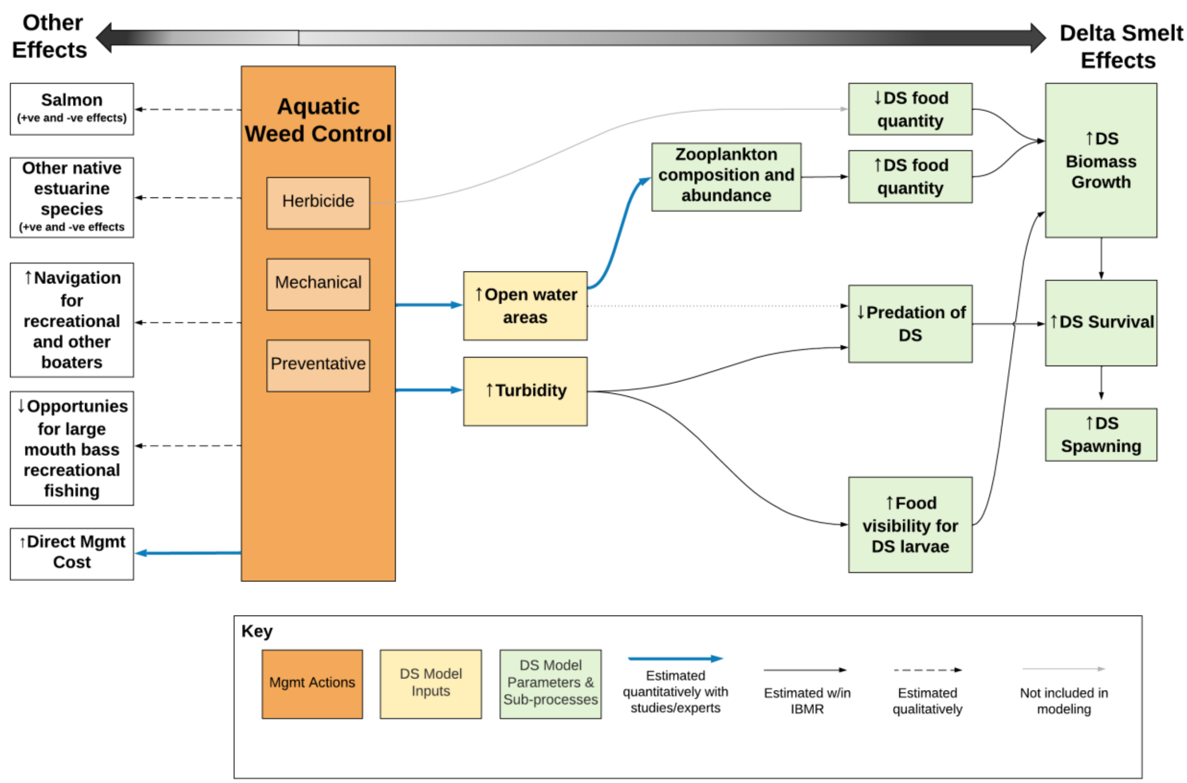
Action Specification Sheet:
Aquatic Weed Control

1 Short Description and Hypothesized Bottleneck

This action involves removal of invasive aquatic vegetation to create more open water habitat and increase turbidity to benefit Delta Smelt. Submerged and floating species of invasive aquatic vegetation have expanded in the Delta, particularly during the recent drought, and now occupy the majority of shallow-water and littoral areas of the system. Between 2008 and 2014, submerged aquatic vegetation (SAV) increased its cover by 50% (estimated coverage of 6,070 acres in 2014), while floating aquatic vegetation (FAV) saw a multi-fold increase, reaching 6,460 acres (Conrad, 2017). Invasive weeds encroach on open water habitat that Delta Smelt depend upon, and often harbor non-native predators. The plants reduce phytoplankton and slow water movement, removing suspended particles that help hide Delta Smelt from predators. The State of California's Delta Smelt Resiliency Strategy (2016) calls for increased treatment of aquatic weeds in the Delta.

2 Influence Diagram



3 Action Evaluation

Table 1. Effect hypotheses for aquatic weed control action to be assessed in SDM analysis.

