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Operational aquatic weed management in the California Sacramento–San Joaquin River Delta

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ABSTRACT

Aquatic weed management in the California Sacramento–San Joaquin Delta (Delta), and its tributaries has been conducted since 1982 by the California Department of Parks and the Recreation Division of Boating and Waterways (CDBW). The program uses chemical, physical, and biological control methods as a part of integrated pest management (IPM) in the Delta, which is approximately 28,000 ha (68,000 ac) of waterways. The CDBW targets nine invasive aquatic plant species, including water hyacinth [*Eichhornia crassipes* (Mart.) Solms] and Brazilian waterweed (*Egeria densa* Planch.). Weed management challenges, such as budget, regulatory requirements, and multiple stakeholder groups, require the program to be flexible and also aim at control of all target weeds in the Delta. An increased number of target invasive plants and trends in target plants and environmental conditions, such as high or low water flow years, have further emphasized the importance of IPM and a flexible toolset to control target invasive plants in the Delta.

Key words: *Alternanthera philoxeroides*, aquatic plant management, *Cabomba caroliniana*, *Ceratophyllum demersum*, *Egeria densa*, *Eichhornia crassipes*, endangered species, herbicides, invasive aquatic plants, *Limnobium laevigatum*, *Ludwigia hexapetala*, *Myriophyllum spicatum*, *Potamogeton crispus*.

INTRODUCTION

The California Sacramento–San Joaquin Delta (Delta) is considered one of the most invaded estuaries in the world (Cohen and Carlton 1998). The California Department of Parks and Recreation, Division of Boating and Waterways (CDBW) has been the lead agency since 1982 to combat aquatic invasive species (AISs). Starting with water hyacinth, the list of species controlled by CDBW has grown to nine AISs. The cost of the control program has risen to $12.5 million annually. The Delta's importance lies in helping support California's $36 billion agricultural industry and providing drinking water hyacinth to 25 million Californians. The Delta is a 28,000 ha (68,000 ac) area in Northern California that is a national heritage area as well as the only inland delta in the United States (DSC 2013). The Delta's tidal exchange can cause the Sacramento River to reverse directions twice a day at river flows less than 566 m^3 s^{-1} (20,000 ft^3 s^{-1}), per a U.G. Geological Survey (USGS) station, as well as affect the rest of the Delta (Perry et al. 2015). The Delta provides water to more than 202,000 ha of agricultural land (DSC 2013). The Sacramento Deep Water Ship Channel is also in the Delta that services the ports of Sacramento and Stockton, providing thousands of jobs and millions of dollars in local tax income to the region.

AISs negatively affect ecosystems over time through their ability to outcompete native species, causing ecological and economic damage (Getsinger et al. 2014). It is estimated that invasive species cost the United States more than $120 billion in damages each year (Pimental et al. 2005). CDBW is the lead agency for cooperating with local, state, and federal agencies in controlling aquatic invasive species, such as water hyacinth [*Eichhornia crassipes* (Mart.) Solms], Brazilian waterweed (*Egeria densa* Planch.), and South American spongeplant [*Limnobium laevigatum* (Humb. & Bonpl. ex Willd.) Heine] in the Delta. Like many other AIS control programs, CDBW had historically relied upon herbicides and mechanical harvesting for AIS control but has adopted an integrated pest management (IPM) approach. Implementing an IPM approach for controlling AIS that includes biocontrol may also realize direct and indirect economic benefits along with increased efficacy and control. (Naranjo et al 2015).

Water hyacinth was first reported in California in 1904 at a Yolo County slough (Bock 1968). Water hyacinth quickly spread in the Delta, negatively affecting the economy, environment, and public health. In response to the infestation, California Senate Bill 1344 was passed in 1982, naming CDBW as the lead agency for controlling that invasive plant. The program now has nine control tools and is making use of a variety of techniques within the framework of IPM to increase the efficacy of the program critical for current and future needs in the Delta.

Compliance with the federal Endangered Species Act is a key driver of AIS management in the Delta. Recent biological opinions by the National Marine Fisheries Service (NMFS) and the U.S. Fish and Wildlife Service (USFWS) allow CDBW to incorporate biological controls as well as more herbicides to help increase the program efficacy against AIS. These new tools also allow CDBW to incorporate an IPM approach to help realize economic and environmental benefits, such as increased efficacy, and to reduce the herbicide active ingredient used. CDBW aims to find increased success through the integration of multiple

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Table 1. Aquatic invasive species currently within the floating or submersed plant control programs for the California Sacramento–San Joaquin Delta (Delta) managed by the California Division of Boating and Waterways.

Common Name	Scientific Name	Growth Form
Water hyacinth	*Eichhornia crassipes* (Mart.) Solms	Floating
Brazilian waterweed	*Egeria densa* (Planch)	Submersed
South American spongeplant	*Limnobium laevigatum* (Humb. & Bonpl. Ex Willd.) Heine	Floating
Curlyleaf pondweed	*Potamogeton crispus* (L.)	Submersed
Coontail	*Ceratophyllum demersum* (L.)	Submersed
Eurasian watermilfoil	*Myriophyllum spicatum* (L.)	Submersed
Uruguayan water primrose	*Ludwigia hexapetala* (Hook. & Arn.) Zardini, H.Y. Gu & P.H. Raven	Emergent
Fanwort	*Cabomba caroliniana* (A. Gray)	Submersed
Alligatorweed	*Alternanthera philoxeroides* (Mart.) Griseb.	Emergent

control methods now and in the future to maintain a successful control program in the Delta.

The presence of many different stakeholders provides challenges and differing viewpoints to controlling AIS in the Delta. Environmentalists and fisheries biologists are interested in maintaining a habitat that is productive and safe for listed species, suggesting CDBW use tools with less effect on the critical habitats of the species. Growers require agricultural intakes be clear of AIS for access to the water to support the large agricultural industry in the Delta. Recreational boaters require accessibility to the Delta and support the marinas and businesses within. Anglers and hunters require water bodies and habitat to be favorable for their activities. Southern California obtains water from the Delta through the Central Valley Project and State Water Project, which convey water from the southern Delta. Weed control helps keep the pumps open for continued operations. Many of the uses within the Delta are competing, e.g., more weeds are favorable for bass fishing, whereas fewer weeds favor yacht and ski clubs, which make the use and flexibility of IPM vital to a weed management program.

