029	54,041
Federal Investments (USBR)	343	833	921	658	215	2,970
Marinas	169	576	943	310	21	2,020
Local entities	348	379	205	155	11	1,097
Total	7,984	9,413	15,787	13,669	13,277	60,129

1.2.2 AIPCP Authorizations

The authorizations needed for the control program require consultation with 8 separate state and federal entities (Figure 3). There are multiple species protected under the federal Endangered Species Act with critical habitat in the Delta, and DBW conducts a Biological Assessment for the effect of its control program on each species. The authorizations under the federal Endangered Species Act, provided by the US Fish and Wildlife Service (USFWS) and the National Marine Fisheries Service (NMFS), generally determine the control tools available to DBW. To be able to test a new control tool, chemical or otherwise, the program must re-initiate the programmatic approval process. DBW, USFWS, and NMFS recently completed a full consultation process and DBW now has updated Biological Opinions for the AIPCP, valid for 2018-2022 (NMFS 2018, USFWS 2019).

DBW also needs to show that its program is consistent with the California Endangered Species Act and the Delta Plan, obtain permits from the National Pollutant Discharge Elimination System (NPDES), and comply with the California Environmental Quality Act (CEQA), among others (Figure 3). The recently completed process of preparing and receiving an approved Biological Opinion and other authorizations required 26 months and approximately 3,100 consultant hours for DBW.

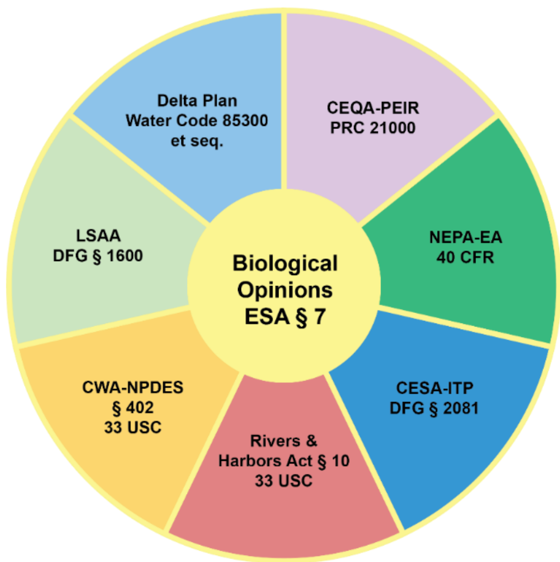

Figure 3. Regulatory Requirements for AIPCP Operations

Under its updated Biological Opinions, the AIPCP is authorized to treat a total of 15,000 acres of combined SAV and FAV. Delta Smelt protections are the primary regulatory limitation to AIPCP operations. The majority of authorized treatment is in the form of approved herbicides, with mechanical harvesting limited to 200 acres per year (NMFS 2018, USFWS 2019). In addition to the routine chemical and physical control methods, the new Biological Opinions authorize limited experimentation with new tools not previously used by DBW. For SAV, the possible new tools include one new herbicide agent and three new physical control methods (Table 2). For FAV, experimentation with biological control agents is also permitted. There are currently no biological control agents identified for SAV.

New control tools must be evaluated in Demonstration Investigation Zones (DIZs), as described in the Biological Opinions (NMFS 2018, USFWS 2019)**.** The new tools that would be tested in DIZs include new herbicides or tank mixes, new physical control methods, and new application methods. DIZs are advised to occur in 10-20-acre sized plots, with each research activity and location defined during an annual review process that will occur prior to the beginning of each treatment season. The Biological Opinions also require an adaptive management approach, including the use of metrics to evaluate efficacy of control measures (e.g., acres of SAV and FAV infestation).

Treatment timing is critical, because if treatment begins after the spring weed growth period, it is extremely difficult to control. In fact, in the early 2000s, treatment efficacy improved in Franks Tract once spring treatments were allowed (Santos et al. 2010). The new Biological Opinions authorize DBW to use herbicides for a suite of submerged and floating species, with treatment permitted from March through November and North Delta (Cache Slough and Liberty Island areas) approval dependent on the presence of spawning and rearing Delta Smelt.