#	Effect Hypothesis	Estimation Method
Delta Smelt		
1	**Aquatic weed removal → Decreased density of aquatic weeds and increased open water areas** Depending on the specific characteristics of a site, herbicides can vary in their effectiveness of removing aquatic weeds. For example, treatment of SAV by fluridone is limited to slow moving and stagnant waters because fluridone works by being taken up through leaves, stems and root systems and needs to be in contact with the plant for a certain length of time for this to occur (USFWS, 2013; E. Hard, pers. comm., 2017).	Used SAV and FAV spatial coverage data from Ustin et al. (2021) to simulate removal of all aquatic weeds in specific subregions, according to the level of management (see Section 10: Intensity Required). For the purposes of the Round 1 evaluation, we assumed completely effective methods of removal are developed and implemented, which includes assuming restrictions of mechanical and other methods do not deter implementation. We also assumed that we can operate outside of the permit limitations and conduct the controls as early as March and have effects system-wide. We assumed that management will reduce SAV and FAV year-round.
1 & 2	**Aquatic weed removal → Increased open water areas → Improved zooplankton composition and abundance for Delta Smelt** It is thought that macrophytes, such as aquatic weeds, compete with phytoplankton such that macrophytes decrease phytoplankton densities and this in turn reduces zooplankton densities. Moreover, it is likely that Delta Smelt will not enter aquatic weed beds to forage, so removing weed beds increases the area in which they can feed (L. Conrad, pers. comm., Aug. 11, 2017).	Used methods developed for the Delta Smelt Demo Project that assumes total biomass of zooplankton in each subregion increases linearly and proportionately with the increase in open water areas. This is the same method as the "low bookend" for food effects of tidal wetland restoration. For the Round 1 evaluation, we assumed no increase in herbicide use in this action, and therefore, no direct negative effect of this action (via herbicides) on zooplankton density.
3	**Aquatic weed removal → Increased turbidity** SAV slows water and makes it clearer (i.e., less turbid) (Moyle et al., 2016). Hestir et al. (2016) estimated that SAV contributed about 20-70% to the trend in declining turbidity in the Delta, suggesting that removing aquatic weeds can help offset the system-wide loss of turbidity due to the effect of dams and other structures. See also Drexler et al. (2021) and Tobias et. al. (2019).	Used relationships described in Hestir et al. (2016) to estimate how much turbidity would change in an area when a given area of aquatic weeds are removed. Hestir et al. (2016) provided trends for turbidity decline as a function of aquatic weeds and sediment supply. This is the method that was used in the SDM Demo Project.
4	**Increased turbidity → Decreased predation** The translucent body color and small size of delta smelt may make them less visible to predators in moderately turbid water (Moyle et al., 2016). Ferrari et al. (2014) find that adult Delta Smelt predation is lower in more turbid water.	Estimated/accounted for in IBMR. See Smith (2022) for how the IBMR relates turbidity to the natural mortality process in the model.

	Note that it has also been hypothesized that removal of aquatic weeds would decrease DS predation because these weeds provide habitat to ambush type predators. However, in Ferrari et al. (2014), there was no difference in predation of DS between vegetated and unvegetated areas. There was only a difference in predation of DS between turbid and clear water.	
5	**Increased turbidity → Increased food visibility for DS larvae** Studies have shown that delta smelt larvae benefit from turbidity to see their prey (Baskerville-Bridges et al., 2004; Hasenbein et al., 2016; Moyle et al., 2016). However, no studies show this relationship for adult and juvenile DS.	Estimated/accounted for in IBMR. See Smith (2022) for how the IBMR relates turbidity to the growth process in the model.
6	**Aquatic weed removal (via herbicide treatment) → Reduction in food quantity** L. Conrad (pers. comm., 2017) stated that a significant research effort would be needed to have confidence that application of herbicides in the Delta at this magnitude would not do harm to delta smelt, their food web, or any other ecological endpoints of concern. Key uncertainties identified by L. Conrad include: 1. Effects of herbicides on phytoplankton; 2. Effects of fluridone settling on sediments; and, 3. Effects of herbicides on Delta Smelt and food web considering possible interaction of these herbicides and additives with other water quality constituents in the Delta. In 2020, Rasmussen et al., conducted a large-scale study to investigate these same questions. Their research found that (1) there was no evidence of an effect of fluridone application on phytoplankton and zooplankton communities in the Delta. (2) sediments had much higher concentrations of herbicides than water by several orders of magnitude (averages >250 ppb)and (3) it did not have significant effects on fish communities themselves or the copepod species they rely on for food.	This pathway was not captured in this SDM process. Landis et al (WWU) could provide average concentrations for select herbicides in a region by month. Assuming a linear relationship with increased control coverage with increased herbicides could be one option and the other would be the increase would be due to alternative methods; therefore, we could see if the benefits could be significant assuming no increase in contaminant toxicity. This way we don't have to evaluate the increase impacts of contaminants and instead put the cost in this action into dollars.