TARGET INVASIVE SPECIES

Nine AISs are now included within the CDBW management program (Table 1). The California Department of Fish and Wildlife define the target plants for CDBW as *invasive*, even if the plants are native to North America, hence the plants are being referenced as *invasive*. Water hyacinth is a free-floating plant that is native to South America and has now spread to tropical and subtropical countries. It was introduced into the United States in 1884 through the ornamental trade and has quickly spread throughout the country, being introduced into California in 1904 (Bock 1968, Thomas and Anderson 1984). Water hyacinth is a fast-growing, floating plant that can rapidly crowd out native plants. This can cause blockages in waterways that negatively affect recreation, navigation, water conveyance, and agricultural irrigation. Water hyacinth has thick, broad leaves, petioles that are bulbous and can have multiple lavender flowers. Water hyacinth can form thick mats that reduce dissolved oxygen (DO) levels, which could displace or kill fish in addition to displacing native plants (Miskella et al. this issue). Water hyacinth generally grows at warmer temperatures than most native species, and growth is primarily from May through October, when the water temperature is above 15 C (59 F) (Madsen 2018). Water hyacinth is the most problematic of the floating weeds in the Delta.

Brazilian waterweed is a submersed, rooted plant that is native to South America and has spread throughout much of the United States. It was introduced as an aquarium plant and was first observed in New York in 1893 (Cook and Urmi-König 1984, USFWS 2018). Only plants producing staminate flowers are found in the United States, meaning the only method of spreading is through fragmentation. The fragments can readily form roots and a new plant. Brazilian waterweed is considered an ecosystem engineer because of its ability to significantly modify or affect a habitat once established (Jones et al 1994, Yarrow et al. 2009). It can be identified by its finely serrated leaves and white flowers with three petals that can grow to the top of a water column. Dense growths of Brazilian waterweed can crowd out native plants as well as reduce turbidity and water flow in an area, negatively affecting fish habitat. It grows during warmer temperatures, using stored starch for growth during the summer and storing starch in the winter (Getsinger and Dillon 1984, Pennington and Sytsma 2009). Brazilian waterweed is CDBW's primary submersed weed-control target in the Delta making up most treatment acres.

Curlyleaf pondweed (*Potamogeton crispus* L.) is a submersed, rooted plant that is native to Eurasia, Africa, and Australia (Catling and Dobson 1985). Curlyleaf pondweed has wavy, olive-green to reddish-brown leaves and grows early in the spring and dies back in summer. Because it grows earlier in the spring than many native weeds, it can more easily outcompete natives. The dense growth can cover large areas and severely restrict recreation and navigation. Reproduction occurs vegetatively and by seed, with vegetative reproduction being the primary means (Catling and Dobson, 1985). Curlyleaf pondweed is not as abundant as Brazilian waterweed but tends to be found in some of the same habitats.

South American spongeplant is a floating aquatic plant that can be rooted in the substrate when stranded with floating stolons. It is native to Central and South America. South American spongeplant has spongy tissues on the underside of the floating leaves and has green to yellow flowers. Spongeplant can be up to 10 cm wide and 15 cm tall (Cook and Urmi-Konig 1983). South American spongeplant forms dense mats and reproduces quickly through seeds and offshoots. South American spongeplant tends to be found less often than the other floating aquatic weeds in the Delta.

Coontail (*Ceratophyllum demersum* L.) is a submersed aquatic plant. It is native to North America. It does not root to the sediments and drifts freely within the water column. Coontail can reproduce through fragmentation or seeds. Coontail has dark green leaves in whorls of six to eight, which are dichotomously divided into linear segments with prominent teeth. Coontail grows in the spring and dies back in the winter, where the loss of nutrients causes much of the plant to decompose and disintegrate before the next growth season (Best et al. 1990). Coontail has been found in Delta waters up to 6 m deep and is found in slower-moving waters. Coontail is not found as often as Brazilian waterweed but tends to be found in some of the same habitats.

Eurasian watermilfoil (*Myriophyllum spicatum* L.) is a submersed aquatic plant with green, brown, or white thin stems. It is native to Europe, Asia, and Africa (Patten 1954). It was introduced into the United States in the 1940s and is now reported in nearly every state and is one of the most widespread invasive plants in the United States. Stems grow up to 3 m long and get thinner the further they grow from the main stem (Aiken et al. 1979). Generally, four feather-like, dissected leaves whorled around the stem are found with more than 14 leaflets on each leaf (Patten 1954). Flowers can be found above the surface of the water on a terminal spike (Patten 1954, Aiken et al. 1979). Eurasian watermilfoil may flower up to twice a year in early summer and late summer or early fall. depending on water depth and temperature, which is followed by autofragmentation (Patten 1954, Nichols 1975). Reproduction occurs through seeds and fragmentation (Patten 1954), although vegetative reproduction is by far the most important to spread. Eurasian watermilfoil is tolerant of lower temperature waters and forms dense canopies on the water surface because of rapid growth that can shade out competing and native weeds (Madsen et al 1991). This species is not found as often as Brazilian waterweed but tends to be found in some of the same habitats.