Notably, the acreage authorization does not cover the full extent of aquatic weed coverage in the Delta. Additionally, existing equipment and personnel resources make meeting this acreage target very difficult. With existing resources, DBW was able to treat approximately 10,000 acres in 2018 and 8,500 acres in 2019. Increased resources would allow for expanded treatment once effective tools are identified for SAV.

Table 2. List of newly proposed control tools for SAV in Biological Opinions for the DBW AIPCP (NMFS 2018, USFWS 2019), noted with their relative applicability to restoration sites and respective regulatory restrictions.

Control Approach	Control Tool	Applicability to Restoration	Regulatory Restrictions
Physical	Benthic Mats	May be feasible for smaller sites (e.g. Decker Island)	May not be used in historical Delta Smelt habitat (USFWS 2019)
Physical	Diver assisted suction removal	May be feasible only at very small sites with new infestation	Max use 1 acre and 4 locations/year (USFWS 2019)
Physical	Curtains, screens	May be useful as a mechanism to maintain target herbicide concentrations within restoration sites	Some cannot be used where they may impede navigation (USFWS 2019). Refer to historical salmonid presence maps and CDFW trawl data when selecting time and location for placement (NMFS 2018).
Chemical	Endothall (Aquathol K)	Used in place of or in combination with current herbicides	AIPCP began testing at 3 sites in 2019 and plan to conduct additional field testing in the Delta (USFWS 2019)

1.2.3 Limitations to Currently Approved SAV Control Methods

Recent studies have demonstrated that current treatment methods for SAV are not sufficient for effective control. For SAV, fluridone is the only herbicide approved for widespread use in the Delta (USFWS 2019, NMFS 2018). Fluridone is a slow-acting, systemic herbicide that functions by inhibiting photosynthesis (Sprecher et al. 1998, Puri et al. 2007). Laboratory and field studies in other systems have demonstrated that this process requires exposure times of up to 60 days to have an effect on plant biomass: for example, maintaining fluridone at a concentration of 12 ppb, for at least 60 days, was necessary for control of Watermilfoil and Hydrilla in Florida (Netherland et al., 1993), which is far above the concentration used in the Delta (1.5-3 ppb) due to label restrictions (DBW 2017). Fluridone has been used to effectively control *Egeria* in lakes and similar closed environments with low flow that allows these concentrations (e.g., Parsons et al. 2009).

In the dynamic flow conditions of the Delta, attaining target concentrations is likely to be a challenge (Anderson 1999). Because of this requirement for long exposure times, DBW conducts repeated, weekly applications for 16 weeks. Water concentrations of fluridone are then measured weekly, targeting a consistent concentration of 1.5 – 3.5 ppb (DBW 2017). However, recent research for the Delta Smelt Resiliency Strategy in the North Delta and at Decker Island illustrated that target concentrations of fluridone were not maintained. In this study, SAV coverage was not reduced in study sites (Rasmussen et al. 2020). **Despite evidence for limited efficacy of fluridone, it is the only tool widely available to DBW in the Delta for SAV treatment.**

In the 2019 USFWS and 2018 NMFS Biological Opinions for the DBW control program, experimentation with new chemical and physical control methods is allowed, but generally not in areas targeted for restoration, where development of more effective tools is needed. At least 143 of the 418 AIPCP sites have limitations on application based on the Biological Opinions, with 73 sites receiving no treatment. Delta Smelt are the main limitation on experimentation with new control tools, with spatial restrictions based on recently published maps of its *historical distribution* (Murphy and Hamilton 2013). For new tools, the Biological Opinions state that "USDA and CDBW will identify DIZ sites that do not co-occur (spatially and temporally) with listed species…". However, Delta Smelt avoid SAV habitat (Ferrari et al. 2014). **Thus, areas invaded with SAV are unlikely to harbor Delta Smelt and are in need of innovative control measures, particularly those that are near or in restoration areas designed to benefit the species.**

1.2.4 Current Monitoring and adaptive management efforts

Proactive adaptive management is critically needed to identify effective control strategies and requires a consistent monitoring program. Adaptive management is a structured approach to environmental decision-making under uncertain conditions, in which learning from a cycle of management actions informs future iterations (Weins et al. 2017). This approach is required for compliance with multiple regulatory processes, including consistency with the Delta Plan. Effective adaptive management requires incorporation of new scientific information to improve management outcomes.

