APPENDIX 5.F
BIOLOGICAL STRESSORS ON COVERED FISH

ADMINISTRATIVE DRAFT
BAY DELTA CONSERVATION PLAN

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Appendix F
Biological Stressors on Covered Fish

F.0 Executive Summary

F.0.1 Aquatic Biological Stressors and the BDCP

Biological stresses can result from competition, herbivory, predation, parasitism, toxins, and disease. In addition to habitat alteration, the introduction of invasive species is one of the most prevalent causes of biological stress for the Bay Delta Conservation Plan (BDCP) covered fish in the Sacramento–San Joaquin River Delta (Delta). More than 250 nonnative aquatic and plant species have been introduced into the Delta (Cohen and Carlton 1995). Of these, at least 185 species have become established and altered the Delta's ecosystem. Current estimates suggest that more than 95% of the biomass in the Delta is composed of nonnative species. These introduced invasive species, along with other changes to the Delta, have contributed to conditions that resulted in the current status of BDCP covered fish (Chapter 3). Factors that either directly or indirectly cause biological stress for BDCP covered fish include invasive aquatic vegetation (IAV), predation, biotoxins, and invasive mollusks. BDCP conservation measures address a wide spectrum of aquatic and terrestrial environmental stressors across the Plan Area. Reducing the negative effects of key biological stressors is an important component of meeting goals and objectives for covered fish (Chapter 3, *Conservation Strategy*). This appendix examines the effects of implementation of 10 BDCP conservation measures that address three key biological stressors:

- IAV
- Predation
- Invasive mollusks

These biological stressors have been identified as potential mechanisms that resulted in the current status of the covered fish as well as potential deterrents to recovery. As such, they were given specific attention in this appendix.

F.0.2 Summary of Conclusions

F.0.2.1 Invasive Aquatic Vegetation

The control of invasive submerged aquatic vegetation (Conservation Measure 13) should reduce predation mortality of covered fish species by removing habitat for predators and increasing turbidity.

IAV control should benefit covered fish species that use shallow-water habitats (habitats prone to IAV growth) like salmonids and splittail, but should have less effect on pelagic fishes like delta smelt and longfin smelt. Removal of IAV likely would improve conditions for delta smelt by removing the aquatic vegetation associated with a decrease in turbidity. Increased turbidity is associated with improved concealment for delta smelt to avoid detection from mainly visual predators like largemouth bass and striped bass. Turbidity in the Delta is lower than it was 30–40 years ago, and decreasing turbidity in the Delta has constrained the distribution of juvenile and possibly spawning delta smelt. The smelt probably avoid overly clear water and thereby reduce risk of predation, but it may be that smelt in too-clear water are eaten.

Control of IAV, and especially submerged aquatic vegetation (SAV), is expected to enhance natural community ecosystem functions by removing ecologically dominant invasive species. Dense SAV provides suitable habitat and cover for nonnative predatory fish, especially centrarchids that prey on juvenile salmon and steelhead. Predation on juvenile salmon, steelhead, and splittail in the migration corridor can be significant; for example, it is well-documented that juvenile Chinook salmon experience predation by largemouth bass lurking in SAV. Removing SAV is expected to reduce the population of nonnative predatory fish.

The control of invasive aquatic vegetation (Conservation Measure 13) should increase food consumption by covered fish species.

Foraging efficiency by delta smelt and longfin smelt larvae and juveniles is expected to be enhanced because of the increased turbidity that would result from removing or reducing SAV. The delta smelt conceptual model indicates that the ability of delta smelt larvae and juveniles to see prey organisms in the water is enhanced by turbidity, and that delta smelt larvae require turbidity to initiate feeding—the larvae do not feed in water that is too clear. The role and importance of turbidity for longfin smelt feeding efficiency are not as well-known as they are for delta smelt. The amount of overlap between invasive SAV treatment areas and delta smelt and longfin smelt food areas is uncertain and may be low; however, although areas currently occupied by SAV are not suitable for delta smelt, removal of SAV helps to restore suitable habitat conditions.

Control of IAV and the restoration of native aquatic plant communities in treated areas are expected to increase the quantity and quality of habitat suitable for some prey resources (such as crustaceans, annelids, mollusks, fish, and midges) important to green and white sturgeon.

Removal of dense stands of IAV is expected to increase food availability for delta and longfin smelt near treatment locations by increasing light levels below vegetation. Dense IAV blocks light penetration into the water column. IAV control allows greater light penetration in the water column, leading to greater phytoplankton productivity, which in turn leads to greater productivity of zooplankton that constitute prey for a variety of covered fish species, primarily smelts and juvenile salmonids. Dense IAV canopies reduce light penetration through the water column more than would the anticipated increases in water turbidity resulting from IAV removal, and as a result, IAV removal is expected to lead to an increase in phytoplankton productivity. IAV removal and control thus would lead to a net increase in food availability for these covered fish species.

The control of invasive submerged aquatic vegetation (Conservation Measure 13) should increase the amount of spawning and rearing habitat for covered fish species.

Dense patches of SAV physically obstruct covered fish species' access to habitat for spawning and rearing. Removal of SAV is expected to increase the availability of freshwater spawning habitat for longfin smelt in the Delta (spawning occurs where average water temperatures are 10–12°C from mid-December to April). There is no indication, however, that the delta smelt population is limited by the amount of suitable spawning habitat area because they spawn throughout the Delta in different years. For river and Pacific lamprey, SAV removal is expected to increase the availability of suitable existing tidal mudflat and channel margins that support larval settlement and development.

Removal of dense stands of egeria from channel edge and shallow-water habitats is expected to increase the amount of suitable rearing habitat for juvenile salmonids and splittail.

Funding efforts that prevent the introduction of new invasive species (Conservation Measure 20) would benefit covered fish species in the Plan Area.

A key component of an integrated aquatic invasives program is prevention, which incorporates regulatory authority, risk analysis, knowledge of introduction pathways, and inspections. Specifically, efforts that prevent the transport of invasive species by requiring recreational boats to be properly cleaned, drained, and dried after leaving a water body that could harbor invasive plant species are considered beneficial.

The boat inspections will direct effort to one of the important routes by which IAV species are moved between water bodies. In addition, the inspections and related public education will inform the public of the threats posed by IAV and how to recognize them, thus increasing the level of vigilance.

F.0.2.2 Predation

Implementation of the water and facilities conservation measure (Conservation Measure 1) would decrease predation on covered fish at the south Delta facilities although predation at the new north Delta facility will occur.

At the south Delta Central Valley Project (CVP) and State Water Project (SWP) facilities, losses due to predation have been estimated at 75% for salmonids in the SWP Clifton Court Forebay (CCF) and 15% for the CVP facilities, and exceeding 90% for delta smelt at the CCF. Once the north Delta facility is operating, reduced pumping at the south Delta facilities is expected to result in substantially reduced entrainment and consequently reduced predation of covered fish species at the facilities. Based on studies of tagged fish released at the CCF, these estimates of predation at the south Delta facilities may be conservative.

The construction of the north Delta export facilities on the Sacramento River likely will attract piscivorous fish around the intake structures. Bioenergetics modeling (modified from Loboschefsky and Nobriga) of striped bass abundance and consumption rates was used to estimate predation losses of juvenile Chinook salmon, steelhead, and splittail. While losses of Chinook salmon and steelhead are predicted to be substantial (thousands), the population level effect is minimal (less than 1%) when compared to the annual production estimated for the Sacramento Valley. The BDCP bioenergetics model likely overestimates predation of juvenile salmon and splittail because of simplified model assumptions (e.g., perfect capture efficiency by all size classes of striped bass).

Some of the benefits associated with implementation of habitat restoration measures (Conservation Measures 2, 4, 5, 6, and 7) could be offset by an increase in predation by centrarchid fishes if these areas are colonized by invasive aquatic vegetation; control of invasive aquatic vegetation (Conservation Measure 13) and removal of predators in hot spots (Conservation Measure 15) should minimize this effect.

If restored habitats become recolonized by IAV, they could provide potential habitat for predatory species. As such, predation risks would increase as largemouth bass become more prevalent in those areas. Fish predators use seasonal wetlands, although warmwater species such as centrarchids typically spawn later in the year when covered fish have already started to emigrate. Habitat design and maintenance to discourage use of the restored areas, including removal of IAV, should minimize this effect. Additionally, these restored areas may be targeted for predator removal during key occurrence of covered species in these areas, which may also reduce this effect.

Removal of predatory fish at targeted localized "hot spots" (Conservation Measure 15) would reduce predation on covered fish species for short periods in these areas.

Predatory fishes such as striped bass and largemouth bass prey on covered fish species and can be locally abundant at predation hot spots. Adult striped bass are pelagic predators that often congregate near screened diversions, underwater structures, and salvage release sites to feed on concentrations of small fish, especially salmon. Striped bass are a major cause of mortality of juvenile salmon and steelhead near the SWP south Delta diversions (Clark et al. 2009). Largemouth bass are nearshore predators associated with beds of IAV.

Targeted predator removal at hot spots would reduce local predator abundance, thus reducing localized predation mortality of covered fish species. Predator hot spots include submerged structures, scour holes, riprap, and pilings. Removal methods will include electrofishing, gill netting, seining, and hook and line. Predator removal measures will be highly localized. As such, they would not appreciably decrease Delta-wide abundances of predatory game fish. Additionally, intensive removal efforts inadvertently could result in bycatch and take of covered species in localized areas.

The benefits of targeted predator removal are likely to be localized spatially and of short duration unless efforts are maintained over a long period of time, but could be key to reducing predation during important migration or other periods. Removal of predators even at a localized scale will be difficult to achieve and maintain without a substantial level of effort. Highly mobile predators like striped bass can rapidly recolonize targeted areas within a matter of days, implying that predator removal will need to be conducted at frequent intervals when covered species are migrating. Overall Delta-wide benefits of focused predator removal are uncertain.

Efforts to reduce fish predation (Conservation Measure 15) have inherent uncertainties at the population scale.

The overall benefit for covered fishes at the population scale is uncertain because (1) local predator controls may not appreciably reduce the size of populations of fish predators Delta-wide and (2) there are uncertainties surrounding the cause and effect relationships between Delta predators and prey that make it difficult to predict the role of piscivorous fish in controlling the size of fish populations Delta-wide (Durand 2008). Predator-prey dynamics are influenced by many interacting factors that directly and indirectly influence prey encounter and capture probabilities (Mather 1998; Nobriga and Feyrer 2007; Lindley and Mohr 2003), such as habitat overlap between predator and prey, foraging efficiency by predators, energetic demands of predator, size, life stage, behavior, and relative numbers of predators and prey. Fish are opportunistic foragers that readily switch from one food species to another to capitalize on highly abundant organisms and therefore tend not to limit annual recruitment.

Nonphysical fish barriers (Conservation Measure 16) could reduce fish predation by deterring covered fish from predation hot spots.

Nonphysical barriers at the head of Old River and at Georgiana Slough are designed to deter juvenile salmonids from entering certain reaches of the Delta associated with poor survival. These barriers operate by using strobe lights and speakers to deter juvenile fish, with a bubble curtain designed to contain the noise and form a wall of sound. Salmon, steelhead, and splittail are expected to be effectively deterred. Sturgeon and lamprey are not expected to be deterred by the presence of the barriers. Delta smelt may be deterred to some extent, although weak swimming as young juveniles decreases their ability to avoid the barriers. Longfin smelt are distributed too far west in the Delta to encounter the nonphysical barriers. There may be a slight risk of predation related to the underwater structures associated with nonphysical barriers that may attract fish predators. If needed, targeted predator removal activities would be implemented in these areas.

Consolidation and screening of nonproject diversions (Conservation Measure 21) in the Delta will have an unknown effect on fish predation.

Much of the effect will depend on where in the Delta these nonproject diversions are, how/when they are operated, the size/extent of submerged structure associated with them, and how they will be modified. Installation of fish screens and other structures intended to reduce entrainment losses of covered fish actually may attract additional predators and increase localized predation risks.

F.0.2.3 Invasive Mollusks

The combined effect of water operations (Conservation Measure 1) that Increase the amount of habitat with salinity greater than 2 ppt compared to EBC2 and increased tidal habitat from restoration (Conservation Measure 4) may facilitate recruitment and expansion of *Corbula,* and result in reductions in food benefits described in Appendix E, *Habitat Restoration.*

Water operations that affect salinity gradients could affect the recruitment and distribution of *Corbula* in the western Delta and *Corbicula* in freshwater habitats. For example, if the lower end in the salinity zone of X2 moves upstream in the Delta during the *Corbula* larval recruitment period, that could increase opportunities for *Corbula* to recruit farther into the central Delta. Conversely, this could reduce available habitat for *Corbicula*, which requires more freshwater conditions (<2 parts per thousand [ppt]). These invasive clams have the potential to reduce food produced in and exported from the Restoration Opportunity Areas (ROAs).

Funding efforts that prevent the introduction of new invasive species (Conservation Measure 20) would benefit covered fish species in the Plan Area.