Uruguayan water primrose [*Ludwigia hexapetala* (Hook. & Arn.) Zardini, Gu & P. H. Raven] is an emergent aquatic plant, native to South America, which forms dense mats on riverbanks and into open water. Uruguayan water primrose forms long, creeping or floating stems with yellow flowers above the water surface (Thouvenot et al. 2013). Uruguayan water primrose can grow in waters up to 3 m in depth, although it is more commonly found in waters up to 1 m in depth. (Lambert et al. 2010). The species is tolerant to many hydrological and environmental conditions, such as low nutrient availability and submersion (Thouvenot et al. 2013). Uruguayan water primrose is semidormant in the winter in California, with shoots present until disturbances, such as high-flow events. Propagules and shoot fragments can be dispersed by high water flow. Uruguayan water primrose also reproduces sexually, flowering and forming seeds in summer to late fall (Skaer Thomason et al. 2018). Uruguayan water primrose management is complicated by the fact that the plants observed in the Delta, as elsewhere, have 80 chromosomes, which makes them more challenging to control compared with other subspecies (Grewell et al. 2016). Different biotypes are not readily distinguishable without genetic verification and may be susceptible to different herbicides at different rates. Water primrose often invades after water hyacinth control and is becoming a larger problem for CDBW.

Fanwort (*Cabomba caroliniana* A. Gray) is a submersed aquatic plant that is native to parts of North and South America, but not California. Fanwort primarily reproduces through fragmentation and has likely been spread through distribution as an aquarium plant (Bickel 2017). Fanwort has fan-shaped leaves. Fanwort cannot grow in high water currents and is likely restricted to standing water or areas of slow-flowing water. Fanwort flowers above the water surface with colors ranging from light to dark yellow. Shoot colors are strongly influenced by light conditions, where low-light conditions have green to olive green shoots and more-intense light may have reddish or brown in color (Ørgaard 1991). Fanwort can grow up to 10 m in length (Wilson et al. 2007). Fanwort is not found as often as Brazilian waterweed but tends to be found in some of the same habitats.

Alligatorweed [*Alternanthera philoxeroides* (Mart.) Griseb.] is a semiaquatic plant that is native to South America and forms tangled, dense root mats in aquatic environments. The species can tolerate a wide range of environmental conditions and appears to be strongly invasive in temperate (15 to 30 C) as well as tropical regions (Julien et al. 1995). Seeds of alligatorweed germinate in spring whereas flowering starts in summer, and the species is quiescent in the winter (Tavneer et al. 2018). Models and predictions suggest that, as climate temperatures increase, areas such as the west and east coasts of the Americas will be more favorable for the species (Julien et al. 1995). Alligatorweed is reported as generally producing viable seeds only in native ranges. Its primary means of spread is through fragmentation. Dense mats can shade out other plants by reducing light penetration in the water (Tavneer et al. 2018), and it can obstruct water flow and navigation. Alligatorweed is a recent introduction in the Delta and is becoming a problem in the central and western Delta.

SPECIAL STATUS SPECIES

Rare, threatened, and endangered species are *special status* species. Fifty-six species in the Delta are categorized as *special status* by at least one of the regulating agencies (DSC 2013). Managing AIS plants is largely influenced by the required mitigation efforts to protect the following eight species (Table 2).

Delta smelt (*Hypomesus transpacificus* McAllister) is a small fish that typically grows up to 70 mm in length. Delta smelt are endemic to the low-salinity and freshwater areas of the Delta and Suisun Bay and are commonly found in the lower Sacramento and San Joaquin rivers. Delta smelt critical habitat severely restricts CDBW's access to many areas of the Delta for all control methods. This species imposes the most restriction on the program because of the status of the species. Delta smelt is one of several species in the *Hypomesus* genus, and it is a member of the Osmeridae family (Bennett 2005). Delta smelt is an annual species that spawns in freshwater upstream and typically migrates into higher salinity waters until it is a maturing adult. Adults migrate

Table 2. Eight of the many rare, threatened, or endangered species protected by the federal (ESA) and state (CESA) endangered species acts and the management issues they create.

Common Name	Scientific Name	Management Issue	Species or Program
Delta smelt	*Hypomesus transpacificus* McAllister	Need to avoid current and historical spawning and food web habitats	CESA 2009, ESA 1993
Valley elderberry longhorn beetle	*Desmocerus californicus dimorphus* Fisher	100-ft (30.5 m) buffer between shrubs and any treatments unless using a backpack sprayer	ESA 1980
Giant garter snake (GGS)	*Thamnophis gigas* Fitch	Site surveys and mechanical harvesting monitoring required to look for GGS	CESA 1971, ESA 1993
Chinook salmon	*Oncorhynchus tshawytscha* (Walbaum in Artedi)	Conduct environmental awareness to avoid take	CESA 1989, ESA 1994/1999 for spring-run/winter-run
North American green sturgeon	*Acipenser medirostris* Ayres	Conduct environmental awareness to avoid take	ESA 2006
Central Valley steelhead trout	*Oncorhynchus mykiss* Walbaum	Conduct environmental awareness to avoid take	CESA 2019, ESA 1998
Longfin smelt	*Spirinchus thaleichthys* (Ayres)	Conduct environmental awareness to avoid take	CESA 2009, ESA 2012
Swainson's hawk	*Buteo swainsoni* Bonaparte	Survey harvesting sites to avoid potential nesting locations	CESA 1983

back to freshwater for spawning. Delta smelt is seen as an indicator species in the Delta, used to determine the overall health of the aquatic environment. There are many threats to the Delta smelt, such as entrainment, lack of food, predation, and toxic substances. Significant habitat changes, along with drought and climate change, are also likely factors in the decline of the Delta smelt. Potentially dire circumstances have affected Delta smelt populations, in which Delta smelt are not spawning as far east as thought and are favoring Suisun Marsh and the Cache Slough complex (Murphy et al. 2013). Delta smelt primarily feed on copepods and zooplankton and use turbidity to increase visual acuity during daytime. (Hobbs et al. 2006)

The valley elderberry longhorn beetle (VELB; *Desmocerus californicus dimorphus* Fisher) is endemic to the Central Valley of California and is found only with its host plant, the elderberry shrub (*Sambucus* L. spp.). There are hundreds of elderberry shrubs found by CDBW in the Delta that require 100-foot buffer zone for herbicide treatments, unless a backpack sprayer is used. The VELB grows to 2 cm in length and feeds on the flowers and foliage of the shrubs between March and June. The VELB larvae develop in the first 1 to 2 yr by surviving inside the shrub stems. After VELB metamorphose into adults, they emerge and leave an exit hole in the shrub. The VELB habitat is best determined by identifying elderberry shrubs with VELB exit holes.