Despite the significance of aquatic weeds to Delta management, ecosystem function, human uses, and restoration, the Delta lacks a consistent monitoring program for aquatic weed coverage. Without a reliably funded program with consistent methodology that collects data from both treated and untreated sites, it is not possible to evaluate the efficacy of new or existing control tools. In fact, recent reviews on aquatic vegetation ecology and management have called for the establishment of a monitoring program to provide a science-based approach to assessing control efforts and planning future efforts (Boyer and Sutula 2015, Ta et al. 2017). While substantial progress has been made over the last two decades in establishing monitoring methods (e.g., Hestir et al. 2008), consistent funding for a systematic monitoring program is still lacking.

DBW has recently conducted boat-based hydroacoustic surveys that use sonar technology to estimate SAV densities (biovolume). This approach helps inform site selection and conduct efficacy analysis for pre- and post-treatment sites. However, because it is labor-intensive and time-consuming, it can only be carried out over approximately 5% of the Delta and thus does not provide a landscape-scale assessment of coverage. An ongoing DBW partnership with NASA developed a satellite-based tool to track new infestations. This tool is generally effective for FAV, but not for SAV. Remote sensing of SAV requires high resolution hyperspectral imagery captured via low-flying aircraft, paired with field monitoring for ground-truthing purposes. The imagery is then classified for SAV presence.

The UC Davis Center for Spatial Technology and Remote Sensing (CSTARS) has partnered with various agencies (DBW, CDFW DWR, DSC) intermittently over the last two decades to collect this imagery and produce maps of SAV coverage (2003-2008, 2014–2019) (Ustin et al. 2019). This effort has been essential for understanding changes in coverage and informing adaptive management efforts. However, there is no sustained funding for this work and each year there is a risk that maps will not be produced until an interested agency agrees to fund another year. Further, expanded field monitoring is needed to accurately identify SAV species. Gaps in the mapping effort affect evaluation of the control program efficacy and eliminate an important tool for planning a science-based control program. Recently, the IEP produced a monitoring framework that identified a range of monitoring scenarios and assessed the knowledge and management-tools gained from each scenario (Khanna et al. 2018). Implementing these recommendations is key for adaptive management.

2 Key Needs to Enhance Adaptive Management and Increase Efficacy of DBW AIPCP

2.1 Testing New Tools

Prioritize regulatory authorization and identify funding to research and implement new tools at two Fish Restoration Program restoration sites (Decker Island and Prospect Island). The latest science on control activities approved under current regulatory authorizations indicate that fluridone, the only tool widely available to DBW, will not have the intended effect at the scale necessary to control aquatic weeds, particularly at large-scale restoration sites (Rasmussen et al. 2020).

To determine the efficacy of new methods identified in the current AIPCP Biological Opinions, rigorous scientific testing at representative sites is critical. We propose a collaborative effort between the DWR/CDFW Fish Restoration Program and the DBW AIPCP to rapidly investigate their effectiveness at two pilot sites, Decker Island and Prospect Island. Decker Island was included in the Delta Smelt Resiliency Strategy Aquatic Weed Control Action but did not respond to fluridone treatment (Rasmussen et al., 2020). Both sites are the target of major investments for weed control in the near term and are candidates for test deployments of new tools such as benthic mats, new herbicides, and bubble curtains (Box 1).