Financial and water resources		
	Aquatic weed removal (via herbicide) → Direct management costs Direct management costs include (E. Hard, pers. comm., 2017): • Herbicide costs • Staff for applying herbicide, environmental costs, managing the program • Transportation costs (boats, trucks) • Regulatory sampling analysis	Compass spoke with Eddie Hard, manager of the Aquatic Weed Control Program at the DBW on Aug.1, 2017. E. Hard provided a ballpark $/acre cost estimate to Compass along with details on the challenges, limitations, and process to ramp up the Aquatic Weed Control Program to 10,000 acres for delta smelt. E. Hard's ballpark estimate is $2500 - $3500 per acre of weeds for the "control phase" or the initial removal of weeds. These costs would be spread over the control phase, which can take about 3 years. E. Hard did not have an estimate for the subsequent "maintenance phase", which would be the ongoing action to prevent weeds from re-establishing themselves in the area. We used the upper estimate of $3500 and lower estimate of $2,333 per acre for control programs. Final annualized cost estimates per acre included the control and maintenance phase costs and used an average of the upper and lower estimates. See Section 13 for details. **Final financial resource estimate: $366,667 per year per 100 ac**

3.1 Implementation Notes

Implementation Need	Notes
Aquatic weed removal → improved navigation for recreational and other boaters (water skiing, sailing, etc.)	The presence of aquatic weeds inhibits the use of an area by boats. The specific benefits of aquatic weed removal for boaters would depend on the specific sites that are treated and the extent to which those areas are valued use areas for boaters.
Aquatic weed removal → Large mouth bass recreational fishing.	Large mouth bass fishery is more prominent in the central (e.g., parts of Lower SJ strata), east, and south Delta. Striped bass fishing is more prominent in the North Delta (Upper Sacramento strata). The areas where aquatic weed control would be targeted for delta smelt are expected to have low to no overlap with areas that are important for large mouth bass fishing, therefore, a healthy large mouth bass fishery can be expected to

	remain if this action is implemented (L. Conrad, pers. comm., Aug. 11, 2017).

4 Evidence / Examples

4.1 Types of Aquatic Weeds in the Delta

Over 20 submerged and floating species comprise the aquatic vegetation community of the Delta, with invasive species making up the majority of the coverage (Rasmussen et al., 2020). The most predominant species by vegetation type are listed below.

4.1.1 Submerged Aquatic Species (SAV)

The Delta SAV community is dominated by the invasive *Egeria densa* (Brazilian waterweed) (Ustin, 2019).

4.1.2 Floating Aquatic Species (FAV)

The floating aquatic vegetation community in the Delta is dominated by two non-native species, water hyacinth (*Eichhornia crassipes)* and water primrose (*Ludwigia spp.*) (Ustin, 2019). Other common species are the native pennywort (*Hydrocotyle umbellata*), fairy moss (*Azolla* spp.) and duckweed (*Lemna* spp.) (Ustin, 2019).

4.1.3 Emergent Aquatic Vegetation (EAV)

The emergent plant community in the Delta is dominated by Typha latifolia, Typha angustifolia and their hybrids; *Schoenoplectus acutus* and *Schoenoplectus californicus*.

4.2 Spatial and Temporal Trends

There are various limitations to understanding spatial and temporal trends of aquatic weeds in the Delta. Most notably, a regular, comprehensive mapping program for aquatic weeds does not exist in the region (Boyer & Sutula, 2015). Consequently, data on the spatial and temporal trends of invasive aquatic weeds in the Delta is limited. To date, data has only been collected sporadically in both space and time and with relatively low detail (Boyer & Sutula, 2015). That being said, there are a few spatial patterns which have been detected and are described below.

4.2.1 SAV Spatial and Temporal Trends in the Delta

The SAV community in the Delta is dominated by *Egeria densa* (Brazilian waterweed) (Ustin, 2019). *Egeria densa* is thought to have been introduced to the Delta in 1946 through aquarium dumping (Boyer & Sutula, 2015). By 1996, it was noticed to have replaced many native SAV species in the area (Boyer & Sutula, 2015). In recent years, *Egeria densa* has increased in coverage -- in 2007 *Egeria densa* was estimated to cover ~2000 hectares (~8%) of Delta waters, it increased to ~2900 hectares (~11%) coverage in 2014 (Boyer & Sutula, 2015).

In the Delta, *Egeria densa* is primarily found in areas of moderate and low flow, such as along the margins of larger sloughs and in more protected areas, such as smaller sloughs and breached islands (e.g., Sherman Lake, Franks Tract) (Boyer & Sutula, 2015). *Egeria densa* grows densely throughout the water column in waters that are less than 7 meters deep but, grows nearer to the surface in turbid waters (Boyer & Sutula, 2015).

4.2.2 FAV Spatial and Temporal Trends in the Delta

The FAV community in the Delta is dominated by *Eichhornia crassipes* (water hyacinth) and *Ludwigia spp.* (water primrose) (Ustin, 2019). *Eichhornia crassipes* was introduced to the Sacramento river in 1904 by horticulturalists (Boyer & Sutula, 2015). Between 2004 and 2008, *Eichhornia crassipes* was estimated to cover between 160-300 hectares (~1%) of the Delta, and by 2014, this species had expanded to cover ~800 hectares (~3%) of the Delta (Boyer & Sutula, 2015). In that same time frame, *Ludwigia spp.* has also expanded in coverage. Whereas in 2004-2008 it had relatively low coverage, by 2014, it was estimated to covers ~800 hectares of the Delta.