The giant garter snake (*Thamnophis gigas* Fitch) is the largest garter snake in North America. It is endemic to the Sacramento and San Joaquin valleys and inhabits irrigation canals, sloughs, ponds, and other low-gradient waterways. Mechanical harvesting requires additional site surveys, harvesting speed limits, and monitoring for giant garter snakes because of the potential for encountering them during harvesting operations. They are rarely found far from the water and balance time in the water for foraging and avoidance of predators in the water. Larger waterways are generally avoided because of predators. The dorsal color of the snake ranges from brownish to olive with a checkered pattern of black spots with yellow and light colors stripes (Hansen 1980). The snakes can grow up to 160 cm in length, with females being slightly longer and heavier than males (Hansen 1980). Giant garter snakes are active between early spring and midfall in wetlands with adequate water throughout the year and emergent wetland vegetation for cover from predators. Giant garter snakes feed primarily on fish and amphibians. Food prey has changed because of declining or extinct historical species. Prey now includes species such as carp (*Cyprinus carpio* L.), mosquito fish (*Gambusia affinis* Baird & Girard), and bullfrogs (*Lithobates catesbeianus* Shaw; previously *Rana catesbeiana* Shaw). The biggest threat is loss of habitat because of the conversion of wetlands to urban or agriculture use.

Chinook salmon (*Oncorhynchus tshawytscha* Walbaum in Artedi) are anadromous fish that spawn in freshwater systems and mature in saltwater systems. CDBW is required to monitor for the species during all operations and in fish-trawl data to avoid the areas in which they are found. The Sacramento River winter-run is *endangered*, whereas the Central Valley spring-run is *threatened*. Chinook salmon migrate through the Delta between November and June. Droughts and increased water temperatures pose threats to the winter-run Chinook salmon. Chinook salmon spawn soon after entering freshwater, and juveniles migrate to the ocean in their first year. Chinook salmon typically spend 1 to 4 yr in the ocean before returning to freshwater to spawn (Crozier et al 2007). Juvenile Chinook salmon can grow between 50 and 57 mm in length and remain in the Delta until they reach a length of around 118 mm, between the age of 5 and 10 months (Fisher 1994). Chinook salmon prey consists of cladocerans, copepods, amphipods, and larvae of diptera, as well as small arachnids and ants (Sommer et al. 2001, MacFarlane and Norton 2002).

North American green sturgeon (*Acipenser medirostris* Ayres) spawning populations are currently found in the Sacramento, Klamath, and Rogue River systems. CDBW is required to monitor for the species during all operations and in fish-trawl data to avoid the areas in which they are found. Adult and subadult North American green sturgeon spend most of their lives in the coastal marine environment.

Tagging data indicate green sturgeon are found in depths of 6 to 21 m in coastal marine environments (Huff et al. 2011). North American Green sturgeon can grow up to 205 cm in length when mature adults (Van Eenennaam et al. 2006). It is estimated that green sturgeon spawn every 2 to 5 yr (Beamesderfer et al. 2007).

Central Valley steelhead trout (*Oncorhynchus mykiss* Walbaum) migrate to the ocean as juveniles between November and May and return to the freshwater when 2 to 4 yr old. CDBW is required to monitor for the species during all operations and in fish-trawl data to avoid the areas in which they are found. Migration through the Delta can occur between August and March. Steelhead are found in the Delta largely during migration. Primary threats to steelhead are loss of spawning habitats because of dams and mixing with hatchery fish. Juveniles prey on insects, invertebrates, and drifting aquatic organisms. Adults prey on insects, small fish, eggs, mollusks, and crustaceans.

Longfin smelt (*Spirinchus thaleichthys* Ayres) is a small, semelparous fish that grows up to 150 mm in length. Longfin smelt can be found as far south as the Delta and as far north as the Cook Inlet in Alaska. CDBW is required to monitor for the species during all operations and in fish-trawl data to avoid the areas in which they are found. Longfin smelt primarily feed on mysid shrimp. There are many threats to the Longfin smelt, such as entrainment, lack of food, predation, and toxic substances. The longfin smelt belongs to the Osmeridae family and is one of the species in the *Spirinchus* genus. Longfin smelt are pelagic and anadromous, although some populations spend their entire life cycle in freshwater habitats. Although longfin smelt can be found in salinities ranging from freshwater to seawater, they are typically found in waters of at least 14 ppt salinity after the juvenile stage. The primary threat to longfin smelt is reduction in freshwater flows, which is related to drought and flood hydrologic cycles. Positive association with longfin smelt abundance can be seen with increased Delta outflows during winter and spring (Stevens and Miller 1983, Jassby et al. 1995, Sommer et al. 2007).

Swainson's hawk (*Buteo swainsoni* Bonaparte) is a raptor that has been adapting to habitat transformed by humans in North America, changing the species nesting and foraging habits (Rodriguez-Estrella 2000). CDBW is required to monitor and perform site surveys before mechanical harvesting to avoid harassing these hawks because of noise. In the California Central Valley, it is estimated that the species has a larger home range area of 4,047 ha compared with 405 ha in northeastern California, likely due to prey density and vegetation height. Swainson's hawk preys on rodents and insects, with ground squirrels (*Spermophilus richardsonii* Sabine) as the main prey in Canada (Babcock 1995, Rodriguez-Estrella 2000). Surveying observations in the Sacramento Valley and Delta in 2002, 2003, and 2009 lead to the estimations of 593, 1,008, and 941 active nests, respectively (Gifford et al. 2012). One of the greatest threats to the species is loss of habitat and access to prey caused by urbanization or transformation of habitat to agriculture (Rodriguez-Estrella 2000).