A key component of an integrated aquatic invasives program is prevention, which incorporates regulatory authority, risk analysis, knowledge of introduction pathways, and inspections. Specifically, efforts that prevent the transport of invasive species by requiring recreational boats to be properly cleaned, drained, and dried after leaving a water body that could harbor invasive mollusk species are considered beneficial.

While no feasible control measures are known for eradicating well-established invasive mollusks such as *Corbicula* and *Corbula*, prevention of further invasions is critical to avoid further stress to the Delta ecosystem.

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Appendix F
Biological Stressors and Covered Fish

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Acronyms and Abbreviations

µg/L	micrograms per liter
µg/g dw	micrograms per gram dry weight
µm/L	micromoles per liter
BAEDN	Bay Area Early Detection Network
Bay-Delta	San Francisco Bay/Sacramento–San Joaquin River Delta
BDCP	Bay Delta Conservation Plan
BiOp	biological opinion
CALFED	CALFED Bay-Delta Program
Cal-IPC	California Invasive Plant Council
CCF	Clifton Court Forebay
CDFA	California Department of Food and Agriculture
cfs	cubic feet per second
CM	Conservation Measure
CSTARS	Center for Spatial Technologies and Remote Sensing
CVP	Central Valley Project
DBW	California Department of Boating and Waterways
Delta	Sacramento–San Joaquin River Delta
DFG	California Department of Fish and Game
DO	dissolved oxygen
DPM	Delta Passage Model
DRERIP	Delta Regional Ecosystem Restoration Implementation Plan
EDCP	*Egeria densa* Control Program
ELT	early long-term
EPA	U.S. Environmental Protection Agency
ERP	Ecosystem Restoration Program
FAV	floating aquatic vegetation
GCID	Glenn-Colusa Irrigation District
HABs	harmful algal blooms
IAV	invasive aquatic vegetation
km	kilometers
KM^2	square kilometers
LLT	late long-term
LSZ	low salinity zone
m/s	meters per second
mg/L	milligrams per liter
NH3	ammonia
NMFS	National Marine Fisheries Service
NOEC	no-observed-effect concentration
NPDES	National Pollutant Discharge Elimination System
NTU	nephelometric turbidity units
OMR	Old and Middle River

POC	particulate organic carbon
ppb	parts per billion
ppt	parts per thousand
RGR	relative growth rate
ROAs	Restoration Opportunity Areas
SAV	submerged aquatic vegetation
SWP	State Water Project
TFCF	Tracy Fish Control Facility
USDA-ARS	U.S. Department of Agriculture, Agriculture Research Service
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
VAMP	Vernalis Adaptive Management Plan
WHCP	Water Hyacinth Control Programs

Appendix F
Biological Stressors and Covered Fish

This appendix focuses on the evaluation of Bay Delta Conservation Plan (BDCP) conservation measures that reduce key biological stressors and provide potential benefits to the Sacramento–San Joaquin River Delta (Delta) ecosystem at landscape, community, and species scales with a focus on BDCP covered fish. Biological stressors examined include invasive aquatic vegetation (IAV), predation, biotoxins, and invasive mollusks. As described in Chapter 3, *Conservation Strategy*, BDCP conservation measures address a wide spectrum of aquatic and terrestrial environmental stressors across the Plan Area. The combined effect of implementing all of the BDCP conservation measures on the Delta ecosystem at various scales is assessed in Chapter 5, *Effects Analysis*. The analysis in this appendix is a qualitative evaluation of potential outcomes (beneficial and detrimental) of implementing BDCP conservation measures designed to reduce four key biological stressors on the covered fish. It is based on information obtained from the scientific literature; consultations with local experts; and conceptual models of key processes, habitats, and covered fish species in the Delta. The conceptual models that were reviewed included models developed previously by the CALFED Bay-Delta Program (CALFED) Ecosystem Restoration Program (ERP) implementing agencies (California Department of Fish and Game [DFG], U.S. Fish and Wildlife Service [USFWS], and National Marine Fisheries Service [NMFS]) as part of the Delta Regional Ecosystem Restoration Implementation Plan (DRERIP). Those conceptual models were developed to aid in CALFED's planning of potential ecosystem restoration actions in the Delta and are relevant to the BDCP conservation strategy.

This appendix is organized into seven primary sections.

- Section F.1, *Aquatic Biological Stressors and the BDCP Conservation Strategy*
- Section F.2 *Conservation Measures*
- Section F.3 *Methods*
- Section F.4, *Invasive Aquatic Vegetation*
- Section F.5, *Fish Predation*
- Section F.6, *Invasive Mollusks*

Each section includes an overview of the stressor, a conceptual model, an overview of the relevant conservation measures, and an analysis of the effects of implementing conservation measures. References are at the end of the appendix.

F.1 Aquatic Biological Stressors and the BDCP Conservation Strategy

Biological stresses are associated with the diverse interactions that occur among organisms of the same or different species. Biological stresses can result from competition, herbivory, predation, parasitism, toxins, and disease. As such, a wide variety of human activities can cause or enhance biological stress. The introduction of invasive species is the most prevalent cause of biological stress for covered fish in the Delta. For the purposes of this discussion, invasive species generally are considered those nonnative species that adversely affect the habitats and bioregions they invade.

The Delta is considered one of the most invaded estuaries in the world (Cohen and Carlton 1995). Species introductions have been increasing since at least the nineteenth century as a function of increasing trade, boat traffic, and recreation, as well as resource management activities. Introductions are of numerous taxa, including copepods, shrimp, amphipods, bivalves, fish, and both rooted and floating plants. Many pelagic species have been introduced through ballast water releases from large ships directly into the estuary. As a result, many of these introduced species originate from estuaries around the Pacific Rim, particularly copepods and mollusks. More than 250 nonnative aquatic and plant species have been introduced into the Delta (Cohen and Carlton 1995). Of these, at least 185 species have become established and altered the Delta's ecosystem. Current estimates suggest that more than 95% of the biomass in the Delta is composed of nonnative species. These introductions have resulted in a whole host of potential mechanisms for biological stress on BDCP covered fish.

Reducing the effect of three key biological stressors is an important component of the overall BDCP conservation strategy in order to meet the goals and objectives of covered fish (Chapter 3, *Conservation Strategy*). This appendix examines the effects of implementation of 10 BDCP conservation measures that address these four key biological stressors (Table F.1-1).

Table F.1-1. Biological Stressors in the Delta and Associated BDCP Conservation Measures

Delta Biological Stressor	Conservation Measures
Invasive Aquatic Vegetation Fish Predation Invasive Mollusks	*CM1 Water Facilities and Operation* *CM2 Yolo Bypass Fisheries Enhancement* *CM4 Tidal Natural Communities Restoration* *CM5 Seasonally Inundated Floodplain Restoration* *CM6 Channel Margin Enhancement* *CM13 Invasive Aquatic Vegetation Control* *CM15 Predator Control* *CM16 Nonphysical Fish Barriers* *CM20 Recreational Users Invasive Species Program* *CM21 Nonproject Diversions*

F.1.1 Invasive Aquatic Vegetation

In the Delta, IAV reduces the amount and suitability of habitat for covered fish species in a number of ways through adverse effects on water quality and the foodweb and by physically obstructing covered fish species' access to habitat. Dense stands of IAV displace native aquatic plants and provide suitable habitat for nonnative fish species, which in turn displace native species through predation. The two most abundant aquatic invasive plants in the Delta are Brazilian waterweed (*Egeria densa*) or egeria and water hyacinth (*Eichhornia crassipes*). Egeria has been present in the Delta for about 50 years and water hyacinth for more than 100 years. Egeria is a rooted aquatic perennial plant that grows in shallow, freshwater areas of the Delta. The plant forms very dense beds and is now the most abundant submerged aquatic vegetation (SAV) in the Delta. Water hyacinth is a floating perennial plant that inhabits calm backwater areas or areas with low velocities and has become one of the dominant components of floating aquatic vegetation (FAV) in these areas.

Because the plant is not rooted in the substrate, its distribution is influenced by water currents and prevailing wind. During the spring and summer, the dominant westerly winds often hold the plants against the lee shorelines or in backwaters of the Delta. In off-channel and backwater sites, water hyacinth mats can become dense enough to close off open water completely. In the fall, when the seasonally predominant westerly winds decline, mats of hyacinth will float out into the main channels where they are moved about by the river and tidal currents. Current management programs have found that herbicide application is the most effective treatment for egeria in the Delta, and herbicide with some mechanical treatment is the best available treatment for water hyacinth. A number of BDCP conservation measures are likely to reduce the biological stress associated with IAV. These include CM1, CM13, and CM20.

F.1.2 Fish Predation

Predator-prey dynamics are influenced by many interacting factors that directly and indirectly influence prey encounter and capture probabilities (Mather 1998; Nobriga and Feyrer 2007; Lindley and Mohr 2003). Factors affecting the opportunity and magnitude of predation include habitat overlap between predator and prey, foraging efficiency by predators, energy demands of predator, size, life stage, behavior, and relative numbers of predators and prey.

Although predation is a natural part of aquatic community dynamics, increased predation rates by nonnative fish species has been identified as a stressor for BDCP covered fish species, especially delta smelt (Baxter et al. 2008), steelhead (Clark et al. 2009; National Marine Fisheries Service 2009), and juvenile Chinook salmon (Good et al. 2005; Moyle 2002; National Marine Fisheries Service 2009). Elevated predation rates are considered a potential indirect effect of water diversion operations (Brown et al. 1996) and a potential hindrance to shallow-water habitat restoration (Brown 2003; Nobriga and Feyrer 2007). Predatory fish species of particular concern in the Delta are striped bass (*Morone saxatilis*), largemouth bass (*Micropterus salmoides*), and Sacramento pikeminnow (*Ptychocheilus grandis*). Nobriga and Feyrer (2007) found numerous invertebrate and fish taxa in the diets of these common species. Many predatory fish species, including striped bass and largemouth bass, are nonnative. Habitat structure and heterogeneity can affect opportunities for encounter and capture by predators. In open water habitats, striped bass are the most likely primary predator of juvenile and adult delta smelt. Other species, such as largemouth bass, are ambush predators that remain close to cover such as in water structures or aquatic vegetation. A number of BDCP conservation measures are likely to reduce the biological stress associated with fish predation. These include CM1 through CM6, CM13, CM16, and CM21.

F.1.3 Invasive Mollusks

The Amur River clam or Asian clam (*Corbula amurensis*) was likely introduced into the Delta through ballast water releases from large ships. Asian clams have significantly reduced the abundance of plankton, the base of the aquatic food supply, and may affect the feeding efficiency and growth of delta smelt larvae. These voracious eaters of plankton have altered entire foodwebs, harming smelt, salmon, and other native Delta species.

Corbula amurensis was discovered in Suisun Bay, in the northern part of San Francisco Bay, soon after a major flood in the spring of 1986, and its increase and spread coincided with a multi-year dry period that began in mid-1986. The 1986 flood had wiped out the benthic community in the Suisun Bay area, which may have facilitated *Corbula amurensis's* establishment. By 1990 *Corbula amurensis* was very common from San Pablo Bay through Suisun Bay and most abundant in the Suisun Marsh region, with mean concentrations of up to 19,000 clams per square meter and peak densities up to 48,000 clams per square meter. It was soon abundant in the south and central bays as well, and occasionally was collected in the western Delta as far upstream as Rio Vista. At many sites in the bay, it constitutes more than 95% of the benthic biomass.

Werner and Hollibaugh (1993) found that *Corbula amurensis* filters bacterioplankton less efficiently than it does phytoplankton but assimilates both well. They calculated that at typical densities in the northern bay of more than 2,000 clams per square meter, *Corbula amurensis* is capable of filtering the entire water column over the channels more than once per day and over the shallows almost 13 times per day. This filtration rate exceeds the phytoplankton's specific growth rate and approaches or exceeds the bacterioplankton's growth rate, and thus could permanently depress the primary productivity and biomass of these organisms. Phytoplankton blooms that had occurred annually in the northern bay in earlier years essentially disappeared after *Corbula amurensis* became established.

A number of BDCP conservation measures are likely to reduce the biological stress associated with predation. These include CM1 through CM6, CM3, CM16, and CM21.

F.2 Conservation Measures

The following sections briefly describe the conservation measures that could affect covered fish species or the outcome of other conservation measures included in the preliminary proposal.

F.2.1 Water Facilities and Operation (Conservation Measure 1)

The north Delta intake structures located on the Sacramento River will include five separate intake structures located onshore along the Sacramento River mainstem. The vulnerability of covered fish to predation at a north Delta intake is, to a large extent, dependent on the physical characteristic of the structure, whether fish would be concentrated or disoriented, and areas of turbulence and lower velocity refuge habitat that attract predatory fish. Relative to other intake design alternatives, the proposed onshore diversions have minimal structures in the main flow of the river. This reduces areas where predators can aggregate.