In the Delta, *Eichornia crassipes* is primarily found in calm waters such as, along channel edges, narrow channels or in low flow basins (e.g., marinas, breached island interiors) (Boyer & Sutula, 2015). In recent years, it has been extremely abundant around the city of Stockton, the Tracy Fish Collection Facility and the River's End Marina on Old River. Similarly, *Ludwigia spp.* is found throughout the Delta in calm waters and typically in shallower areas (Boyer & Sutula, 2015).

4.2.3 SAV and FAV Spatial and Temporal Trends in the Delta from Remote-sensing Data

Ustin et al. (2021) used remote-sensing data to map and calculate annual area of non-native, invasive submerged aquatic vegetation (primarily *Egeria densa* [Brazilian waterweed]) and floating aquatic vegetation (*Pontederia crassipes* [water hyacinth] and *Ludwigia spp.* [water primrose]). The study used field-collected data of aquatic vegetation types to validate predictive models that used remote-sensing data. The study found that in the summer of 2020, SAV covered 3776 ha (9331 ac, 23.2% of the waterway area assessed); water primrose covered 514 ha (1270 ac), and water hyacinth covered 232 ha (573 ac). See key results from this study in Figure 1. Spatial datasets by year are available at https://knb.ecoinformatics.org/view/doi:10.5063/F1K9360F.

Figure 1. Key results tables from Ustin et al. (2021) on the annual area and percentage of cover of invasive, non-native submerged and floating aquatic vegetation types in the eastern region of the Delta (Confluence and east) between 2004 and 2020.

Table 7-3: Area in hectares of Submerged Aquatic Vegetation (SAV), shadow, water hyacinth, water primrose, total Floating Aquatic Vegetation (FAV), within the common area (Central Delta + Liberty Island Cache Slough complex).

Year	Area (ha) for common area among all years					
	SAV	Shadow	Water hyacinth	Water primrose	Pennywort	Total FAV
Summer 2004	2558	161	234	280	129	643
Summer 2005	2284	175	153	125	98	375
Summer 2006	2457	377	369	171	102	641
Summer 2007	2442	338	74	183	107	364
Summer 2008	1161	549	83	157	142	382
Fall 2014	2094	1050	806	272	0	1,078
Fall 2015	3436	835	299	390	22	711
Fall 2016	2881	1379	185	456	0	641
Fall 2017	4293	621	108	671	0	779
Fall 2018	4416	689	181	473	0	654
Fall 2019	3987	377	195	599	0	794
Summer 2020	3776	158	232	514	0	746

Table 7-4: Percent cover of waterways for Submerged Aquatic Vegetation (SAV), shadow, water hyacinth, water primrose, total Floating Aquatic Vegetation (FAV), within the common area (Central Delta + Liberty Island Cache Slough complex).

Year	% of waterways for common area among all years					
	SAV	Shadow	Water hyacinth	Water primrose	Pennywort	Total FAV
Summer 2004	15.7%	1.0%	1.4%	1.7%	0.8%	3.9%
Summer 2005	14.0%	1.1%	0.9%	0.8%	0.6%	2.3%
Summer 2006	15.1%	2.3%	2.3%	1.1%	0.6%	3.9%
Summer 2007	15.0%	2.1%	0.5%	1.1%	0.7%	2.2%
Summer 2008	7.1%	3.4%	0.5%	1.0%	0.9%	2.3%
Fall 2014	12.9%	6.4%	4.9%	1.7%	0.0%	6.6%
Fall 2015	21.1%	5.1%	1.8%	2.4%	0.1%	4.4%
Fall 2016	17.7%	8.5%	1.1%	2.8%	0.0%	3.9%
Fall 2017	26.4%	3.8%	0.7%	4.1%	0.0%	4.8%
Fall 2018	27.1%	4.2%	1.1%	2.9%	0.0%	4.0%
Fall 2019	24.5%	2.3%	1.2%	3.7%	0.0%	4.9%
Summer 2020	23.2%	1.0%	1.4%	4.8%	0.0%	6.2%

5 Intensity & Locations

The TWG has specified a set of actions and portfolios that include aquatic weed removal in different combinations of subregions in the Delta. Three levels of aquatic weed control that vary in spatial extent are proposed by Compass, based on previous TWG input, that will allow comparison of Delta Smelt outcomes in Round 1. Compass calculated areas of aquatic vegetation using spatial datasets from Ustin et al. (2021). Specifically, Compass summarized spatial data (Table 1Table 2) showing aquatic weed coverage in 2004, since this year was the median year of the timeframe for the SDM evaluation (1995-2014). The dataset included specific coverage for Brazilian waterweed, water hyacinth, and water primrose, and Compass summed the total acreage of all three species of SAV and FAV by subregion. Compass also summarized total acreage in the Franks Tract area for use in the third level of aquatic weed control (described below).