REGULATORY COMPLIANCE

The CDBW Aquatic Invasive Plant Control Program (AIPCP) must comply with numerous regulations related to control methods, including the use of herbicides in the project area. All herbicides used are registered by the Environmental Protection Agency (USEPA) and the California Department of Pesticide Regulation (CDPR). The National Pollutant Discharge Elimination System (NPDES) requires anyone discharging pollutants into the waters of the United States (WOTUS) to have a NPDES permit. The NPDES permit provides limitations on what can be discharged, on reporting and monitoring requirements, and on additional precautions, as needed, to meet Clean Water Act requirements. In addition, the program requires submission of an Aquatic Pesticide Application Plan (APAP), which provides details on the program activities and best-management practices.

The presence of listed endangered species in the project area requires CDBW to follow additional permit and regulatory requirements. The USFWS and NMFS require CDBW to submit a Biological Assessment to determine whether program actions would affect any listed species per the regulations in Section 7 of the Endangered Species Act (50 CFR 402, 16 U.S.C. 1536 [c]) and the Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA). Biological assessments are comprehensive documents using the best scientifically and commercially available information to assess the actions and risks to the listed species and is produced by the program to be submitted to USFWS and NMFS (Services). After review, the Services will submit either a Letter of Concurrence that agrees that species will not be adversely affected or a Biological Opinion (BiOp) that authorizes incidental take (potential harm) of a species. The BiOp outlines agreements, recommendations, or additional measures and requirements to minimize the potential of harm to threatened and endangered species. The biological controls used by CDBW are approved by the USDA and the Services.

Incidental take authorization or permits are required at both the federal and state levels, depending on whether the listed species are considered endangered at either state or federal level and whether the proposed actions may result in incidental take. The CDFW can issue an incidental take permit (ITP) under the California Endangered Species Act. Incidental take is defined as "harass, harm, pursue, hunt, shoot, wound, kill, trap, capture, or collect, or to attempt to engage in any such conduct" (16 US Code §1532) to endangered and threatened species. The NMFS and USFWS have both authorized incidental takes with their BiOps for the program. The NMFS authorized incidental take for Sacramento River winter-run Chinook salmon, Central Valley spring-run Chinook salmon, California Central Valley steelhead, and the Southern Distinct Population Segment of North American green sturgeon. The USFWS authorized incidental take for Delta smelt, giant garter snake, and VELB. The CDFW has a Streambed Alteration and Routine Maintenance Agreement (RMA) with CDBW because of the potential chance that the mechanical harvesting of water hyacinth may affect listed species. Adverse effects could be "temporary degradation of bank,

Table 3. Management techniques used in the California Sacramento–San Joaquin Delta (Delta) aquatic plant management program.

Method	Targeting	Restrictions	Control Type
2,4-D	Water hyacinth, spongeplant, water primrose	Only used between 15 June and 15 September in legal Delta. Southern Delta can only used between 15 June and 15 August; cannot be used in historical Delta smelt habitat and spawning areas when Delta smelt are present	Herbicide
Diquat	Brazilian waterweed, coontail, water milfoil, waterhyacinth	Only allowed 61 ha (150 ac) of treatment with request and approval by USFWS and NMFS; cannot be used in historical Delta smelt habitat and spawning areas when Delta smelt are present	Herbicide
Endothall	Curlyleaf pondweed, coontail, water milfoil	Can be used between 1 March and 30 November; currently testing before making operational	Herbicide
Fluridone	Brazilian waterweed, water milfoil	Can be used between 1 March and 30 November	Herbicide
Glyphosate	Water hyacinth, water primrose, spongeplant	Cannot be used in historical Delta smelt habitat and spawning areas in which Delta smelt are present	Herbicide
Imazamox	Water hyacinth, spongeplant	Cannot be used in historical Delta smelt habitat and spawning areas when Delta smelt are present	Herbicide
Penoxsulam	Water hyacinth, water primrose, alligatorweed	Cannot be used in historical Delta smelt habitat and spawning areas when Delta smelt are present	Herbicide
Mechanical harvesting	Water hyacinth	Can only be used on water hyacinth; limited to 81 ha (200 ac) annually; cannot use near Swainson's hawk nesting sites	Physical
Hand and net removal	Water hyacinth		Physical
Water hyacinth weevil	Water hyacinth	Can only be released in USFWS- and NMFS-approved sites	Biocontrol
Water hyacinth plant hopper	Water hyacinth	Can only be released in USFWS- and NMFS-approved sites	Biocontrol

Abbreviations: NMFS, National Marine Fisheries Service; USFWS, U.S. Fish and Wildlife Service.

increase of bank erosion during hyacinth removal, temporary change in turbidity from water hyacinth draining on bank, and temporary disruption to nesting birds due to disturbance from project activity" per the RMA.

Physical tools that may be considered structures in or over any navigable WOTUS require authorization from the U.S. Corps of Engineers (USACE). Physical tools may include dredging or disposal of dredged materials, excavation, filling, rechannelization, or any other modification of a navigable WOTUS. CDBW is pursuing a Regional General Permit (RGP) to make use of booms, bladders, benthic mats, diver-assisted suction, or submersed weed harvesting.

CONTROL METHODS USED

The latest management plan implements biological, chemical, and mechanical means of control for AIS (Table 3).