In addition, operations of the south Delta State Water Project (SWP) and Central Valley Project (CVP) facilities will change. Predation in the Clifton Court Forebay (CCF) has been documented to be high for covered fish species. Striped bass readily enter and exit the forebay through the radial gates. As pumping at the south Delta is reduced in coordination with the exports at the north Delta facility, entrainment into the CCF will be reduced, and consequently predation losses are expected to be reduced.

F.2.2 Yolo Bypass Fisheries Enhancement (Conservation Measure 2)

Yolo Bypass enhancement (CM2) intends to improve passage at the Fremont Weir and increase Yolo Bypass inundation, which may reduce predation risk on migrating covered fish by providing a migration route with potentially lower predation and entrainment risk (i.e., avoiding the north and south Delta diversions). Enhancement measures also include increasing flows into the Yolo Bypass and creating additional floodplain habitat in the area. While the creation of more floodplains is intended to increase habitat availability for covered species, there is the potential for predator fish species to use these additional improved habitats. Feyrer and coauthors (2006) and Moyle and coauthors (2007) observed predatory fish in restored seasonal floodplain habitats, but noted that predators typically spawned later than covered fishes, after much of the seasonal floodplains have receded in late spring and early summer. There is still little known about the effect of increased seasonal floodplain habitats on predatory fish, so the effect of the Yolo Bypass restoration on predation rates of covered fish is uncertain.

F.2.3 Aquatic Habitat Restoration (Conservation Measures 4, 5, 6, 7)

Aquatic habitat restoration will increase the amount of tidal wetlands (CM4), seasonally inundated floodplains (CM5), channel margin habitat (CM6), and riparian vegetation (CM7) in the Delta. This is expected to provide cover, foraging, and rearing habitat for many covered species as well as for certain predators. The benefits and risks will vary depending on species and life stage, which affect habitat use.

F.2.4 Submerged Aquatic Vegetation Control (Conservation Measure 13)

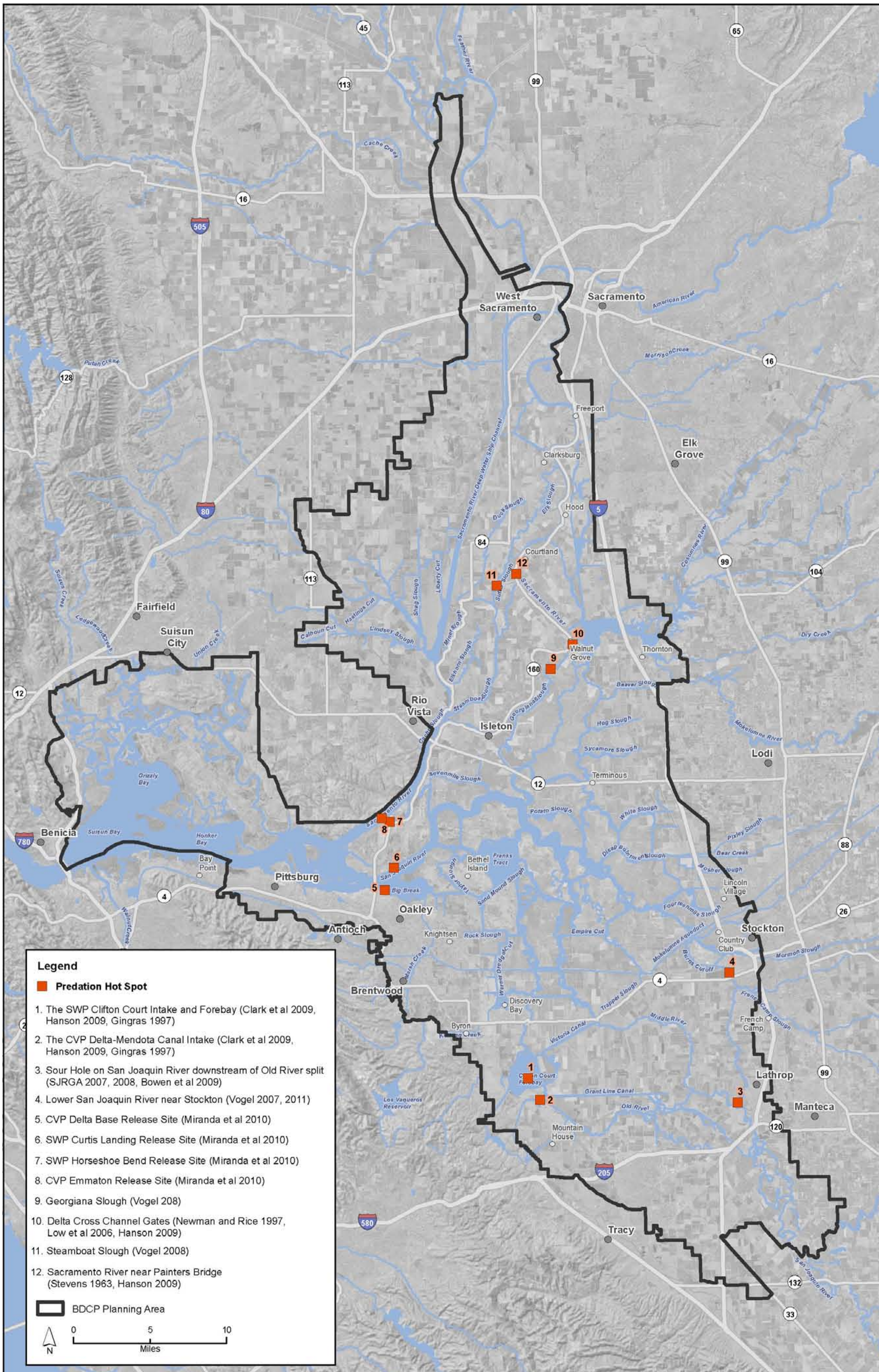
CM13 provides for control of IAV, including both SAV and FAV, that degrades habitat for covered fish species. IAV control will be conducted as required with the focus on areas that provide the greatest biological benefits to covered fish species: in subtidal habitats restored under BDCP conservation strategy tidal habitat restoration actions, salmonid migration routes, and other areas deemed biologically important to covered fish species. Some tidal habitat restoration sites may require IAV treatment prior to restoration, and IAV control. Other priority areas could include established egeria source populations that are near or upstream of restoration areas that could spread into the restored sites. BDCP conservation strategy methods of control will be dictated by site-specific conditions. Application of herbicides or other means to control IAV will be timed to eliminate or minimize potential negative effects on covered species, building on the long-term experience of the California Department of Boating and Waterways (DBW) in implementing their control programs (*Egeria densa* Control Program [EDCP] and Water Hyacinth Control Programs [WHCP]) and monitoring the effects (California Department of Boating and Waterways 2006) to comply with permit conditions. Control methods currently employed by DBW are primarily application of herbicides, with limited mechanical removal of small infestations of water hyacinth by “herding,” in which small rafts of water hyacinth are pushed into a flowing channel to be washed downstream into saline water where they die. Chapter 3 discusses this conservation measure in detail. CM13 also includes other important components of an effective invasive plant control program (Myers et al. 2000): support of early detection and rapid response programs; research on effective treatment methods, which would include research on the biology of potential and known IAV species; and investigation of biological control methods. An additional important component, public education on the transport and introduction of IAV and the consequences of introduction, is provided in CM20.

F.2.5 Predator Control (Conservation Measure 15)

CM15 will conduct localized predator control at hot spots in the Delta to reduce local predator abundance, thus reducing localized predation mortality of covered fish species. The BDCP conservation strategy does not intend to conduct the mass removal of predatory fish populations, however.

The Implementation Office will review fish monitoring data, bathymetry data, and radio and acoustic tagging study results to determine the locations and causes of predator hot spots throughout the Plan Area. Some representative locations are indicated in Figure F.2-1. Hot spots in which focused predator control will occur are likely to include, but may not be limited to the following locations.

- Old structures in or hanging over Delta waterways, such as pier pilings or other human-made structures that are no longer functional or have been abandoned but affect flow fields or provide shade or overhead cover (target: 10–20 structures removed per year).
- Known predator spawning areas where large numbers of predators may be captured and capture of covered fish species may be avoided or minimized.
- Nonproject screened diversions where predators may congregate and forage on covered fish species and other native fish species.
- Boats that have been abandoned throughout the Delta and provide cover for predators (target: five to 10 boats removed per year).
- The new intake structures for the north Delta diversions (target: daily focused removal methods when sensitive life stages of covered fish species are present).
- The deep hole just downstream of the head of Old River in the San Joaquin River (target: daily focused removal when sensitive life stages of covered fish species are present. Additional control efforts may be needed in conjunction with operation of nonphysical fish barriers, as described in *CM16 Nonphysical Fish Barriers*).
- Specific locations in Georgiana Slough, as identified by the fish and wildlife agencies (target: daily focused removal in up to three specific locations when sensitive life stages of covered fish species are present).
- Specific locations in Sutter and Steamboat Sloughs, as identified by the fish and wildlife agencies (target: daily focused removal of predators in up to two specific locations per slough when sensitive life stages of covered fish species are present).
- Release sites of salvaged fish from CVP/SWP facilities (target: focused removal at each salvage release site just prior to release when sensitive life stages of covered fish species are being salvaged).



Sources: BDCP Plan Area, DWR 2010a; Streets, ESRI 2010; Aerial Photograph, NAIP 2010; USBR Hydrology, HDR 2011; Hydrology, HDR 2011; Clark et al. 2009; Hanson 2009; Gingras 1997; San Joaquin River Group Authority 2007, 2008, 2011; Bowen et al. 2009; Vogel 2007, 2008, 2011; Miranda et al. 2010; Low et al. 2006; Newman and Rice 1997; Stevens 1963.

Figure F.2-1. Representative Locations of Known or Suspected High-Level Predation (Hot Spots) in the Delta

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A variety of methods will be used to control predator populations in hot spots, including removal of predator hiding spots; modification of channel geometry; and targeted removal of predators through beach seining, gill netting, angling, and electrofishing when the capture of targeted predators can be maximized and the potential capture of covered fish species can be avoided or minimized. Other focused methods may be dictated by site-specific conditions and the intended outcome or goal. For some predators, such as striped bass, capturing fish during key life stages may maximize capture of the target predator while avoiding or minimizing capture of covered fish species. For example, it may be most efficient to capture striped bass during their spawning period (typically April through June), when fish are relatively concentrated along 70 kilometers (43 miles) of the Sacramento River. Spawning surveys that identify areas with high densities of striped bass may help target specific methods of removal, such as electrofishing or beach seining. Priority will be given to predator hot spots in areas with high numbers of covered fish, such as major migratory routes or spawning and rearing habitats, and to methods that maximize the capture of predators and minimize the capture of covered fish species. This may require some experimentation with field methods, such as the mesh size of nets; time of day, month, or year; and control sites.

Site-specific control plans will be developed in consultation with DFG, NMFS, and USFWS and will include expected benefits, methods, and a monitoring design that will provide information necessary to determine the effectiveness of the predator control actions.

CM15 also will increase the number of salvage release sites from four to eight and remove debris near release sites on a monthly basis from October through June to reduce the predation loss of released fish.

F.2.6 Nonphysical Fish Barriers (Conservation Measure 16)

Nonphysical barriers are intended to guide juvenile fish away from migration routes with low survival and high predation risk, such as the head of Old River, toward safer routes. Nonphysical barriers currently used in the Delta include large in-water structures that incorporate directional strobe lighting, sound signals, and air bubble curtains to contain the noise and form a wall of sound. These stimuli are intended to deter juvenile fish from passing and to choose an alternative migration path. The substantial amount of submerged structures associated with the fish barrier infrastructure, however, has the potential to attract piscivorous fish predators.

F.2.7 Recreational Users Invasive Species Program (Conservation Measure 20)

Under *CM20 Recreational Users Invasive Species Program*, the BDCP Implementation Office will fund actions to reduce the invasion of nonnative invasive species into the Plan Area. Funding will be provided to implement the DFG Watercraft Inspection Program in the Delta. One important component of an integrated invasive species program is prevention, which incorporates regulatory authority, risk analysis, knowledge of introduction pathways, and inspections.

F.2.8 Nonproject Diversions (Conservation Measure 21)

Nonproject diversions are defined as diversions of the natural surface waters in the Plan Area for purposes other than meeting SWP/CVP water supply needs; most nonproject diversions serve agricultural needs or provide water for waterfowl rearing areas. An estimated 2,200 nonproject diversions are used to irrigate crops in the Delta (Herren and Kawasaki 2001). All are shore-based and operate using pumps or gravity flow, and almost all are small (30–60 cm pipe diameter) and unscreened (Nobriga et al. 2004).

Under this conservation measure, the BDCP Implementation Office will provide funding support for landowners and local entities to remediate nonproject diversions to reduce entrainment. This measure proposes screening and/or consolidating these diversions. The most common screen designs used in the Sacramento Valley and Delta for diversions from 1 to 500 cubic feet per second (cfs) are cylindrical or cone screen systems that can be attached to the end of an intake pipe. These types of screens can be attached permanently or designed to be removable from the water seasonally.