As testing of new control tools must occur in DIZs that are approved by USFWS and NMFS, Decker Island and Prospect Island would need to be prioritized for authorization in order to investigate the efficacy of these newly proposed tools. If DIZs at these sites are approved, efforts are funded, and testing of control tools (e.g., benthic mats or a combination of physical controls with herbicide treatment) can be implemented in 2020, preliminary results for efficacy of new tools would be available in 2021, significantly advancing our knowledge of how to proceed with addressing SAV infestations. If experimental treatments are successful, Decker and Prospect

Islands will benefit from reduced weed coverage and could become models for effective SAV treatment in restoration areas.

This experimental approach is called for in the Water Resilience Portfolio, Action 12, to curb invasive species that are altering California waterways. Specifically, Action 12.2 calls for agencies to "Support programs that prevent, detect, and manage invasive species and pests… support early detection programs, and evaluate and improve weed management efforts" (CNRA, CalEPA and CDFA Water Resilience Portfolio, draft January 2020).

BOX 1: NEW TOOLS FOR SAV CONTROL

Due to the limited efficacy of fluridone for control of SAV in restoration areas, new approaches need to be explored to improve treatment outcomes. New treatment approaches (both chemical and non-chemical, Table 2) will require considerable investment to determine their efficacy and safety but may provide long-term cost savings. The most promising tools for planned and existing restored areas included in the current AIPCP Biological Opinions are as follows:

Benthic mats: Benthic mats are thick material laid over the bottom of a water body to prevent growth of submerged vegetation. Following installation, this method is likely to be minimally invasive, but would require maintenance if mats are left in place to avoid sediment accumulation and subsequent plant growth. This method is likely to be cost and time intensive in the short-term but may have lasting impacts on SAV cover.

Bubble Curtains: An air bubble curtain, which produces a wall of bubbles from a series of closely spaced release points forms a "curtain" of bubbles in the water column. Bubble curtains would be used in tandem with herbicides to increase water holding time in the treatment areas, thereby holding herbicide concentrations for maximum efficacy.

New Chemical Control Methods: Other herbicides hold promise for improving SAV control methods (Madsen et al. 2019), but will require additional approvals for use in the Delta (Table 2).

2.2 CONSISTENT MONITORING

Identify funding for consistent Delta-wide monitoring of aquatic weeds based on the recently published recommendations of the IEP. Aquatic vegetation monitoring to date has only been funded opportunistically. Comprehensive monitoring is essential for evaluating the efficacy of new and existing control measures and tracking the expansion of aquatic weeds across the system. Currently, resource limitations mean that some data is collected on treatment sites, but there is no reliable Delta-wide program that provides a consistent methodology across both treated and untreated sites. For robust scientific interpretation of trends, comparisons with untreated sites is essential. System-scale mapping will help describe the impact of treatment by tracking coverage at both treated and untreated sites. It will also facilitate assessment of how the aquatic weed problem is changing over time and where control efforts can be prioritized to have the greatest return on investment. The monitoring framework developed by IEP recommends a combination of aerial and ground surveys to document trends and inform control efforts (Khanna et al. 2018). System-wide data is critical for determining the most cost-effective means of controlling aquatic invasive species, and adaptive management of control efforts across the Delta landscape.

3 Conclusion

Confronting the problem of aquatic weeds is essential to the missions of DPIIC agencies. Aquatic weed invasions negatively impact a wide range of Water Resilience Portfolio, Delta Plan, and Endangered Species Act priorities. Thus, collaborative action is needed to improve control efforts.

For about the last decade, collaborative science in the area of aquatic vegetation in the Delta has been advancing, gaining in energy and productivity. Major examples of this include the USDA-ARS Delta Region Areawide Aquatic Weed Project, state investments in the Delta Smelt Resiliency Strategy for Aquatic Weed Control, and the IEP's Project Work Team for Aquatic Vegetation. This momentum in science, along with identification of potentially successful control tools for SAV in the newly approved Biological Opinions for the DBW AIPCP, positions the Delta science and management community to take action. In these respects, the science enterprise and the management community are poised to rapidly and collaboratively push on the problem of aquatic weeds. The matter is urgent, given the rapid spread of invasive SAV in parallel with imminent investment in tens of thousands of acres of tidal wetland restoration. It is critical that resources for both restoration and invasive aquatic weed control are put to productive use. Rapid investigation of new tools in relevant areas for restoration, along with a landscape scale monitoring program, are critically needed actions for this issue of socioeconomic and ecological importance to the Sacramento-San Joaquin Delta.