Floating Aquatic Vegetation (FAV)

The herbicide 2,4-dimethylphenoxyacetic acid (2,4-D) is postemergent, fast acting, and systemic and is effective on broadleaf plants. It acts as a growth regulator by mimicking the plant's hormone auxin, which initiates rapid cell division and increased, abnormal growth that causes rapid injury and can lead to death in susceptible plants. This herbicide has been used in the United States since the 1940s. In addition, 2,4-D is water soluble and can be used in combination with an adjuvant to increase efficacy. An adjuvant activates or enhances the herbicide by altering the physical or chemical characteristics to improve efficacy. Moreover, 2,4-D breaks down by bacterial decomposition (Shaner 2014). The soil adsorption coefficient (KOC) is a measure of mobility through soil. A high KOC means strong adsorption to soil. The KOC of 2,4-D dimethylamine salt is between 72 and 136, which indicates weak adsorption to soil. The half-life ranges from 0.5 to 6.6 d in natural waters. Degradation products include 1,2,4-benzenetriol, 2,4-dichlorophenol, 2,4-dichloroanisole, 4-chlorophenol, chlorohydroquinone, carbon dioxide, and volatile organics. The herbicide 2,4-D is used primarily to control water hyacinth, South American spongeplant, and Uruguayan water primrose (Madsen et al. 1998). Application of 2,4-D is foliar between 5 and 10 L ha^{-1} (2 to 4 qt ac^{-1}), which is equivalent to 1.7 to 3.4 kg ha^{-1} (1.9 to 3.8 lb ac^{-1}) of active ingredient. The NPDES receiving-water limit is 0.07 ppmw. In 2018, 158 ha of plants were treated in the Delta Project using 2,4-D, which is 672 kg of active ingredient.

Glyphosate is a broad-spectrum, systemic herbicide that inhibits the 5-enolpyruvylshikimate-3-phosphate synthase plant enzyme. The herbicide has been used in the United States since the 1970s. Glyphosate is water soluble and, with adjuvants in a foliar application, is efficacious against a wide range of weeds. Glyphosate is not persistent in the water column and binds to sediment. The KOC of glyphosate is between 300 and 20,100, indicating strong adsorption to soil. The half-life ranges from 12 d to 10 wk (Sparling et al. 2006). It is used at a rate of up to 4.1 lb/ac or the equivalent of 4.6 kg ha^{-1} of active ingredient. In 2018, 694 ha were treated using glyphosate which is 3,934 kg of active ingredient.

Penoxsulam is a broad-spectrum systemic herbicide that inhibits the acetolactate synthase (ALS) enzyme, which regulates three essential amino acids: valine, leucine, and isoleucine. Penoxsulam has been registered for use in United States waters to control aquatic weeds since 2009. Penoxsulam is moderately water soluble and very mobile in the soil. The KOC of penoxsulam ranges between 13 and 305, indicating weak soil adsorption. The primary route of

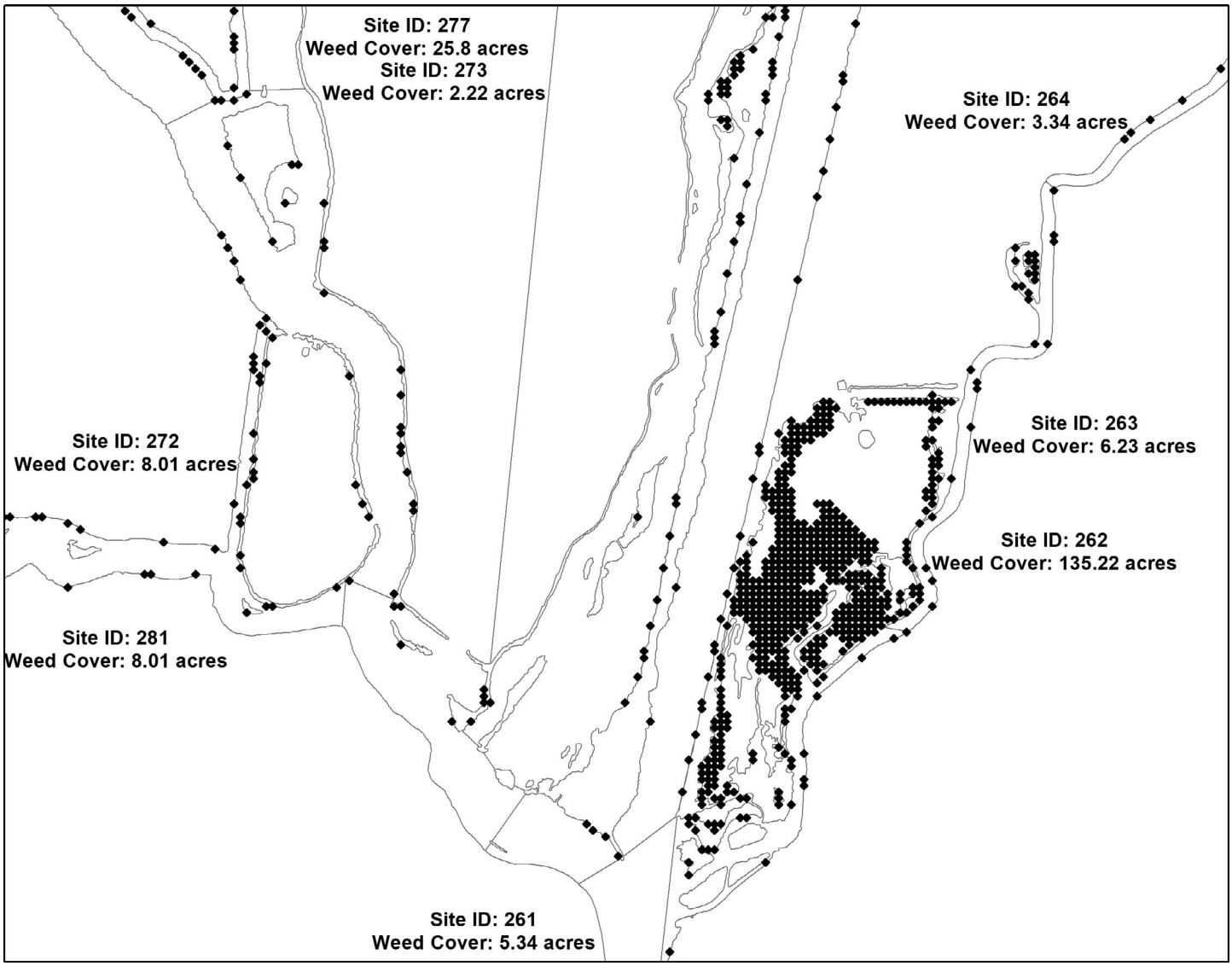

Figure 1. Map of Liberty Island in the California Sacramento–San Joaquin Delta (Delta) from Landsat 8 data processed by a National Aeronautics and Space Administration–developed algorithm. Dots indicate pixels of at least 50% weed coverage.

degradation for penoxsulam is photolysis. The half-life ranges from 1.5 to 14 d. Penoxsulam is used at rates between 0.2 to 0.4 L ha^{-1}, which is estimated to be between 2.7 to 5.5 oz/ac of active ingredient. This herbicide was not used in the Delta Project in 2018.