Table 2. Total acres of submerged and floating aquatic vegetation (SAV and FAV: Brazilian waterweed, water hyacinth, and water primrose) by subregion in the Delta. SAV and FAV coverage was obtained from remote-sensing data in 2004 from Ustin et al. (2020). Area of current tidal wetlands and open water were calculated using GIS data from the SFEI Landscape Scenario Planning Tool (https://www.sfei.org/projects/delta-landscapes-scenario-planning-tool).

Strata #	Strata Name	Acres of current tidal wetlands and open water	Acres of SAV and FAV	Proportion of strata targeted
1	Yolo/Cache	11,874	603	5%
2	Upper Sacramento	6,695	410	6%
3	South Delta	21,944	-	-
4	East Delta	6,060	-	-
5	Lower Sacramento	3,809	56	1%
6	Lower San Joaquin	15,072	2,309*	14%
7	Confluence	9,621	363	4%
8	South Suisun East	6,902	-	-
9	North Suisun East	6,516	-	-
10	Suisun Marsh	14,597	-	-
11	South Suisun West	2,644	-	-
12	North Suisun West	12,609	-	-
		Total acres of SAV and FAV:	3,470	

* This value reflects SAV and FAV only in Franks Tract.

Aquatic weed control Level 1: Yolo/Cache Slough Complex only

- Removal of 603 ac of SAV and FAV (5% of area of this subregion).
- This level corresponds to Portfolio 2b and 2c.

Aquatic weed control Level 2: North Delta Arc (Confluence, Lower Sacramento, Upper Sacramento, Yolo/Cache Slough Complex)

- Removal of 1,431 ac of SAV and FAV (4.5% of total area of these subregions).
- This level does not specifically correspond to a portfolio, but will serve as an intermediate point of comparison.

Aquatic weed control Level 1: North Delta Arc + Franks Tract (Confluence, Lower Sacramento, Upper Sacramento, Yolo/Cache Slough Complex, Franks Tract area)

- Removal of 3,470 ac of SAV and FAV (7.4% of total area of these subregions).
- This level corresponds to Portfolio 3a and 3e.

6 Timing / Lifestage / Triggering Conditions

Non-native SAV (most notably, *E. densa*) has two growth peaks, one in summer and one in late fall (Hestir et al., 2016). A study conducted by Santos et al. (2009) found that "the effective use of the systemic herbicide fluridone was clear only when it was applied in early spring, during the period of rapid plant growth".

To establish a "best-case" of the potential benefits of this action, the Round 1 SDM evaluation will represent sufficient removal of SAV and FAV such that coverage is reduced year-round in all model years for subregions in which the action is applied.

7 Delta Smelt Model Results

The table below shows predicted population outcomes across the 20-year model timeframe for several versions of the action that were tested with three Delta Smelt population models.

		Population Growth Rate			% Change in Population Growth Rate from Baseline		
		IBMR	LF	LCME	IBMR	LF	LCME
Action run ID	Scenario name	Average lambda (1995-2014)	Average lambda (1995-2014)	Median lambda (1995-2014)	% change in average lambda (1995-2014)	% change in average lambda (1995-2014)	% change in median lambda (1995-2014)
8.1	AWC Yolo	1.04	0.97	-	6%	13%	-
8.2	AWC Yolo - food only	0.99	-	-	1%	-	-
8.3	AWC Yolo - turbidity only	1.00	-	-	2%	-	-
8.4	AWC NDA	1.28	1.01	-	30%	18%	-
8.5	AWC NDA and LSJ	1.47	1.02	1.00	49%	19%	4%
8.1.2	AWC Yolo - 20% effectiveness	0.99	-	-	1%	-	-
8.4.2	AWC NDA - 20% effectiveness	1.04	-	-	6%	-	-
8.5.2	AWC NDA and LSJ - 20% effectiveness	1.06	-	-	8%	-	-

- Multiple runs were used to explore population outcomes while varying the spatial scale of the action and assumptions of effectiveness.
- Action runs 8.1 – 8.5 assume 100% effectiveness of aquatic weed removal methods; the bottom 3 Action runs assume 20% effectiveness of methods.
- Action runs 8.1 – 8.3 were exploratory runs to test the sensitivity of population outcomes when the small-scale action included both food and turbidity effects, food only, and turbidity only, respectively.
- **Model runs 8.1, 8.4, and 8.5 were used as the "primary" runs for the Round 1 portfolio evaluation and food, turbidity, and flow sensitivity analyses.**

8 Discussion and Next Steps

Model runs of aquatic weed control showed increased benefits to Delta Smelt as acreage of control increased. Results also showed interactive effects in the IBMR, as the predicted population growth was higher when effects of food and turbidity were included together (Run 8.1) then if their individual effects were added together (Runs 8.2 and 8.3). This interactive effect was also seen in other runs in Round 1 that combined food and turbidity actions.