4 References

Anderson, Lars W.J. 1999. Egeria Invades the Sacramento-San Joaquin Delta. Aquatic Nuisance Species Digest. 3:4.

Borgnis E, Boyer KE. Salinity tolerance and competition drive distributions of native and invasive submerged aquatic vegetation in the Upper San Francisco Estuary. Estuaries and coasts. 2016 May 1;39(3):707-17.

Boyer, K. and M. Sutula. 2015. Factors Controlling Submersed and Floating Macrophytes in the Sacramento-San Joaquin Delta. Southern California Coastal Water Research Project. Technical Report No. 870. Costa Mesa, CA.

Brown, L. R., and D. Michniuk. 2007. Littoral fish assemblages of the alien-dominated 3777 Sacramento-San Joaquin Delta, California, 1980–1983 and 2001–2003. Estuaries and 3778 Coasts 30:186–200.

Brown, L. R., W. Kimmerer, J. L. Conrad, S. Lesmeister, and A. Mueller–Solger. 2016. Food webs 3774 of the Delta, Suisun Bay, and Suisun Marsh: an update on current understanding and 3775 possibilities for management. San Francisco Estuary and Watershed Science 14.

California Natural Resources Agency. What is California EcoRestore? https://resources.ca.gov/Initiatives/California-EcoRestore/What-is-California-EcoRestore Retrieved 02/24/2020.

California State Parks, Division of Boating and Waterways (DBW). 2017. Floating Aquatic Vegetation Control Program 2017 Annual Monitoring Report. California State Parks Division of Boating and Waterways. http://dbw.parks.ca.gov/pages/28702/files/2017%20FAV%20Annual%20Report.pdf.

Conrad, Louise, Andrew J. Bibian, Kelly L. Weinersmith, Denise De Carion, Matthew Young, Patrick Crain, Erin L. Hestir, Maria J. Santos and Andrew Sih. 2016. Novel Species Interactions in a Highly Modified Estuary: Association of Largemouth Bass with Brazilian Waterweed Egeria densa. Transactions of the American Fisheries Society 145:249-263.

Ferrari, Maud CO, Lynn Ranåker, Kelly L. Weinersmith, Matthew J. Young, Andrew Sih, and J. Louise Conrad. 2014. Effects of turbidity and an invasive waterweed on predation by introduced largemouth bass. Environmental Biology of Fishes 97, no. 1: 79-90.

Gallardo, B., M. Clavero, M. I. Sánchez, and M. Vilà. 2016. Global ecological impacts of invasive species in aquatic ecosystems. Global Change Biology 22:151–163.

Grossman, G. D. 2016. Predation on fishes in the Sacramento–San Joaquin Delta: current knowledge and future directions. San Francisco Estuary and Watershed Science, 14(2).

Hestir, E.L., Khanna, S., Andrew, M.E., Santos, M.J., Viers, J.H., Greenberg, J.A., Rajapakse, S.S. and Ustin, S.L. 2008. Identification of invasive vegetation using hyperspectral remote sensing in the California Delta ecosystem. Remote Sensing of Environment, 112(11), pp.4034-4047.

Hestir, E. L., D. H. Schoellhamer, J. Greenberg, T. Morgan-King, and S. L. Ustin. 2016. The Effect of Submerged Aquatic Vegetation Expansion on a Declining Turbidity Trend in the Sacramento-San Joaquin River Delta. Estuaries and Coasts 39:1100–1112.