The intake structures associated with these nonproject diversions are potential sites for increased predation on covered fish species. Reducing the amount of in-water structures could reduce cover for nonnative predatory fish.

F.3 Methods for Analysis

F.3.1 Invasive Aquatic Vegetation Analysis

The analysis in this section is a qualitative evaluation of potential outcomes (beneficial and detrimental) of implementing BDCP conservation measures associated with reducing the effects of IAV on BDCP covered fish. It is based on information obtained from the scientific literature; consultations with local experts; and conceptual models of key processes, habitats, and covered fish species in the Delta. Review of conceptual models included models developed previously by the CALFED ERP implementing agencies (DFG, USFWS, and NMFS) as part of the DRERIP. Those conceptual models were developed to aid in CALFED's planning of potential ecosystem restoration actions in the Delta and are relevant to the BDCP conservation strategy.

F.3.2 Fish Predation Analysis

Best professional judgment based on the available scientific information was used to characterize predator distribution and abundance within Delta habitats, covered fish species losses attributed to predation, and the anticipated effectiveness of the predator control conservation measures on predation effects in the Delta. This included information from studies of marked or radio-tagged steelhead, Chinook salmon, and delta smelt at the SWP's CCF (Gingras 1997; Clark et al. 2009; Castillo et al. in review) and Chinook salmon at the San Joaquin River and head of Old River (Bowen and Bark 2010). Other studies provided information on Delta habitat use by covered fish species and nonnative predators (Nobriga and Feyrer 2005, 2007) and the effectiveness of fish predator control efforts in the Delta (Cavallo et al. in press) and elsewhere (Mueller 2005; Porter 2010).

Two quantitative analyses were used to estimate predation-related effects of water diversions and facilities (CM1). For the new north Delta intakes, bioenergetics modeling was used to estimate relative consumption of juvenile Chinook salmon and splittail by striped bass. The original model estimated consumption based on water temperature, striped bass size, and the density and size of prey encountered (Loboschefsky et al. in review; Loboschefsky and Nobriga, unpublished). For the south Delta facilities, salvage-density and the Kimmerer (2008) Old and Middle River (OMR) entrainment values were used to estimate pre-screen entrainment losses that typically are ascribed to predation. These methods are described in detail in the following sections.

F.3.2.1 Bioenergetics Model

Bioenergetics models provide a quantitative approach for estimating the energy budget of an individual species by partitioning consumed energy to three components: metabolism, wastes, and growth (Chipps and Wahl 2008). Because these models are driven by a mass-balance equation, they are used mostly to estimate growth or consumption given information on other variables (Chipps and Wahl 2008). The growth or consumption estimates of an individual species often are expanded to the stock or population level. This is done by multiplying single fish dynamics by estimates of the population size and cohort mortality (Hartman and Margaf 1992; Hansen et al. 1993), thereby illustrating the energy allocation of the population. The most common application of bioenergetics modeling is to estimate the dynamics of predator-prey interactions. Often, estimates of population-level parameters such as food consumption or growth of fish stocks are taken from these models and are linked in larger models to examine more complex foodweb interactions such as predation rates, energy or nutrient cycling, and trophic efficiency (Stewart et al. 1981; Hansen et al. 1993). Using these approaches, the rate at which predators will consume prey populations, especially for sensitive fish populations, can be quantitatively estimated over a given period of time. Moreover, such models can be a useful tool for species conservation measures when used to compare estimated consumption of prey by predators based on their responses to management actions and predator-prey interactions (see Hansen et al. 1993; Rand et al. 1995; Loboschefsky et al. in review).

A bioenergetics model has been applied to estimate predation by striped bass on migrating juvenile Chinook salmon in the vicinity of the north Delta intakes. The model was developed by Loboschefsky and coauthors (in review) for striped bass in the San Francisco estuary and subsequently was modified by Loboschefsky and Nobriga (2010) for use in the BDCP conservation strategy analysis. The model estimates consumption based on water temperature, striped bass size, and the density and size of prey encountered.

Application of the bioenergetics model involves the following assumptions.

- Bioenergetics models represent the best available scientific method to factor fish physiology into estimates of prey consumption. The bioenergetics model–based consumption estimates are subject to the input parameter sensitivities and assumptions described by Hartman and Brandt (1993, 1995).
- Consumption estimates are highly sensitive to striped bass size because consumption increases as a log-function of striped bass length. Thus, it was necessary to estimate adult striped bass lengths by extrapolating beyond the length-weight ranges. This includes the potential for overestimating or underestimating consumption depending on whether the length-weight equation overestimates or underestimates the length of adult striped bass based on their weight.
- The functional response equations are prey-dependent and density-dependent functions developed for capture rates of common, nonnative prey fishes by striped bass. It is not known how accurately these functions predict predator-prey dynamics involving rare native fish species. However, this modeling step is necessary to estimate striped bass consumption in response to changes in prey fish density. The BDCP covered fish species are narrow-bodied fish lacking substantial fin spines. The same is true of the prey fishes for which the functional

response curves were developed. Thus, if used as recommended, the functional responses should approximate striped bass predation of fishes other than those for which they were developed.

- Predation of juvenile salmon is proportional to their relative abundance, regardless of size. Many juvenile winter-run salmon are big enough to escape predation from most of the more abundant younger striped bass, but this bioenergetics model does not incorporate hunting or feeding efficiency into its parameters. This results in an overestimation of predation loss.
- Uncertainties exist for striped bass densities associated with structures. Estimates of predator abundances are based on a few underwater pictures of predators observed holding around the Glenn-Colusa Irrigation District (GCID) fish screens (Vogel 2008) and extrapolated to estimate predator abundances at north Delta intakes. These predators may be Sacramento pikeminnow, not striped bass, based on Vogel's (1995) review of GCID studies.
- Loboschefsky and Nobriga (2010) provide estimates of striped bass predation rates on "small prey" and "large prey." This bioenergetics analysis incorporates only the large prey equation, although smaller salmon fry would fall under the small prey category. The large prey predation regression was based on data for small striped bass (69–478 mm); thus they mainly reflect responses of juvenile striped bass. Therefore, they are not as applicable for larger striped bass and for larger sized prey fishes.
- Not all juvenile fish traveling past the proposed north Delta intakes may be vulnerable to the increased predation risks associated with the structures. Human-made structures can create water turbulence, which disorients juveniles fish and makes them more vulnerable to predators. Some juveniles will not be affected by the increased turbulence or swim close to the intake structures, but the model assumes an equal elevated predation risk across the Sacramento River channel for all migrating juveniles. Therefore, predation risk may be overestimated.

F.3.2.1.1 Methods

The bioenergetics model developed by Loboschefsky and coauthors (in review) and Loboschefsky and Nobriga (2010) was used to estimate striped bass annual consumption of migrating juvenile salmon at the north Delta intake sites. The model also was used to calculate splittail predation loss at the north Delta intakes. The model used the empirical data from Loboschefsky and Nobriga (2010) for striped bass in the Delta. Additional data inputs used in the model were obtained from USFWS's Delta Juvenile Fish Monitoring Program for juvenile Chinook salmon weekly catch and fork lengths (1994–2006), and BDCP water quality model simulation for water temperatures.

To estimate the number of juvenile Chinook salmon consumed by striped bass at the north Delta intakes, the following inputs were used in the model (Figure F.3-1).

1. Weekly prey density for juvenile Chinook salmon (all races combined) (U.S. Fish and Wildlife Service 1994–2006 trawl data).
2. Weekly striped bass fork length by age class (Loboschefsky and Nobriga 2010).
3. Weekly average water temperature (DSM2-QUAL).
4. Weekly Chinook salmon proportional abundance by race (U.S. Fish and Wildlife Service 1994–2006 trawl data).

5. Weekly Chinook salmon average fork lengths by race (U.S. Fish and Wildlife Service 1994–2006 trawl data).
6. Estimated number of striped bass at north Delta intakes (Vogel 2008).
7. Striped bass age class composition (California Department of Fish and Game).
8. Chinook salmon average annual juvenile (and smolt-only) production for each race (California Department of Fish and Game GrandTab 2010; California Department of Water Resources 2001; Cavallo et al. 2009; Fisher 1994; Killam 2009; Lee and Chilton 2007; Poytress and Carillo 2010; U.S. Fish and Wildlife Service, unpublished data).

Estimates of splittail predation were based on the steps similar to those for juvenile Chinook salmon, but inputs were based on monthly averages instead of weekly averages.

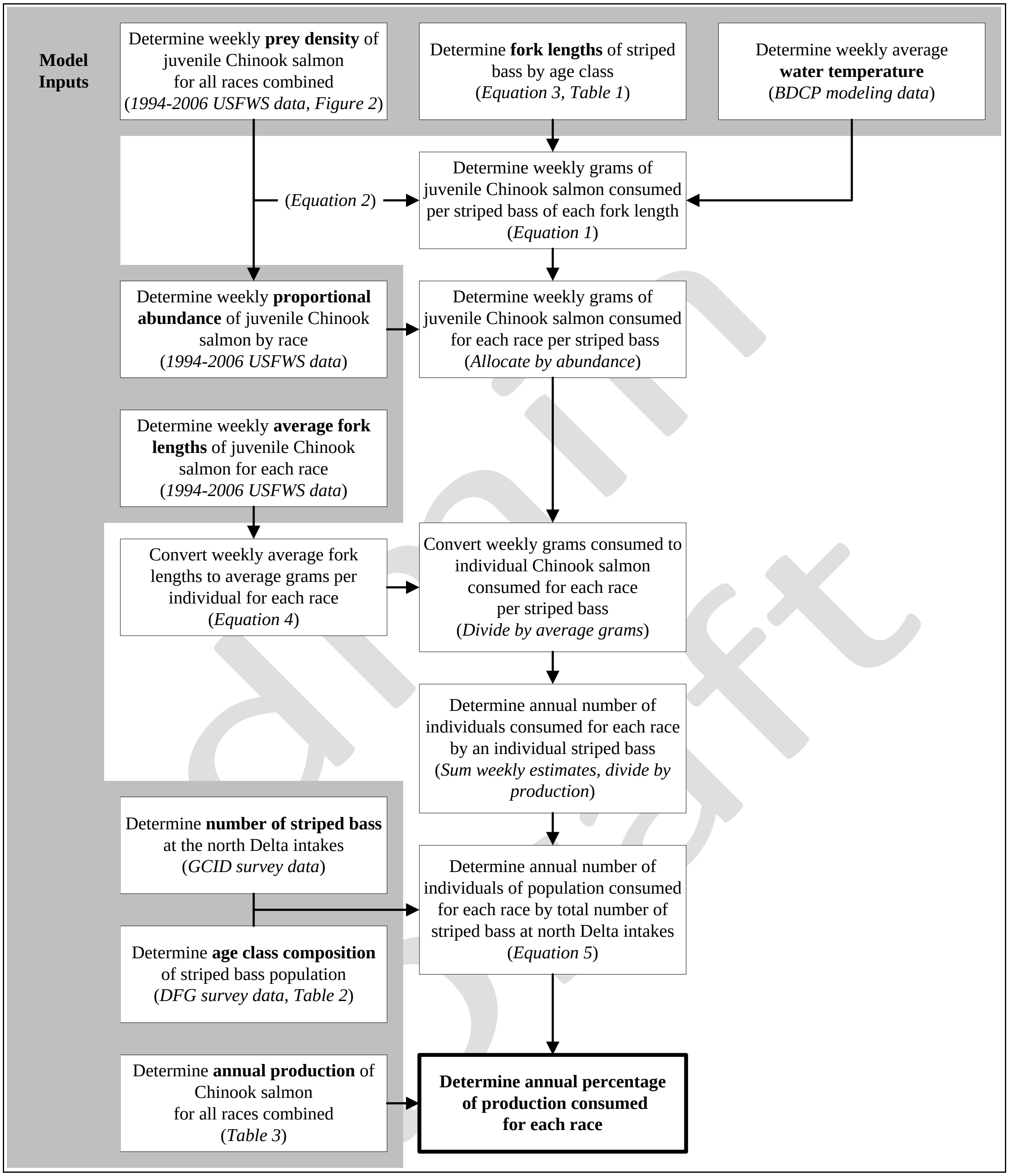


Figure F.3-1. BDCP Bioenergetics Model Calculation Steps

The weekly consumption of juvenile salmon by an individual striped bass was modeled as a logistic function of striped bass fork length in mm (FL), average water temperature in °C (T), and the proportion of the diet composed of a particular prey taxon (P):

$$C_{individual,\ weekly} = [0.002103(FL) + 0.02488(T) - 0.3565]\ P; \qquad \text{(Equation 1)}$$

where C is the log transformed grams of prey consumed.

The equation used to predict *P* was expressed as:

$$P = \left(\frac{1}{1 + e^{(-5.8136 + 0.0091239 FL + 0.72985 CPUE)}} \right); \qquad \text{(Equation 2)}$$

where *CPUE* = salmon density as $\log_{10}$-transformed number of salmon per 10,000 m^3 of water sampled.