Compass and Shawn Acuna met with IEP's Aquatic Weed Control Project Work Team (PWT) on 7 Dec 2023 to review the methods and assumptions used in the SDM evaluation. The PWT expressed these results are overly optimistic and gave two important pieces of feedback: (1) there is little evidence of any effect of food from aquatic weed control, and we should consider removing this effect when modeling the action, and (2) current research and monitoring show that a "best-case" of current methods is 20% effectiveness of vegetation removal, and our assumption of 100% effectiveness is unrealistic given current methods. This feedback prompted us to rerun the action assuming 20% effectiveness (shown above) as a point of comparison, but we did not rerun all versions of this action and portfolios that had previously been reviewed, discussed, and reported in the SDM process. Therefore, the results from this evaluation represent an optimistic, "best-case" scenario where more effective methods can be developed and implemented at broader scales for aquatic weed control.

Considerations for future modeling and implementation include:

- Revisit assumptions about 100% effectiveness and use a lower assumption (e.g., 20% effectiveness) in any future evaluation of actions or portfolios with aquatic weed control.
- Revisit assumptions about effects on food from the action, and consider removing food effects in future evaluation of actions and portfolios with aquatic weed control.
- Continue investigating feasible methods for aquatic weed control (see Action Specification section below).

9 Relationships with other actions

9.1 Operation of the Suisun Marsh Salinity Control Gates

Some aquatic weeds that are invasive to the Delta have a preference for water with less than 5 ppt salt concentrations. Therefore, freshening the marsh below 5 ppt may increase the risk of aquatic weed spread in Suisun Marsh (T. O'Rear, pers. comm., 2021). DWR is implementing annual aerial surveys of weeds to enable them to adaptively respond to this issue if the Summer/Fall operation of the SMSCG is leading to increased spread of weeds (R. Hartman, pers. comm., 2022).

9.2 Tidal wetland restoration

Shallow water habitats such as those that are created in tidal wetland restoration projects are vulnerable to invasion from aquatic weeds, particularly if they are located adjacent to infested areas. If they become infested with invasive vegetation, they may become inhospitable to Delta Smelt and could limit the amount of food production benefits they may have (Brown et al., 2016).

10 Action Specification

- This action was initially identified in the 2016 Delta Smelt Resiliency Strategy and then further specified in the SDM Demo Project based on communications with E. Hard, Program Manager of the Aquatic Weed Control Program of the Division of Boating and Waterways and L. Conrad of the Delta Stewardship Council in 2017.

- An effective method of control for large-scale removal of SAV and FAV has not yet been identified. Four different methods for controlling aquatic weeds are described below.

10.1 Chemical (Herbicide)

In the Delta, the Department of Boating and Waterways (DBW) is the only organization permitted to apply herbicides for the treatment of aquatic weeds. The chemical herbicide used by DBW to treat submerged aquatic vegetation (SAV) is fluridone.

In a 3-year study to test the application of fluridone on SAV in areas believed to be of importance to Delta Smelt (Little Hastings Tract and Decker Island), the study concluded: “The result that aggressive and sustained fluridone application did not have an impact on SAV density **indicates that this herbicide is likely not effective for addressing large-scale infestations in a tidal environment** and does not bode well for our ability to control SAV in newly-created tidal wetland restoration areas or manage infestations in existing habitat for the benefit of native fishes” (Rasmussen et al., 2020). The authors of this study go on to suggest that the efficacy of chemical herbicide treatments could be improved if they were supplemented with additional chemical, physical or biological control mechanisms such as chemical agents/tank mixes, benthic mats, hand/net removal and booms/floating barriers.

10.2 Physical

Various methods of physical aquatic weed removal exist and are described below. Physical removal can be effective at removing aquatic weeds however, it can often lead to population expansion or reinfestation due to the release of propagules when vegetation is cut (Rasmussen et. al., 2020). Species like, Egeria and Water Primrose will vegetatively propagate from smaller portions not fully removed. In fact, one 2006 study which evaluated the efficacy of water hyacinth (the most common form of FAV in the Delta) removal using cutters, showed that it “did not immediately (i.e., within six months) produce weed free areas of open water in habitats typical of those found in the Sacramento/San Joaquin Delta” (Spencer et. al., 2006; Ustin, 2019). Common forms of physical aquatic weed control are described below.

10.2.1 Benthic Mats

Benthic mats consist of physical covers which rest over aquatic weeds. They block sunlight from reaching plants, thus preventing them from photosynthesizing. Without this ability, plants will typically die back within 4-8 weeks. Benthic mats are non-selective meaning they will kill all plants that fall underneath its cover. Depending on the material, some benthic mats have also been proven to kill macroinvertebrates.

Benthic mats may be especially effective in high-water flow areas of the Delta where herbicide treatments will not be effective. Outside of that, benthic mats will most likely only be effective in relatively small areas of the Delta (2 acres or less), and high-intensity use areas such as docks and boat launches or relatively small patches (2 acres or less) (Madsen, 2019).