Imazamox is a systemic herbicide that inhibits the ALS enzyme, which regulates three essential amino acids: valine, leucine, and isoleucine. Imazamox is absorbed into the foliage and translocated throughout the plant. The USEPA registered imazamox for use in waters in 2008. The CDPR approved the aquatic use of imazamox in 2012. Imazamox is highly mobile in soil and water with a KOC of 5 to 143, indicating weak soil adsorption. Imazamox is not significantly volatile and has low potential for bioaccumulation. The primary mode of degradation is photolytic. The half-life ranges between 5 and 15 d. Imazamox is used at a rate between 2.3 to 4.6 L ha^{-1}, which is between 0.28 an 0.56 kg ha^{-1} active ingredient. In 2018, imazamox was applied to control 77 ha of plants in the Delta Project, which is 106 kg ha^{-1} of active ingredient.

Mechanical harvesting is used during emergencies or when other control tools are not available or practicable. Mechanical harvesting uses some combination of surface excavators, harvesters, cutters, and shredders. Surface excavators are used to lift water hyacinth from the waterway or barges into a dump truck for transport. Harvesters are used to remove water hyacinth from waterways using a conveyor belt system. When the vessel has reached capacity, the water hyacinth is offloaded to a nearby dump truck for transport to an authorized location away from the water. This control tool is used infrequently for water hyacinth. In 2018, about 4 ha were harvested.

Hand or net removal is used for pulling water hyacinth whenever other control tools are unavailable or not practical. This requires physically removing weeds by hand or with a pool-skimmer–type net, generally in heavily

Figure 2. Map of the percentage of plant biovolume from King's Island (California Sacramento–San Joaquin Delta) from 20 September 2017 to 11 October 2018. The hydroacoustic data were processed by BioBase.[2] The scale indicates biovolume cover ranging from full biovolume cover to no biovolume cover per pixel.

infested or sensitive areas. This control tool is highly labor intensive and, therefore, rarely used. This method was not used in 2018.

Two weevil species have been approved for release by the USDA. The chevroned water hyacinth weevil (*Neochetina bruchi* Warner) and the mottled water hyacinth weevil (*Neochetina eichhorniae* Hustache) are biocontrol agents for use on water hyacinth. The weevils feed on water hyacinth leaves, with adults generally feeding on unfurled leaves at night and hiding in the day. Adult weevils are around 5 mm long (Warner 1970). Adult females lay eggs in older leaves. Larvae tunnel through the spongy petioles of the leaves and reach the central growth point of the plant by the final larval stage (Center and Dray 1992). When both species of *Neochetina* listed above are present, effects on water hyacinth include increased rate of leaf death, reduced formation of daughter plants, decreased biomass and plant size, reduced flowering and seed production, and reduced competitiveness. The weevils increase the rate at which plants sink, reducing growth and spread (reviewed in Center et al. 1999a; Center and Dray 2010). Weevils were released in the early 1980s and are still present in significant numbers today (Hopper et al. 2017). Although they damage and stress water hyacinth, they have not controlled water hyacinth without integrating them with other management tools.

Water hyacinth planthopper (*Megamelus scutellaris* Berg) is a biocontrol agent for use on water hyacinth. Planthoppers feed primarily on phloem tissues (Hernandez et al. 2011) with damage leading to reduced plant growth, premature leaf death, and ultimately, plant death (Sosa et al. 2007, Tipping et al. 2011, Fitzgerald and Tipping 2013). Adults are white with light-brown markings and grow to be up to 3 mm in length. The macropterous (long-winged, flying, and hopping) and brachypterous (short-winged, hopping only) forms are the two forms of adults, and the latter is predominant (Fitzgerald and Tipping 2013, Moran et al. 2016). Adults live only a few weeks, and females lay around 50 eggs (Tipping et al. 2011). Experimental testing in laboratory conditions found a single generation of the brachypterous adult can reduce biomass by 10 to 35%, and two generations achieve a 67% reduction (Sosa et al 2007, Fitzgerald and Tipping 2013, Sutton et al. 2016, Tipping et al 2011). Planthoppers were released at select sites in 2018 and 2019.

Submersed Aquatic Vegetation (SAV)

Fluridone is a slow-acting, selective, systemic herbicide used to control submersed aquatic weeds. Fluridone inhibits the formation of carotenoid pigments that protect chlorophyll from degradation via sunlight. Fluridone has been used as an aquatic herbicide since approval by the USEPA in 1986. Fluridone has a KOC of 350 to 2,460, indicating a moderate to strong adsorption to soil (Shaner 2014). West et al (1983) reported an average half-life of 20 d in pond water and 3 mo in pond hydrosoil for fluridone formulations. Fluridone is applied at rates of 5 to 30 ppb depending on plant susceptibility. Because of the slow-acting nature of fluridone, 8 to 16 wk of exposure is necessary. This usually requires monitoring and additional applications to maintain the prescribed dose. In 2018, 1,841 ha were treated with 4726 kg of fluridone active ingredient.

Diquat is a fast-acting, nonselective contact herbicide that is a desiccant, causing injury only to the plant with contact to the herbicide. Diquat has been used for aquatic plant management since approved by the USEPA in 1962. Diquat is water soluble with KOC values ranging from 32,000 to 7,900,000, indicating strong soil adsorption. Diquat is not persistent in water. Diquat is applied for a target concentration of 370 ppb active ingredient. In 2018, 19 ha were treated using 574 kg of diquat active ingredient.