The salmon density estimates (weekly number of fish per 10,000 m^3) combined for all juvenile Chinook salmon races were collected from 1994–2006 trawling data in the Sacramento River obtained from the USFWS's Delta Juvenile Fish Monitoring Program (Figure F.3-2).

The logistic regressions that are used to estimate total consumption to consumption of a particular prey are approximations of striped bass functional responses to changing prey density that were developed from field data collected in the Delta (Nobriga and Feyrer 2008). The BDCP covered fish species are relatively rare, and thus there were not enough found in stomachs (and in some cases not any) to develop response equations specific to them. However, there is a large amount of scientific literature on the feeding ecology of piscivorous fishes, and these modeled responses follow expectation. The prey equation used above is the modeled response of striped bass to threadfin shad.

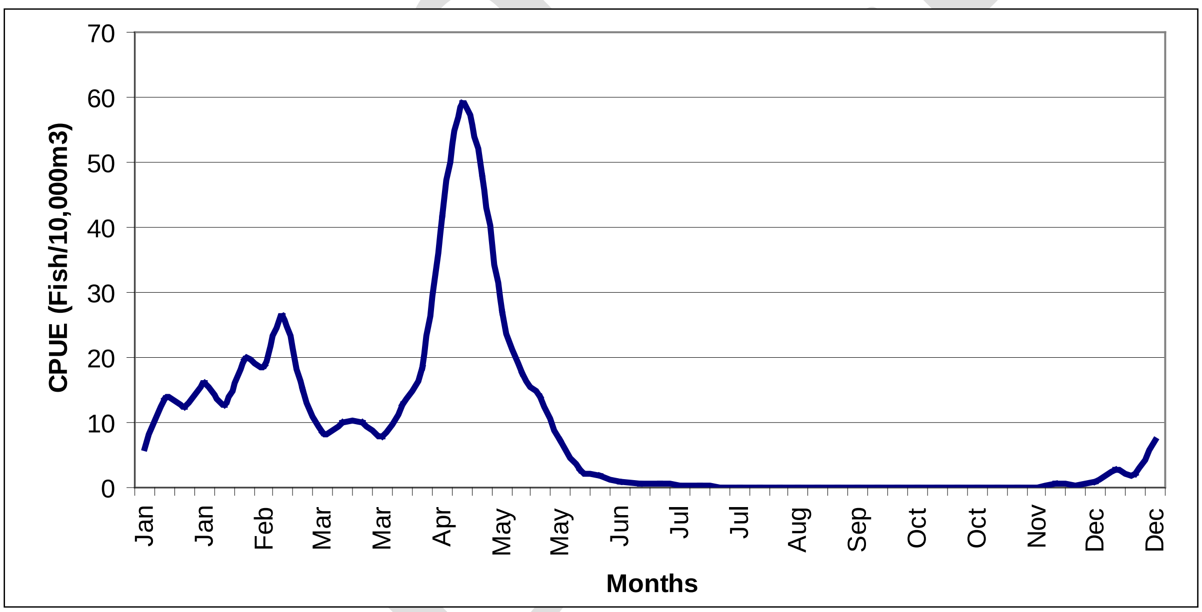


Figure F.3-2. Juvenile Chinook Salmon CPUEs (Fish/10,000m^3) Collected from 1994–2006 Trawling in the Sacramento River by the U.S. Fish and Wildlife Service

The fork lengths of individual striped bass for each age class that were applied in the model were taken from Loboschefsky and Nobriga (2010) (data shown in Table F.3-1). These were calculated based on the size of striped bass in weight (g), and converted to fork lengths (mm) using the length-weight conversion of Kimmerer and coauthors (2005):

$$W = 0.0066 \cdot \left(\frac{1}{1 + e^{(-5.8136 + 0.0091239 FL + 0.72985 CPUE)}} \right) \cdot L^{3.12}; \qquad \text{(Equation 3)}$$

where *W*=striped bass weight in g, and *L*=striped bass fork length in mm.

Table F.3-1. Estimated Fork Lengths (mm) of an Individual Striped Bass by Age Class Used in This Model

Striped Bass Age (Year)	Fork Length (mm)			
	Spring	Summer	Fall	Winter
1	172	188	204	220
2	254	301	353	412
3	448	471	493	516
4	537	555	573	592
5	611	629	646	664
6	680	694	709	723

Source: Loboschefsky and Nobriga 2010.
Note: For adult fish (age 3 and older), the lengths were averages of male and female size.

The average early long-term and late long-term weekly water temperatures were derived from model simulations of DSM2-QUAL averaged from stations in the north Delta. The temperatures represent realistic water temperatures observed in the Sacramento River where the north Delta intakes are proposed.

The weekly grams of juvenile Chinook salmon consumed per striped bass for all races then was converted to race-specific weekly consumption estimates. The average weekly proportional abundance for each race observed by USFWS Sacramento trawls (1994–2006) was multiplied by the weekly grams of juvenile Chinook salmon consumed across all races to determine the weekly race-specific grams consumed.

In order to convert the weight of juvenile salmon consumed by striped bass into the number of salmon consumed, the weekly average fork lengths for each race from USFWS Sacramento trawls (1994–2006) and the length-weight relationship developed by Petrusso and Hayes (2001) for Chinook salmon in the Sacramento River were used:

$$W = 0.000004 \cdot \left(L^{[3.2578]}\right); \qquad \text{(Equation 4)}$$

where W=Chinook salmon weight in g, and L=Chinook salmon fork length in mm.

After converting average weekly fork lengths (mm) to average weight (g), the model estimates of weekly grams of juvenile Chinook salmon consumed for each race were divided by the weekly average weight for individuals of each race to obtain the number of juvenile Chinook salmon of each race consumed per striped bass.

Weekly race-specific consumption estimates then were summed across all weeks to calculate annual consumption of Chinook salmon juveniles per striped bass for each race of salmon. The annual number of Chinook salmon juveniles (C_{total}) consumed by the total number of striped bass at the north Delta intakes (N_i) was calculated:

$$C_{total} = \sum_{i=1}^{age} N_i \times C_i ; \qquad \text{(Equation 5)}$$

where N_i is the number of striped bass per age class at the north Delta intakes and C_i is the annual number of Chinook salmon juveniles consumed by an individual striped bass per age class.

In the model, the assumed striped bass abundance at the north Delta intakes ranged from approximately 20 to 245 fish per intake, with a median value of 133 striped bass. These estimates were based on fishery surveys of the GCID fish screen evaluation program, which found predator density of 0.39 per meter of intake structure or approximately 133 fish associated with each of the intake structures (Vogel 2008). The GCID fish screens are large, on-bank diversions comparable to the diversions proposed as part of the BDCP conservation strategy.

To determine the striped bass densities per age class, the total number of striped bass (e.g., 133) were multiplied by the proportion of striped bass in each age class (Table F.3-2). The age distribution of striped bass was from 36 years of historical survey data (data obtained from DFG). While a different age composition of striped bass might be expected to occur in association with the north Delta intake, no data were available to develop a site-specific age composition.

Table F.3-2. Age Distribution of Striped Bass Used in the Model

Age	Proportion
1	0.38
2	0.25
3	0.17
4	0.11
5	0.06
6	0.03

Finally, the annual percentage of Chinook salmon juveniles for each race consumed by the total number of striped bass at the north Delta intakes was calculated by dividing race-specific annual consumption by the average annual race-specific production estimated for brood years 2000–2009 (Table F.3-3).

Table F.3-3. Summary of Data and Data Sources Used to Estimate Average Annual Production of Total Juveniles and Smolts-Only Arriving at the Delta for Fall-Run, Winter-Run, Spring-Run, and Late Fall–Run Chinook Salmon

Data Type	Chinook Salmon Run				References
	Winter	Spring	Fall	Late Fall	
Total in-river escapement	7,634	8,924	293,393	16,214	DFG GrandTab (March 2010), 10-year average
Pre-spawning mortality	5%	5.53%	42%	42%	Winter: Poytress and Carillo 2010 Spring: McReynolds and Garman 2008; McReynolds et al. 2005–2007 Fall, late fall: California Department of Water Resources 2001
Percent female	53.50%	54.60%	46%	46%	Winter, fall, late fall: Killam 2009 Spring: McReynolds and Garman 2008; McReynolds et al. 2005–2007
Fecundity	3,859	5,300	4,500	5,800	Winter: Poytress and Carillo 2010; Spring: Cavallo et al. 2009; Fall: Lee and Chilton 2007; Late Fall: Fisher 1994
Egg to fry survival	33%	33%	33%	33%	Poytress and Carillo 2010
Fry to Delta survival	53%	53%	53%	53%	USFWS unpublished data
Total juveniles reaching Delta	2,600,000	4,200,000	61,600,000	4,300,000	
Percent smolts entering Delta	82%	86%	52%	84%	USFWS Sacramento trawls
Total smolts reaching Delta	2,100,000	3,600,000	32,000,000	3,600,000	Rounded to nearest 100 thousand

F.3.2.1.2 Differences from Original Loboschefsky and Nobriga (2010) Model

Loboschefsky and Nobriga (2010) provided prey use regressions for small prey and large prey, although only the large prey regression is used in this bioenergetics model. Loboschefsky and Nobriga note that small salmon fry that wash down in the winter months are likely more accurately modeled as small prey. Loboschefsky and Nobriga also calibrated their temperature data so that they resulted in modeled striped bass growth rates that were within 0.1% of the observed annual growth. In this bioenergetics model, the data were derived from average weekly DSM2-QUAL outputs for temperatures at stations in the north Delta for both early long-term and late long-term. This bioenergetics model also does not incorporate capture efficiency of striped bass on prey fish. In reality, as striped bass consume their prey whole, capture rates are low when prey size is large compared to the predator. Loboschefsky and Nobriga provide a regression equation that predicts prey capture rates are very low when prey length exceeds 0.47 x of predator size. In this bioenergetics model, large smolts still theoretically can be eaten by all size classes of striped bass, even when the salmon prey is larger than the juvenile striped bass predator.

F.3.2.2 Pre-Screen Entrainment Loss at South Delta Facilities

Predation at the SWP and CVP south Delta facilities can be quite high, as inferred from pre-screen entrainment losses, most notably in the CCF. Pre-screen loss rates for Chinook salmon and steelhead are assumed to be 75% and 15% at the SWP CCF and CVP south Delta facilities, respectively (Gingras 1997; Clark et al. 2009). As less water is exported at the south Delta under the BDCP conservation strategy (due to availability of the new north Delta diversion facility), entrainment of covered fish presumably will be reduced at the south Delta facilities. Under this analysis, it is presumed that exposure to predation is proportional to entrainment of covered fish in the south Delta export facilities.

The salvage density method represents the simplest model for estimating the total salvage that occurs at the south Delta pumping facilities. Total monthly salvage numbers were calculated by extrapolating estimates of the total number of fish salvaged based on a subsample that actually was identified, counted, and measured. Salvage and loss data for analysis were normalized by measures of annual population abundance in the year of entrainment for winter-run Chinook salmon (based on juvenile production estimate), spring-run Chinook salmon (adult run size), delta and longfin smelt (Fall Midwater Trawl). No normalization was undertaken for steelhead because there are no suitable indices of annual abundance. These data provided the basic estimates of fish density (number of fish salvaged per unit of water exported) that subsequently were multiplied by simulated export data from CALSIM modeling outputs. Further details are provided in Appendix 5.B, *Entrainment*.

However, it is acknowledged that the assumption of a linear relationship between entrainment and flow may be an oversimplification given evidence of nonlinear relationships, as seen with delta smelt (Kimmerer 2008). Thus, the salvage density method functions simply as a description of changes in flow weighted by seasonal changes in salvage density of fish. For delta smelt, entrainment estimates also were based on the proportional OMR method (Kimmerer 2008).

F.3.2.3 Predation Risk in Restored Habitats

Aquatic habitat restored under the BDCP conservation strategy (CM2, CM4, CM6 and CM7) will be used by both native and nonnative species, including predatory fish. The degree to which these actions could offset predation losses or contribute to predation risk will depend on the species-specific habitat use patterns, abundance of predators, and predator consumption rates. Daily consumption rates of native fish can be estimated from studies of fish predator stomach contents in the Delta (Stevens 1963; Stevens 1966; Thomas 1967; Nobriga and Feyrer 2007, 2008).

A quantitative assessment is difficult because data are lacking on predator densities associated with different restored habitats. Predation risk could be estimated with data on predatory fish densities in similar habitats, consumption rates of juvenile salmonids, and the amount of restored habitat. The USFWS sampled Liberty Island by gill netting and beach seining and documented densities of predators (largemouth bass, striped bass, and pikeminnow combined). However, these estimates have a degree of uncertainty associated with them depending on assumptions of habitat availability, quality (e.g., depth, vegetation), and use by different species.