Jetter, Karen M. and Kjersti Nes. The Cost to Manage Invasive Aquatic Weeds in the California Bay-Delta. ARE Update 21(3)(2018):9-11. University of California Giannini Foundation of Agricultural Economics.

Keller, R.P., Masoodi, A. and Shackleton, R.T. 2018. The impact of invasive aquatic plants on ecosystem services and human well-being in Wular Lake, India. Regional environmental change, 18(3), pp.847-857.

Khanna, Shruti, Shawn Acuna, Dave Contreras, W. Kyle Griffiths, Sarah Lesmeister, Rene C. Reyes, Brian Schreier and Brandon J. Wu. 2019. Invasive Aquatic Vegetation Impacts on Delta Operations, Monitoring, and Ecosystem and Human Health. Interagency Ecological Program Newsletter.

Khanna, Shruti, J. Louise Conrad, Jeff Caudill, Maggie Christman, Gina Darin, Daniel Ellis, Patricia Gilbert, Rosemary Hartman, Karen Kayfetz, Wendy Pratt, Vanessa Tobias, Amanda Wasserman.

2019. Framework for Aquatic Vegetation Monitoring in the Delta. Interagency Ecological Program Technical Report 92.

Lampert, Adam, Alan Hastings, Edwin D. Grosholz, Sunny L. Jardine and James N. Sanchirico. 2014 Optimal approaches for balancing invasive species eradication and endangered species management. Science 344 6187:1028-1031.

Madsen, J.D, Morgan, C., Miskella, J., Kyser, G., Gilbert, P., O'Brien, J., Getsinger, K.D. Herbicide trials with Brazilian Egeria for management in the Sacramento/San Joaquin River Delta. Poster. Aquatic Plant Management Society Annual Meeting, July 14-17, San Diego, California.

Moyle, P. B, Lund, J. R, Bennett, W. A, & Fleenor, W. E. 2010. Habitat Variability and Complexity in the Upper San Francisco Estuary. San Francisco Estuary and Watershed Science. 8(3).

Murphy, D. D, & Hamilton, S. A. 2013. Eastward Migration or Marshward Dispersal: Exercising Survey Data to Elicit an Understanding of Seasonal Movement of Delta Smelt. San Francisco Estuary and Watershed Science.11(3).

National Marine Fisheries Service (NMFS). 2009. Biological Opinion and Conference Opinion on the Long-Term Operations of the Central Valley Project and State Water Project. https://archive.fisheries.noaa.gov/wcr/publications/Central_Valley/Water%20Operations/Operations,%20Criteria%20and%20Plan/nmfs_biological_and_conference_opinion_on_the_long-term_operations_of_the_cvp_and_swp.pdf.

National Marine Fisheries Service (NMFS). 2018. Endangered Species Act Section 7(a)(2) Programmatic Biological Opinion, Magnuson-Stevens Fishery Conservation and Management Act Essential Fish Habitat Response and Fish and Wildlife Coordination Act Recommendations for the Aquatic Invasive Plant Control Program located in the Sacramento-San Joaquin Delta, its surrounding tributaries and Suisun Marsh, California. https://dbw.parks.ca.gov/pages/28702/files/2018-05-15_AIPCP_Programmatic_BiOp_Final.pdf.

Netherland, M., K. Getsinger, and E. Turner. 1993. Fluridone concentration and exposure time requirements for control of Eurasian watermilfoil and hydrilla. Journal of Aquatic Plant Management 31:189–189.

Parsons, J. K., A. Couto, K. S. Hamel, and G. E. Marx. 2009. Effect of Fluridone on Macrophytes and Fish in a Coastal Washington Lake. Journal of Aquatic Plant Management 47:31–40.

Puri, A., G. E. MacDonald, W. T. Haller, and M. Singh. 2007. Growth and reproductive physiology of fluridone-susceptible and-resistant hydrilla (*Hydrilla verticillata*) biotypes. Weed science 55:441–445.