Endothall is a fast-acting, selective, systemic herbicide that damages cells at the point of contact. The exact mode of action is not known; hypotheses include cellular disruption and disrupting nutrient transport across cell membranes (Madsen et al 2010). Endothall was registered by the USEPA for use as an aquatic herbicide in 1960. The CDBW uses the potassium salt formulation. The log KOC of endothall is −0.87 with a half-life in water of 4 to 7 d. Endothall is mobile in soil but degrades rapidly (Reinert and Rodgers 1987, Howard 1991). Endothall is used at between 0.75 and 5 ppm. This herbicide was not used operationally in 2018.

The CDBW primarily relied on herbicides and mechanical harvesting until 2019. The work done by CDBW has increased during the past 10 yr, as seen in Figure 3. The Endangered Species Act BiOps were provided annually before 2013, which resulted in uncertainty and variability in

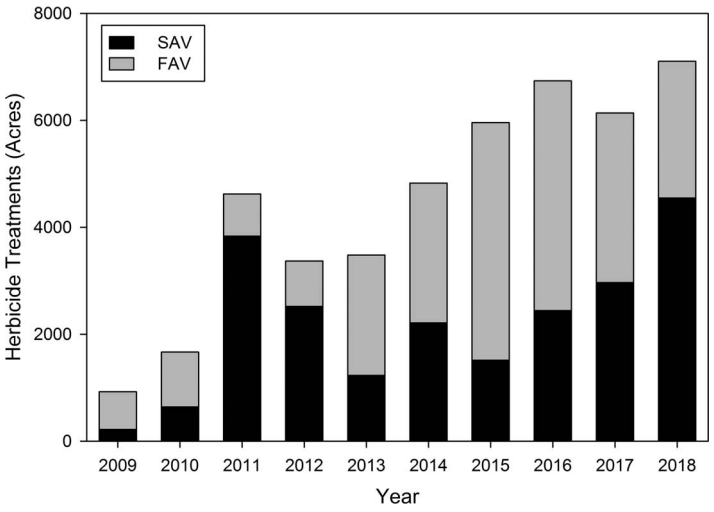

Figure 3. Herbicide treatments by California Division of Boating and Water in the California Sacramento–San Joaquin Delta from 2009 to 2018 for floating, aquatic vegetation (FAV) and submersed aquatic vegetation (SAV) by acres treated.

the start date of treatments. Since 2013, BiOps have been granted for 5-yr periods, allowing for a more consistent start date for treatments. The primary herbicides used in the program until 2018 were 2,4-D, glyphosate, and fluridone with smaller trials of imazamox and penoxsulam. Mechanical harvesting has been a small fraction of the total acreage managed because of cost and complexity and is generally used only for immediate or emergency needs. The only aquatic plant biocontrol agents present in the Delta are the water hyacinth weevils, released in the early 1980s, and planthoppers, which were released on water hyacinth sites in 2018 and 2019. Hand picking remains very rare and is generally only used when other treatment methods cannot be used. The FAV infestations, such as water hyacinth, tend to increase in drought years, likely because of higher water temperatures and slower water flow to flush FAV out of the Delta into salinity areas.

MONITORING

Floating aquatic vegetation

Remote-sensing technology has been used to detect many types of invasive species found in many different environments. The first satellite offering continuous coverage with multispectral data was launched in 1972 by the National Aeronautics and Space Administration (NASA) to cover the surface of the earth (Lass et al. 2005). The program has been using data from the Landsat 8 satellite, which was launched in 2013, in collaboration with NASA scientists. The satellite imagery provides information (Figure 1) on the extent of infestation as well as visual information about where weeds are located. The Landsat 8 imagery has pixel sizes of 15, 30, and 100, based on thermal bandwidths. Each red dot represents a pixel that is at least 50% covered with weeds. Images are taken every 16 d pending cloud cover, allowing for full Delta images. The information also provides the percentage of cover information by site and by project area for estimations of total weed coverage in the Delta. In 2018, CDBW and NASA began evaluation of the Sentinel satellites as a source to address the temporal and spatial limitations associated with Landsat-based operations. Field evaluation of Sentinel products and associated improvements in frequency of remote-sensing acquisitions (weekly) and pixel size (10 m^2) are the basis for migration of operational support to a Sentinel-based mapping tool.

Photo monitoring is an effective and inexpensive method of monitoring changes over time in weed population and coverage. Photo locations are selected at the start of a management season to provide information on the same site over a period of time. The information helps to ground truth other monitoring data, such as remote sensing, and complaints or feedback provided to CDBW.

Submersed aquatic vegetation

Submersed weeds are more challenging to monitor because of a more-limited toolset effective for large areas, such as the Delta. CDBW uses a sonar system that is a combination of a Lowrance High-Definition System consumer echosounder[1] using a BioBase cloud-based algorithm[2] designed to process data obtained by the Lowrance systems for mapping submersed weeds. This setup was chosen over other hydroacoustic systems because of lower hardware and analytical requirements and costs combined with shorter processing timelines (Radomski and Holbrook 2015). To account for the Delta's tides, CDBW uses the mean lower low tide for all measurements. CDBW also uses the recommended settings through BioBase with the units collecting 20 acoustic pings s^{-1} and global positioning system (GPS) coordinates. Biovolume maps (Figure 2) are produced for sites treated for submersed weeds. The biovolume value is the relation between the aquatic plant height divided by the height of the water column. Vegetation cover measures any aquatic plant cover in which the biovolume value is greater than 0.05. The data are used to compare before and after treatment maps for efficacy.

SOURCES OF MATERIALS

[1]Lowrance High-Definition System consumer echosounder, Navico, 4500 S. 129th East Avenue, #200, Tulsa, OK 74134

[2]BioBase, CMap, 1229 Tyler St. NE Ste 120, Minneapolis, MN 55413.

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