To understand the overall effect of habitat restoration on covered fish species, these estimates of predation would have to be placed in the context of predation under existing conditions, numbers of covered species with and without restoration, and proportion of population lost to predation. For example, Table F 3.3 estimates annual production of different Chinook salmon runs. However, population estimates are not available for all covered species.

F.3.2.4 Effects of Predator Removal

The effects of predator removal efforts (CM15) are assessed qualitatively, using information from a fish removal experiment in the Delta (Cavallo et al. in press), as well as control programs implemented on other systems such as the Columbia River (Porter 2010) and Colorado River (Mueller 2005).

F.3.3 Invasive Mollusks Analysis

To estimate the potential effect of BDCP measures on the spatial extent of *Corbula*, the change in X2 position is a proxy for the change in potential new habitat. *Corbula* larvae require salinities greater than 2 parts per thousand (ppt), potentially limiting the easterly invasion of *Corbula* in the Delta as flows become fresher. Changes in water operations (CM1) may shift X2 positions compared to EBC2 by altering the amount of freshwater flows through the West Delta. By analyzing the amount of habitat in Suisan Bay and the West Delta with salinity greater than 2 ppt (based on X2 position), it is possible to roughly determine the predicted extent of the potential *Corbula* occurrence. The main caveat to this approach is that adults can tolerate nearly freshwater conditions (down to 0.1 ppt salinity), meaning that *Corbula* can invade areas with average salinities of below 2 ppt, if for a brief period salinity is greater than 2 ppt to allow for successful settlement and recruitment of larval *Corbula*. This may underestimate the potential for occurrence, while other factors such as substrate and density of existing benthic populations are not accounted for, which may overestimate the potential for occurrence in specific regions of the Plan Area.

F.4 Invasive Aquatic Vegetation

F.4.1 Ecological Impact Pathways

The San Francisco Bay/Sacramento–San Joaquin River Delta (Bay-Delta) region is one of the most invaded aquatic ecosystems in North America. In a 1995 review (Cohen and Carlton 1995), more than 200 invasive species were tallied, including about 25 plant species. A later review (Light et al. 2005) listed 69 nonnative aquatic plants known from the Delta, including riparian and wetland plants, as well as fully aquatic species, dividing them into definite and probable invaders. Of great concern in the Delta is the presence of IAV. It has the ability to significantly alter habitat conditions for aquatic animals, including BDCP covered fish species, by changing the hydrologic regime, sedimentation, water quality, and nutrient cycling.

The term *IAV* is used to describe invasive nonnative aquatic plant species that have the capacity to grow and spread rapidly. IAV includes both SAV (plants that root in the sediment and remain below the water surface) and FAV (plants that float freely on the water surface). The term *SAV* includes all submersed plants, native as well as nonnative, and similarly, FAV includes all native and nonnative floating aquatic plants.

Two invasive aquatic plant species have invaded the Delta and expanded greatly over the past decade and have received the bulk of the attention to date in terms of ecological research, surveys, and control efforts: Brazilian waterweed or egeria and water hyacinth (*Eichhornia crassipes*). Both plants have spread rapidly throughout the Delta. Because of the problems these two species create for navigation, The DBW was mandated legislatively to control both egeria and water hyacinth in the Delta and its tributaries. In tandem with implementing control treatments (begun in 2001 for egeria and 1983 for water hyacinth), DBW has been researching and developing methods and protocols for chemical, and to a lesser extent mechanical, treatments and supporting research on the biology of these species in the Delta. Both plant species have no known natural predators or parasites in the Delta environment.

F.4.1.1 Brazilian Waterweed/Egeria

Brazilian waterweed, also known as egeria, is a submersed aquatic perennial plant that grows rooted in sediment in shallow, freshwater areas of the Delta. The plant forms very dense beds and is now the most abundant component of SAV in the Delta, displacing most of the native SAV (Santos et al. 2011). It can grow at depths up to about 2 to 3 meters in the Delta, but has the potential to grow as deep as 6 meters in clear water (Anderson and Hoshovsky 2000); it occurs in freshwater areas, primarily upstream from Antioch. Egeria grows very rapidly under good conditions such as those that occur in the shallow-water areas of the Delta. Recent research on the ecology of egeria has shown that climate and temperature conditions in the Delta are ideal for year-round growth (Pennington and Sytsma 2009). Reproduction in the Delta is solely by vegetative fragmentation—only male plants are present in the United States, so no seed is produced. Under ideal experimental conditions, a relative growth rate (RGR) of 6.3% per day, equivalent to a biomass doubling time of 12 days, has been recorded (Pistori et al. 2004), making this species one of the fastest-growing aquatic plants. In 2006, under field conditions in the Delta, RGRs as high as 2.42% per day were measured (Spencer and Ksander 2005).

In 2006, DBW estimated that approximately 11,500 to 14,000 acres were infested, and the weed was spreading at an estimated rate of 10–20% per year, potentially doubling in acreage every 10 years based on observed expansions at sites where egeria was present (California Department of Boating and Waterways 2006). More recent estimates, based on aerial imagery analysis, estimated approximately 10,000 acres in 2007 (Ustin 2008), and confirmed the overall rate of increase was similar to that estimated by DBW in 2006 (Table F.4-1).

Table F.4-1. Aerial Extent of SAV (acres) in the Delta from 2004 to 2007, Estimated Using a Polygon-Based Approach

Area	2004	2005	2006	2007
Total (Acres)	7,001	10,383	10,377	10,021
Source: Data from Ustin 2008.				

Control of these invasive species is difficult and challenging for several reasons.

1. The species exhibits high growth rates and large amounts of biomass accumulation.
2. Mechanical removal fragments the plants, the fragments disperse and readily multiply as new plants, and disposal of harvested plants is difficult.
3. Herbicides effective at killing the plants have risks associated with their use. To date, the only practical and successful control measure has been herbicide application.

F.4.1.1.1 Water Hyacinth

Water hyacinth is a floating perennial aquatic plant that inhabits calm backwater areas or areas with low velocities and is the dominant component of FAV in many areas of the Delta. Water hyacinth proliferates during the warmer summer months and dies back during the winter. Reproduction is by seed and vegetatively, by production of stolons and budding. Seeds sink into the sediment and can remain dormant for 15–20 years. Doubling times in surface area covered of 6 to 15 days have been reported (Harley et al. 1996). Because the plant is not rooted in the substrate, its distribution is influenced by water currents and prevailing wind. During the spring and summer, the dominant westerly winds often hold the plants against the lee shorelines or in backwaters of the Delta. In off-channel and backwater sites, hyacinth mats can become dense enough to close off open water completely. In the fall, when the seasonally predominant westerly winds decline, mats of hyacinth will float out into the main channels where they are moved about by the river and tidal currents.

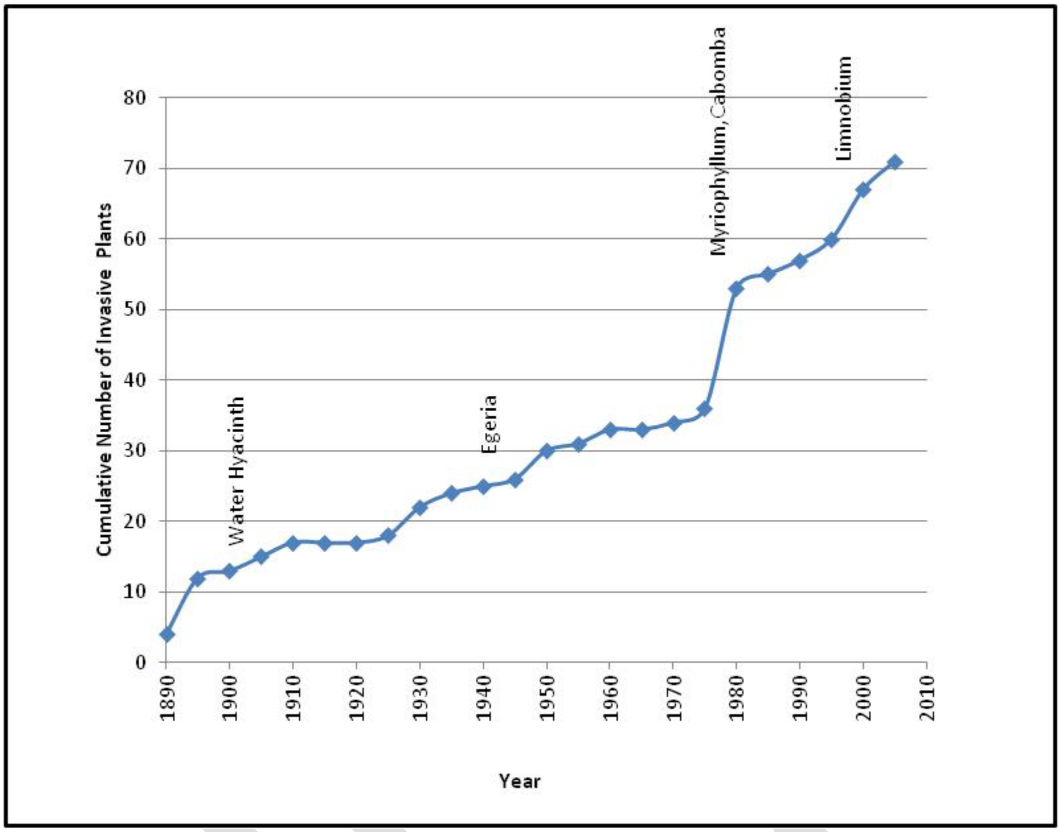
F.4.1.1.2 Other New and Potential Invasive Aquatic Vegetation

Several potential invasive IAV species are already present in the Delta, for example Eurasian watermilfoil (*Myriophyllum spicatum*), Carolina fanwort (*Cabomba caroliniana*), and curly pondweed (*Potamogeton crispus*) (Santos et al. 2009).

A very recent invader, South American spongeplant (*Limnobium laevigata*) appeared in the Delta in 2007 and was documented in 2009–2010 (California Department of Food and Agriculture 2011; Anderson and Akers 2011). This species is considered a serious threat to the Delta. Responsibility for its control has been given to California Department of Food and Agriculture's (CDFA's) Hydrilla Eradication Program, which is aggressively targeting new infestations in an effort to achieve eradication (Akers 2010). Overall, South American spongeplant is potentially a more serious threat than water hyacinth. It also has a high growth rate and spreads rapidly, but the individual plants are much smaller than water hyacinth and can be transported easily with the water currents. Additionally, it produces abundant seeds that can remain dormant in sediment. Management actions that include vigilance and early eradication before the plant becomes established are vital (Akers 2010).

Additional invasive aquatic species that have been detected elsewhere in California but are not yet known to occur in the Delta are giant salvinia (*Salvinia molesta*) and hydrilla (*Hydrilla verticillata*) (San Francisco Estuary Institute 2003). The notorious hydrilla occurs in Clear Lake, within the watershed of the Delta, and is considered such a high threat that it is targeted by CDFA for complete eradication.

Over the 50-year life of the BDCP conservation strategy, it is likely that nonnative aquatic species would continue to be introduced as they have in the past (Cohen and Carlton 1995), and it is likely that some would be invasive and could spread rapidly to become problematic, as egeria and water hyacinth already have. The introduction of new species is a continuing threat, as shown by the dates of introduction of more than 70 nonnative plant species in the Delta (Light et al. 2005). Figure F.4-1 shows graphically that the rate of invasion by nonnative plant species has been relatively constant since records began and shows no sign of decreasing.



Source: Data from Light et al. 2005.

Figure F.4-1. Cumulative Number of Nonnative Plant Species in the Delta Region

Projected increases in summer residence time resulting from climate change and the preliminary proposal (See Appendix 5.C, *Flow, Passage, Salinity, and Turbidity*) and temperatures due to climate change may increase the potential for growth of IAV in areas with appropriate environmental conditions and suitable salinities (Cache Slough, West Delta, North Delta, South Delta, and East Delta subregions).

The California Invasive Plant Council (Cal-IPC) is working to develop climate suitability modeling and range change maps for weeds listed in their inventory (California Invasive Plant Council 2011) that could help to predict which plant species could establish and spread in the Delta.; however, distribution models are not yet available for IAV species.

F.4.2 Conceptual Models, Hypotheses, and Assumptions

F.4.2.1 Conceptual Model

This section describes a conceptual model for IAV (including both SAV and FAV) based on information in the scientific literature and the draft DRERIP aquatic vegetation growth conceptual model (Anderson 2008). The conceptual model includes the primary drivers, stressors, and their effects (linkages) related to IAV and is a useful guide for generating hypotheses, highlighting uncertainties, predicting outcomes, and directing research (Figure F.4-2). The model is qualitative because quantitative information on the relationships between drivers and effects is largely lacking. The Delta is a complex interconnecting series of sloughs, channels, and basins, with salinities and flow regimes that vary in space and time, both short-term and long-term. This variability introduces uncertainty and unpredictability in evaluating effects. Recent and ongoing research in the Delta is beginning to address quantitatively some of the drivers and stressors and their effects on IAV, and on the responses of IAV species to environmental variables. The following discussion highlights these studies.