10.2.2 Booms and Floating Barriers

Booms and floating barriers prevent the spread of SAV and FAV. They can be used on their own to contain aquatic weeds within a particular location, or in conjunction with herbicides or physical/mechanical treatment methods to capture plant fragments that may be dispersed preventing regrowth. The efficacy of booms and barriers in the water column beneath the surface can be enhanced with curtains (see section 3.2.3).

In the Delta, booms and barriers are most likely to be effective in high-use areas such as marinas and shipping channels. They can also be useful in areas where herbicides or mechanical removal may not be feasible (Madsen, 2019).

10.2.3 Curtains and Screens

Curtains and screens are barriers that typically extend up to one meter below the surface level of water. Screens are generally permeable, while curtains generally restrict the flow of water. On their own, curtains and screens can contain plants within particular locations however, they are particularly useful when used in conjunction with mechanical harvesters, shredders or cutters that disperse plant fragments. The use of curtains and screens will require frequent inspection and monitoring to remove plant biomass (Madsen, 2019).

10.2.4 Hand/Net Removal

Hand/net removal is most useful in areas with dense infestations or locations where herbicide treatments are not possible (Madsen, 2019).

10.2.5 Diver Hand Removal/Diver Hand Pulling

This method involves a contracted SCUBA diver using a small rake or hand tool to remove targeted SAV plants and fragments. All plant fragments are placed in net bags where they are taken to nearby approved locations (away from water's edge) for disposal.

In the Delta, diver hand removal/pulling will be most effective in treating small, localized infestations, and/or in conjunction with benthic barriers described above (Madsen, 2019).

10.2.6 Diver Assisted Suction Removal

This method employs a vacuum to suction out SAV and FAV. Divers may use small rakes or tools to ensure that the plant is removed at the root, and then guide the plant into the hose. Plant fragments are disposed of on land, in approved areas distant to the shore. While this method can be highly selective, in the Delta, it is limited to areas less than 1 acre in area, four times a year per location (Madsen, 2019).

10.2.7 Surface Excavators

This method involves the use of an excavator and dump truck on a concrete boat ramp or levy to mechanically lift FAV from the waterway.

This mechanical removal approach is most effective in areas where plant growth is concentrated near a boat ramp. There are relatively few locations within the Delta that are appropriate for excavation (Madsen, 2019).

10.2.8 Harvesters

Harvesters use cutters and conveyors to physically remove plants from the water, and onto the bed of a vessel. The vessel is then used to transport the material to land where it is offloaded onto a dump truck that will deliver it to an authorized location for disposal. Vessels can typically transport between 2,000 and 15,000 pounds of plant material at a time (Madsen, 2019).

10.2.9 Cutters & Shredders

Cutters and shredders are mechanical equipment that mince or grind FAV into small, non-viable fragments or pulps. Because cutters/shredders render plants non-viable, plant biomass can be left in the water to decompose. In cases where viable plant fragments are found, curtains and/or booms can be used to contain biomass to specific areas, thus reducing the risk of reinfestation. Cutters and shredders are most useful in areas where immediate treatment is needed or areas where herbicide treatments must be avoided (Madsen, 2019).

10.3 Biological

Several insect species have been released as forms of biological control for different aquatic weed species. These include *Neochetina bruchi, Neochetina eichhorniae, Sameodes albiguttailis and Megamelus scutellaris.* In studies that investigated the success of these species in controlling SAV/FAV in the Delta, only *Megamelus scutellaris* was found to have any meaningful control potential (though further research is required). Other species were shown to have been unable to establish themselves in densities necessary to enforce any meaningful weed control (Rasmussen et. al., 2020).

10.4 Preventative

Some activities can lead to the colonization of invasive aquatic weeds into new areas – its generally better to prevent new colonization from happening compared to trying to control the weeds in an area once they are established.

11 Key Contacts

- Delta Interagency Invasive Species Coordination (DIISC) Team – Rachel Wigginton is coordinator
- IEP's Aquatic Vegetation Project Work Team – Nicholas Rasmussen is coordinator (Nicholas.Rasmussen@water.ca.gov)

12 References

Boyer K., Sutula M. (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. 86 pp.

Caudill, J. (2019). Aquatic plant community restoration following the long-term management of invasive egeria densa with fluridone treatments. *Management of Biological Invasions, 10*, 473-485. doi:10.3391/mbi.2019.10.3.05

Drexler J. Z., Khanna, S., Lacy, J.R. (2021). Carbon storage and sediment trapping by *Egeria densa* Planch., a globally invasive, feshwater macrophyte. *Science of the Total Environment,* 755, 142602.

Greenfield, B. K., Blankinship, M., & McNabb, T. J. (2006). Control costs, operation, and permitting issues for non-chemical plant control: case studies in the San Francisco Bay-Delta Region, California. Journal of Aquatic Plant Management, 44(1), 40-49.