Rasmussen, N., J. L. Conrad, H. Green, S. Khanna, J. Caudill, P. Gilbert, P. Goertler, H. Wright, K. Hoffmann, S. Lesmeister, J. Jenkins, L. Takata, D. Bosworth, T. Flynn, E. Hard, T. Sommer. 2020. 2017-2018 Delta Smelt Resiliency Strategy Action for Enhanced Control of Aquatic Weeds and Understanding Effects of Herbicide Treatment on Habitat. Interagency Ecological Program Technical Report. 324 pp.

Santos, M.J., Anderson, L.W. & Ustin, S.L. 2011. Effects of invasive species on plant communities: an example using submersed aquatic plants at the regional scale. Biol Invasions 13, 443–457.

Schreier, B.M., Baerwald, M.R., Conrad, J.L., Schumer, G. and May, B., 2016. Examination of predation on early life stage Delta Smelt in the San Francisco estuary using DNA diet analysis. Transactions of the American Fisheries Society. 145(4), pp.723-733.

Shanab, S.M., Shalaby, E.A., Lightfoot, D.A. and El-Shemy, H.A., 2010. Allelopathic effects of water hyacinth [Eichhornia crassipes]. PloS one. 5(10).

Sprecher, S. L., M. Netherland, and A. Stewart. 1998. Phytoene and carotene response of aquatic plants to fluridone under laboratory conditions. Journal of Aquatic Plant Management 36:111–120.Ta, J., L. W. Anderson, M. A. Christman, S. Khanna, D. Kratville, J. D. Madsen, P. J. Moran, and J.H. Viers. 2017. Invasive aquatic vegetation management in the Sacramento–San Joaquin River Delta: status and recommendations. San Francisco Estuary and Watershed Science 15.
Ta, J., L. W. Anderson, M. A. Christman, S. Khanna, D. Kratville, J. D. Madsen, P. J. Moran, and J. H. Viers. 2017. Invasive aquatic vegetation management in the Sacramento–San Joaquin.
River Delta: status and recommendations. San Francisco Estuary and Watershed Science 15.
Toft, J. D., Simenstad, C. A., Cordell, J. R., & Grimaldo, L. F. 2003. The effects of introduced water hyacinth on habitat structure, invertebrate assemblages, and fish diets. Estuaries. 26(3), 746-758.

US Fish & Wildlife Service. 2008. Formal Endangered Species Act Consultation on the Proposed Coordinated Operations of the Central Valley Project (CVP) and State Water Project (SWP) https://www.fws.gov/sfbaydelta/Documents/SWP-CVP_OPs_BO_12-15_final_OCR.pdf.

US Fish & Wildlife Service. 2018. Biological Opinion for the Aquatic Invasive Plant Control Program 2018-2022. https://dbw.parks.ca.gov/pages/28702/files/08FBDT00-2018-F0029%20BO%20fpr%202018-2022%20Aquatic%20Invasive%20Plant%20Control%20Program.pdf.

Ustin, Susan L., Shruti Khanna, Mui Lay and Kristen Shapiro. 2019. Enhancement of Delta Smelt (Hypomesus transpacificus) habitat through adaptive management of invasive aquatic weeds in the Sacramento-San Joaquin Delta & Suisun. California Department of Water Resources.

Vanderstukken, M., Mazzeo, N., Van Colen, W., Declerck, S.A. and Muylaert, K., 2011. Biological control of phytoplankton by the subtropical submerged macrophytes Egeria densa and Potamogeton illinoensis: a mesocosm study. Freshwater Biology. 56(9), pp.1837-1849.

Wiens, J. A, Zedler, J. B, Resh, V. H, Collier, T. K, Brandt, S., Norgaard, R. B. 2017. Facilitating Adaptive Management in California's Sacramento–San Joaquin Delta. San Francisco Estuary and Watershed Science. 15(2).

Yarrow, M., V. Marín, M. Finlayson, A. Tironi, L. Delgado, and F. Fischer. 2009. The ecology of Egeria densa Planchon (Liliopsida: Alismatales): A wetland ecosystem engineer? Revista Chilena de Historia Natural 82: 299-313.