The primary drivers affecting establishment, growth, and spread of IAV are salinity, turbidity, nutrients, flow regime, and light. In terms of effects on covered fish species and ecosystem change, a primary focus has been on the interaction between water flow, turbidity, and IAV. A second set of interactions exists between the presence of invasive SAV and changes in the fish population composition.

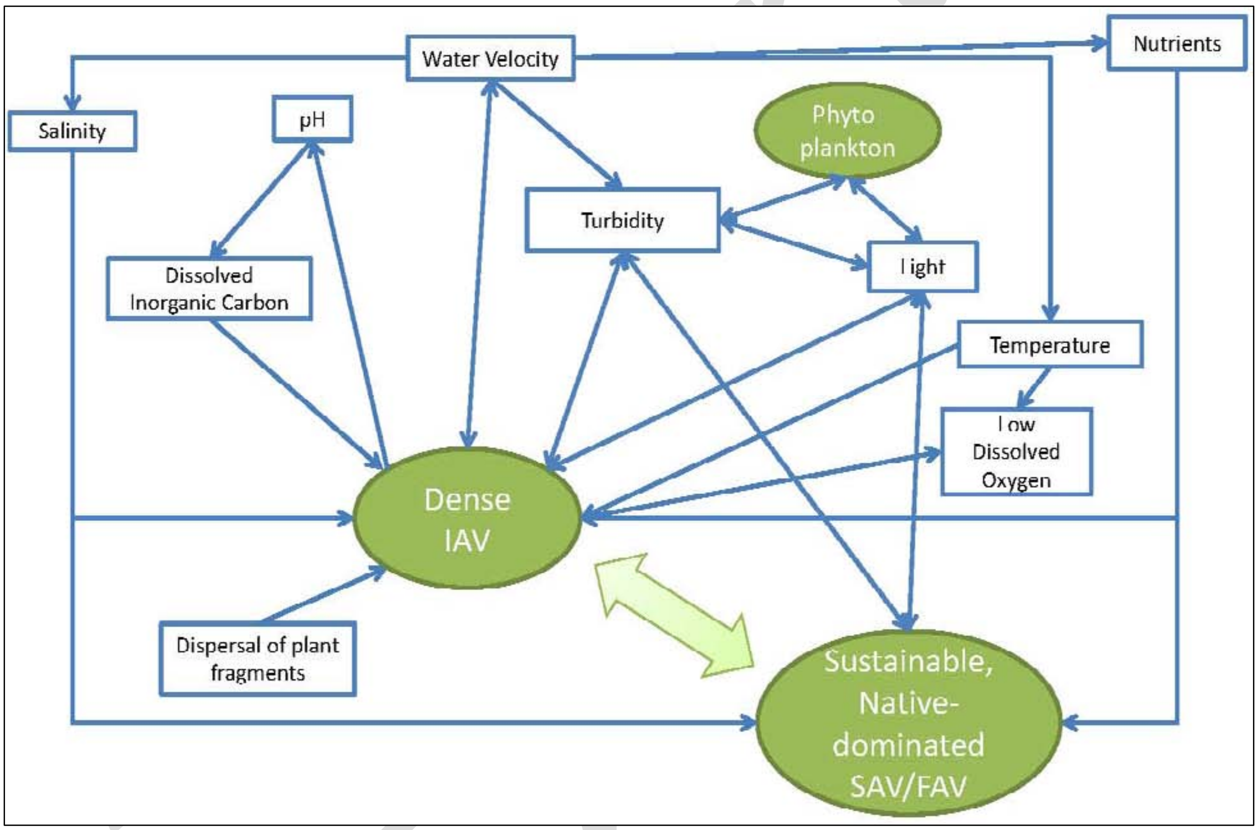


Figure F.4-2. Conceptual Model of Invasive Aquatic Vegetation in the Delta

F.4.2.1.1 Habitat for Nonnative Predatory Fish

The rapid expansion of IAV, especially egeria, has caused changes in the physical habitat and water quality that have displaced native fish and favor a foodweb more suitable for nonnative centrarchid fish, such as largemouth bass. Over recent years coincident with this expansion, there has been an increase in the abundance of nonnative fish, including predatory species, and a decline in native fish, including covered species (Brown and Michniuk 2007). Largemouth bass are the most abundant and effective predator in the areas with high SAV cover (Grimaldo et al. 2004; Nobriga and Feyrer 2007), and it is hypothesized that SAV provides habitat for largemouth bass that prey on native fish (Brown 2003; Nobriga et al. 2005). The effects of nonnative predatory fish on covered species are discussed in further detail in Section F.5.

F.4.2.1.2 Habitat Alteration by Invasive Aquatic Vegetation

Invasive SAV can act as an ecosystem engineer, defined as "organisms that directly or indirectly modulate the availability of resources to other species by causing physical state changes in biotic or abiotic materials" (Jones et al. 1994). Specifically, it fundamentally alters the aquatic environment by increasing sedimentation and reducing turbidity. The relationship between turbidity and IAV therefore is modeled as a positive feedback loop. Large dense stands of SAV reduce flow velocity and decrease water turbulence, reducing resuspension of sediments and thereby reducing turbidity (Yarrow et al. 2009; Hestir et al. 2010a, 2010b). The decreased turbidity increases the light penetration through the water column and increases growth. Surface cover of water hyacinth also impedes water flow and causes sediment to settle. This positive feedback may be an important factor contributing to the ecological regime shift (Scheffer and Carpenter 2003) that has occurred in the Delta from a turbid phytoplankton-dominated system to the current clear-water SAV-dominated state of the Delta (Baxter et al. 2010). This effect is well known to occur in shallow freshwater lakes, but it is uncertain how strong this feedback would be in the Delta because of high inputs of mineral sediment and temporal and spatial variations in flow, turbidity, and SAV distribution (Hestir et al. 2010a).

F.4.2.1.3 Physical Displacement of Native Fish Species

Dense stands of SAV physically occupy nearshore habitat and thereby displace larval and juvenile smelt and juvenile salmonids that otherwise may have inhabited the shallow-water habitat. In particular, the dense wall of egeria that grows along channel margins in the Delta prevents juvenile native fish from accessing their preferred shallow-water habitat (California Department of Boating and Waterways 2006). Dense IAV also could produce a biological barrier between nearshore open waters and tidal wetlands (Brown 2003) or along migration routes through the Delta (California Department of Boating and Waterways 2006; National Marine Fisheries Service 2007; Baxter et al. 2010) and block rearing habitat for juvenile salmon and splittail (Interagency Ecological Program 2008).

The observed decline in delta smelt occurrence in areas where invasive SAV has become established (Nobriga et al. 2005) may be related, in part, to the physical displacement of delta smelt from spawning areas. Delta smelt are thought to scatter their eggs over open substrate (Mager et al. 2004), probably spawning on or over sandy substrates at subtidal elevations (Moyle 2002). However, specific delta smelt spawning sites have never been documented in the wild, and spawning migrations are poorly understood. Invasive SAV has been documented physically occupying both the open water column over potential spawning habitat and the substrate itself. As a result, spawning delta smelt are displaced from these areas. Additionally, invasive SAV causes fine material to settle out of the water and accumulate, which could reduce the amount of suitable substrate for spawning if the accumulated material is finer-grained than the sandy substrate that may be used by delta smelt for spawning (Bennett 2005).

Less is known about spawning locations of longfin smelt, but they are known to spawn in freshwater portions of the Delta (Baxter et al. 2010). General spawning areas for both delta smelt and longfin smelt have been inferred based on the capture location of small larvae during winter/spring larval surveys. If the spawning areas of longfin smelt overlap SAV infested areas, the smelt may be displaced from those areas.

F.4.2.1.4 Changes in Water Quality

IAV can take advantage of Delta water quality conditions and trends, such as water temperatures, salinity, and nutrient enrichment. Conversely, IAV can alter water quality, including parameters important for covered fish species such as dissolved oxygen (DO), water velocity, turbidity, and nutrient flux and balance that may affect planktonic foodweb dynamics.

Salinity

Salinity is an important factor controlling invasive SAV growth in the Delta. Salinity limits the spread of egeria westward into the estuary. Egeria in its native range is a freshwater plant and tolerates salinity of up to 5 parts per thousand (ppt) (Hauenstein and Ramirez 1986). However, in laboratory conditions, shoots continued to grow at salinity of 6 ppt, although growth did show a decrease with increasing salinity (Obrebski and Booth 2003). Hauenstein and Ramirez (1986) found no growth of roots or stems at salinity greater than 10 ppt, suggesting that suppression of egeria would require salinity levels of a least 10 ppt.

Different SAV species respond differently to different salinities; for example, biomass of three species in the Delta, Eurasian watermilfoil, curlyleaf pondweed, and Canadian waterweed, was positively associated with salinity (Santos et al. 2011).

Temperature

Warm water and air temperatures in the Delta are conducive to year-round growth of IAV species. Winter temperatures low enough to limit growth are rare; although the occasional frost can damage water hyacinth leaves and cause dieback, freezing temperatures are seldom sustained long enough to kill plants. Egeria does not show winter dormancy in the Delta (Pennington and Sytsma 2009).

The effect of IAV cover and biovolume water temperature has not been quantified in the Delta, but it is likely that the reduced water flow caused by dense SAV cover could increase water temperature locally, which in turn would enhance growth of SAV. This can lead to vertical stratification of temperature in the water column (Grimaldo and Hymanson 1999; Wilcox et al. 1999). This effect may be offset to an unknown extent by the shading effect of SAV on the water column, which could decrease water temperatures. If dense IAV limits water flow between open water areas and the IAV stands, horizontal temperature gradients may develop (Stacey 2003).

Biochemistry

The role of nutrient enrichment in the high growth rates and spread of IAV is unclear. Potential links between IAV and nutrient inputs in the Delta are the subject of ongoing studies and require further research.

Alkalinity is important for some aquatic plants, especially those like egeria that can assimilate bicarbonate as an alternative source of inorganic carbon when carbon dioxide is limiting, allowing high photosynthetic rates, and hence, growth rates (Kahara and Vermatt 2003; Sousa 2011). High photosynthetic rates, in turn, deplete carbon dioxide and increase pH to high levels (Sand-Jensen 1983). Elevated bicarbonate is known to cause long-term stimulation of growth rates in egeria and similar species in laboratory and field experiments (Madsen and Sand-Jensen 1987, 1994).

In the laboratory, egeria grew significantly better at high alkalinity (500 micromoles per liter [μM/L]) than at low alkalinity (100 μM/L), alkalinity values similar to those observed in the field

(Freitas and Thomaz 2011). The observation that egeria grew faster at higher alkalinity led Freitas and Thomaz (2011) to suggest that organic carbon may limit egeria growth, and that therefore nitrogen and phosphorus may not be limiting and may be secondary in controlling growth, leading to the further suggestion that reducing nitrogen and phosphorus may not be effective in reducing egeria growth and spread.

However, elevated levels of ammonium and other nutrients may benefit IAV species such as water hyacinth (Reddy and Tucker 1983) and egeria (Feijoó et al. 2002). Studies on egeria in its native range have shown that biomass is positively correlated with ammonium in the water (Feijoó et al. 1996) and that egeria absorbed more nitrogen from the water when nitrogen was present as ammonium than when it was present as nitrate (Feijoó et al. 2002).

Dense IAV also can cause biogeochemical changes in water quality. For example, high levels of photosynthesis increase pH, leading to an increase in the toxic form of ammonia (NH_3) and an increase in the phosphate flux from sediments.

Dissolved Oxygen

Dense mats of water hyacinth produce large amounts of dead vegetative matter that decrease the DO level under the mats as they decay, and respiration of the high plant biomass causes nighttime depletion of DO (Penfound and Earle 1948; Ultsch 1973; Center and Spencer 1981), especially at high water temperatures (National Marine Fisheries Service 2006). This effect may be exacerbated by lack of water flow water-air interface mixing, leading to zones of hypoxic or anoxic water conditions (National Marine Fisheries Service 2006). In the Delta, beneath water hyacinth mats, levels have been recorded below 5 milligrams per liter (mg/L) to as low as 0 mg/L, below sustainable levels for fish (Toft 2000). These extremely low DO levels also may explain the absence of epibenthic amphipods and isopods beneath the water hyacinth canopy (Toft 2000). Dense egeria also may deplete DO levels at night (Wilcox et al. 1999).

F.4.2.1.5 Water Velocity/Flow Regime

Flow regime is an important influence on distribution of IAV. In the Delta, water velocity influences IAV distribution, limiting it to channel margins, shallow basins, and slow-moving channels. High water velocity inhibits SAV growth by physically washing plants out of the sediment, and perhaps also by scouring out the finer sediment in which SAV root. Similarly, water and wind currents control the distribution of FAV, especially the larger plants like water hyacinth. In a recent study, Hestir and coauthors (2010a) found that annual maximum water velocity limits SAV cover above 0.49 meter per second (m/s). As IAV beds expands in an area, its dense structure reduces local water velocity, which can lead to fine particles of sediment falling out of suspension from the water column.