Hestir, L. E., Schoellhamer, D. H., Greenberg, J., Morgan-King, T., Ustin, S. L. (2016). The Effect of Submerged Aquatic Vegetation on a Declining Turbidity Trend in the Sacramento River Delta. *Estuaries and Coasts, 39*, 1100-1112. Doi 10.1007/s12237-015-0055-z

Jetter, K. M., Nes, K., & Tahoe, L. (2018). The cost to manage invasive aquatic weeds in the California Bay-Delta. ARE Update, 21(3), 9-11.

Moran, P. J., Pitcairn, M. J., & Villegas, B. (2016). First establishment of the planthopper, *megamelus scutellaris* berg, 1883 (hemiptera: Delphacidae), released for biological control of water hyacinth in california. *The Pan-Pacific Entomologist, 92*(1), 32-43. doi:10.3956/2016-92.1.32

O'Rear, Teejay (Durand Lab, UC Davis). Personal communication, August 30, 2021. Expert interview on silverside population management and other topics related to Delta Smelt management actions.

Rasmussen, N., L. Conrad, H., Green, S., Khanna, J., Caudill, P., Gilbert, P., Wright, H., Hoffman, K., Lesmeister, S., Takata, L., Bosworth, D., Flynn, T., Hard, E., Sommer, T. (2020). 2017-2018 Delta Smelt Resiliency Strategy action for enhanced control of aquatic weeds and understanding effects of herbicide treatment on habitat.

Santos, M. J., Khanna, S., Hestir, E. L., Andrew, M. E., Rajapakse, S. S., Greenberg, J. A., . . . Ustin, S. L. (2009). Use of Hyperspectral Remote Sensing to Evaluate Efficacy of Aquatic Plant Management. *Innvasive Plant Science and Management, 2*, 216-229. doi:10.1614/IPSM-08-115.1

Smith, W.E., 2022. A delta smelt Individual-Based Life Cycle Model in the R statistical environment (Technical Note). Prepared for CSAMP Delta Smelt SDM Technical Working Group (TWG).

Spencer, D. F., Ksander, G. G., Donovan, M. J., Liow, P. S., Chan, W. K., Greenfield, B., . . . Andrews, S. P. (2006). Evaluation of waterhyacinth survival and growth in the Sacramento delta, California, following cutting. *Journal of Aquatic Plant Management, 44*

Tobias, V.D., Conrad, J.L., Mahardja, B., Khanna, S. (2019). Impacts of water hyacinth treatment on water quality in a tidal estuarine environment. *Bioloical Invasions.*

USDOI. (2019). Biological opinion for the 2018-2022 aquatic invasive plant control program.

Ustin, S. L. (2019). Enhancement of delta smelt (*Hypomesus transpacificus*) habitat through adaptive management of invasive aquatic weeds in the Sacramento-San Joaquin delta & Suisun June 2019 report.

Ustin, S.L., Khanna, S., Lay, M., (2021). Remote sensing of the Sacramento-San Joaquin Delta to enhance mapping for invasive and native aquatic plant species (Technical Report). Center for Spatial Technologies and Remote Sensing, Department of Land, Air, and Water Resources. Available at https://knb.ecoinformatics.org/view/doi:10.5063/F1K9360F.

13 Appendix 1 – Financial Resource Cost Calculations

The table below provides cost estimates and assumptions used for the action. It shows an example calculation for 603 ac of aquatic weed control, which was applied to Portfolios 2b and 2c in the Round 1 evaluation. The orange cell indicates the annualized cost used for this action in those portfolios.

Aquatic Weed Control
Portfolio(s) **2b, 2c**
Source: See table notes

Component		**Notes**	**Area**		**Unit Cost**		**Duration**		**Total**	
Initial costs to establish control										
	High	[a]	603	ac @	$7,000	/ac/application for	3	years	$ 12,663,000	
	Best				$5,000					
	Low	[b]	603	ac @	$3,000	/ac/application for	3	years	$ 5,427,000	
Annual Operating Costs										
	High	[c]	603	ac @	$3,500	/ac/yr			$ 2,110,500	/yr
	Low	[d]	603	ac @	$2,333	/ac/yr			$ 1,407,000	/yr
Undiscounted annual costs			20	years						
High									$ 2,743,650	/yr
Average of high and low									$ 2,211,000	/yr
Low									$ 1,678,350	/yr

Notes - the following information is from Compass meeting with DBW staff on Jan. 6, 2023

[a],[b]	Assume one application per year but need to check this assumption
[a],[b]	DBWprovided ball park estimate for upfront SAV control costs of $3,000-$4,000 per acre for 3-4 ft depth and $5000-$7000 for 8ft average depth for three years (need to confirm whether there is just one application per year or multiple). FAV initial control cost is $300-$400 per acre). These costs include the costs of chemicals and labour for application.
[c], [d]	DBW says to maintain an area weed free, expect to have to reapply chemicals every year to a third or half of the area.
	Chemical application is used instead of mechanical. Mechanical cost is $53,000/acre - DBW has a 200 acre/year limit for mechanical removal because it kills species (e.g., snakes set up places in FAV)