F.4.2.1.6 Changes in Turbidity

Dense beds of egeria-dominated SAV reduce water turbidity by filtering sediment from the water column (Brown and Michniuk 2007; Yarrow et al. 2009; Hestir et al. 2010a). Recent research has shown that turbidity in the Delta has been declining gradually for several decades, and decreased in a step-wise manner in 1999 (Schoellhamer 2011). Analysis of historical turbidity data and estimates of SAV cover from 1975 to 2008 were studied to reveal any relationship over time between increasing SAV cover and decreasing turbidity across the Delta (Hestir et al. 2010b). The analysis showed that SAV cover explains an estimated 21–70% of the trend of decreasing turbidity, and turbidity declines attributable to SAV cover were greater as SAV cover increased (Hestir et al. 2010b).

Delta smelt are positively associated with highly turbid water (Grimaldo et al. 2009). The areas with the greatest extent of invasive SAV in the Delta are the channels and flooded islands of the West and South Delta subregions such as Frank's Tract, Mildred Island, Big Break, Sherman Lake, and OMR. These areas generally also have the highest water clarity in the Delta and now are used less often by delta smelt than they were historically (Nobriga et al. 2005; Feyrer et al. 2007). There is a significant relationship between turbidity and delta smelt populations in the San Joaquin region of the Delta during the summer months (Nobriga et al. 2008) and in the fall (Feyrer et al. 2011). The reduced turbidity may alter habitat for delta smelt in the central and south Delta and result in reduced use of this area by delta smelt. To successfully feed, larval delta smelt need a high turbidity level; Baskerville-Bridges and coauthors (2004) found that delta smelt were less successful feeding in clear water than in highly turbid water, although turbidity in this study resulted from phytoplankton rather than suspended sediment. It is unknown whether turbidity is important for longfin smelt feeding. Low turbidity also is associated with increased predation by nonnative fish on native fish, including covered species.

F.4.2.1.7 Changes in Nutrient Dynamics and Foodweb Structure

Dense patches of IAV may fundamentally change the foodweb in nearshore and shallow-water habitats. The sedimentation caused by IAV affects phytoplankton and zooplankton abundance by sequestering nutrients, resulting in a decrease in phytoplankton in the water column. In lakes, dense IAV has been shown to serve as a refuge from predators for zooplankton (Stansfield et al. 1997).

Dense patches of IAV block light penetration into the water column in nearshore, shallow, freshwater habitat, which can create an undesirable and anoxic habitat for diatoms, phytoplankton, and zooplankton. Consequently, these organisms are less successful in areas occupied by SAV. These organisms are the primary food of copepods, which in turn are the primary food of all life stages of delta smelt and the early life stages of longfin smelt. The presence of SAV displaces planktonic foodwebs that would occur in warm, well-lit, shallow nearshore habitats.

IAV may reduce downstream transport of organic material. The presence of IAV, especially SAV, can influence the distance that exported organic material can travel, potentially reducing transport of food resources from the upstream Restoration Opportunity Areas (ROAs) (e.g., Cache Slough, Yolo Bypass, and South Delta) to areas within the distribution of delta smelt (Kneib et al. 2008).

F.4.2.1.8 Increased Predation Risk on Covered Species

Dense stands of SAV increase the predation risk on covered species in two ways by:

1. Providing cover for nonnative predatory fish.
2. Enhancing predator foraging efficiency by decreasing turbidity.

These relationships are discussed in Section F.5.

F.4.2.1.9 Alternative Paths to Control the Spread of Invasive Aquatic Vegetation

If the underlying cause(s) of the recent rapid spread of IAV in the Delta were known, one path to controlling the spread could be to address those causes. One hypothesis is that the IAV is a symptom of recent changes in nutrient load (Glibert et al. 2011) and that shifting the nutrient load back to some pre-existing level could control IAV. Alternatively, the symptom—IAV—can be dealt with directly by removing the IAV by chemical or mechanical treatments. The nutrient shift hypotheses (Glibert et al. 2011; but see Cloern et al. 2011) is an emerging idea that is not yet well understood, and because it would be very difficult to change quickly, manipulating nutrient levels in the Delta is not a feasible method of controlling IAV. Furthermore, laboratory results show that, in egeria at least, growth may be limited by inorganic carbon shortage, suggesting that nitrogen and phosphorus may be secondary in controlling growth (Freitas and Thomaz 2011). Therefore, controlling eutrification as a strategy to reduce IAV may not be successful. In contrast, removal of IAV using mechanical, chemical, and biological means has proven effective in many cases.

F.4.2.2 Invasive Vegetation Removal Hypotheses and Assumptions

The general hypothesis is that CM13 can achieve SAV control at a magnitude sufficient to result in beneficial outcomes on water quality and covered fish species populations without significant negative effects, in particular, avoiding adverse effects from the use of herbicides.

To achieve control, the amount of IAV successfully treated must be greater than the growth and dispersal rate of the plant, or in other words, the reduction in area resulting from treatment must exceed the rate of spread. To address the potential effectiveness of the proposed CM13, it is useful to review the established DBW egeria and WHCP, in terms of the amount of area treated annually and results of post-treatment monitoring, to assess the effectiveness of treatments in relation to changes in the extent of egeria and water hyacinth. Note that eradication or complete removal from the ecosystem of these IAV species in the Delta is not considered possible, and the aim is effective control or reduction of the IAV area and biomass to the level where it no longer causes adverse effects on water quality, aquatic habitats, covered fish, and other native fish and wildlife described above.

F.4.2.2.1 Brazilian Waterweed/Egeria

This species is the main concern currently and the focus of much of the recent and current control efforts (water hyacinth, less so). To date, egeria has been the most extensive and problematic IAV in the Delta and is likely to continue to require the majority of effort and resources to achieve effective control. Based on several factors shown below, it is reasonable to express doubt that eradication of egeria in the Delta is feasible.

1. The current extent of egeria, estimated in 2007 at about 10,000 acres (Ustin 2008).
2. The current distribution of egeria, distributed over an extensive area of the Delta in sloughs, channels, and basins.
3. The biology of egeria that makes it a highly effective invader (high growth rate, tolerant of a wide variety of environmental conditions, easily fragmented and transported).
4. The inauspicious results from the first few years of the DBW egeria control efforts.

Between 2001 and 2006, DBW treated 268–622 acres per year of egeria. These amounts are lower than planned—only 1/3 of the total allowed treatment acres—because of resource limitations related to permit conditions and funding. An additional barrier to achieving effective control was permit conditions that imposed seasonal restrictions, which meant that herbicide treatment could not be started early in the season when control would be most effective (California Department of Boating and Waterways 2006).

Laboratory experiments demonstrated that growth rates were highest at the beginning of the experiment when the density of egeria was low and declined as the experiment progressed because of the increase in biomass and density, rather than depletion of nutrients or reduction in light penetration (Pistori et al. 2004). This may translate, in the favorable temperature conditions in the Delta, to a rapid regrowth of egeria after an immediate post-treatment decline, especially because it has a bi-modal growth rate in the Delta, with a second peak in growth in late fall (Pennington and Sytsma 2009). DBW found that grow-back can be significant after treatment; for example a 55% increase was recorded within 1 year at nine sites (California Department of Boating and Waterways 2006).

Estimates of the rate of spread of egeria in the Delta from 2001 to 2005 were approximately 10–20% per year (California Department of Boating and Waterways 2006; Ustin 2008); even at the low end of this estimate, if this rate continued year after year, egeria would double every 7 years. In 2006, DBW concluded that its program of herbicide treatment can be effective on a site-specific level, but it was not containing egeria in the Delta—it was not keeping up with the overall rate of spread (California Department of Boating and Waterways 2006). Because of resource limitations, the program was not able to treat enough sites across the Delta, could not treat a large enough proportion of the treated sites, and was not able to treat sites intensively enough to achieve overall control. Because of permit conditions, DBW was not able to treat egeria early in the year when treatment was known to be much more effective.

Two important changes occurred in 2006: toxicity monitoring was no longer required as a permit condition, saving $1 million/year in environmental monitoring costs; and early application in April was permitted, allowing much more effective control. Beginning in 2007, DBW instituted a 3,000-acre, 3-year, Franks Tract area management focus. The net result was a reduction in 1,500 acres of cover of egeria, a 47% reduction (Ustin 2008; Santos et al. 2009), and significant reduction in biovolume (Ruch and California Department of Boating and Waterways, Aquatic Weed Unit 2006). Additional treatment in 2008 yielded a further 50% reduction (Santos et al. 2009). Similar results were achieved at Fourteenmile Slough, a smaller site (Santos et al. 2009).

Over the Delta as a whole, an analysis of aerial imagery using revised methods gave the following estimates for aerial cover of egeria-dominated SAV: June 2005—10,382 acres; June 2006—10,025 acres; and June 2007—10,021 acres (Ustin 2008). Delta-wide, the loss between 2006 and 2007 was relatively small at only 357 acres, a 0.65% reduction, but there were large reductions at Franks Tract (1,598 acres less than 2006) and Big Break (472 acres less than 2006). These large site-specific losses were offset by continued spread throughout the rest of the Delta. These figures suggest an annual rate of increase in the order of 1,500 acres, or about 15%; this is in line with earlier DBW estimates of 10–12% increase per year (California Department of Boating and Waterways 2006).

Based on these figures, therefore, treatment of 1,500 acres would maintain the current status-quo Delta-wide, and the success of the Franks Tract special management focus in 2007 and 2008 has demonstrated that treating this number of acres is feasible and successful. CM13 proposes to treat between 1,679 acres per year (low estimate) and 3,358 acres per year (high estimate), which based on the total cover estimate of approximately 10,000 acres, would represent a 17% to 34% reduction Delta-wide, which compounded over the life of the Plan, would result in a large reduction in egeria cover. An additional consideration is the idea that the recently observed slowdown in the rate of spread of egeria is because it has occupied most of the suitable habitat (Hestir 2010 pers. comm. in Baxter 2010). However, the shallow freshwater areas created by habitat restoration under the Plan have the potential to create additional suitable habitat for IAV, and egeria in particular. In a study of three breached levee wetlands, egeria was found to be the dominant SAV species that colonized the shallow (<4 meters deep) subtidal areas (Grimaldo and others cited in California Department of Boating and Waterways 2001). Measures such as manipulation of water velocity (see Section F.2.2.1.5) could be incorporated into the design of restoration sites to reduce the risk of egeria colonization restoration sites.

F.4.2.2.2 Water Hyacinth

Water hyacinth is the second species targeted by DBW. In 1981, it covered 1,000 acres of the Delta (U.S. Army Corps of Engineers 1985). Water hyacinth mats may double in size in 6 to 15 days during the warm summer months (Harley et al. 1996). The DBW control program began in 1983. Overall, water hyacinth cover declined between 2003 and 2006 (Santos et al. 2009). In 2006, water hyacinth was estimated to cover 700 acres, almost double the area in 2005; in 2007 cover was 139 acres; in 2008, the extent of water hyacinth was below the level that could be estimated (Ustin 2008). Between 1988 and 2008, a total of 10,360 acres was treated (Santos et al. 2009), an average of 518 acres per year. The evidence suggests that the DBW program has reduced water hyacinth cover, and therefore the program can be considered successful in controlling water hyacinth across the Delta (Santos et al. 2009; Baxter et al. 2010). Evidence from both large-scale ecosystem-level studies and small-scale field experiments has demonstrated the link between turbidity and SAV. As discussed above, turbidity in the Delta has been declining gradually for several decades, while SAV has been increasing. Analysis of historical turbidity data and estimates of SAV cover has shown that the increase in SAV explains 21–70% of the trend of decreasing turbidity (Hestir et al. 2010b). Field experiments have shown that SAV can significantly reduce turbidity. For example, in one experiment using agricultural drainage water, channeling water through reservoirs stocked with SAV demonstrated that SAV reduced turbidity, i.e., decreased turbidity by 30% (Reddy et al. 1983).

F.4.3 Potential Effects: Benefits and Risks

F.4.3.1 Invasive Aquatic Vegetation Removal (Conservation Measure 13)

F.4.3.1.1 Potential Beneficial Outcomes

Reduced Predation of Delta Smelt as a Result of Increased Turbidity

The potential effects of IAV control on fish predator reduction are discussed in Section F.5.

Increased Food Consumption by Delta and Longfin Smelt due to Higher Turbidity

Removal of IAV, particularly SAV, aims to improve conditions for delta and longfin smelt by removing the aquatic vegetation associated with a decrease in turbidity. The delta smelt model (Nobriga and Herbold 2008) indicates the ability of delta smelt larvae and juveniles to see prey is enhanced by turbidity, although it is uncertain whether this depends on concentration of suspended sediment or suspended algae. The implications for longfin smelt are unclear. Removal of SAV likely would improve conditions for delta and longfin smelt by removing the aquatic vegetation associated with a decrease in turbidity. Reduced IAV would improve habitat conditions for delta smelt and perhaps improve the ability for larval fish to feed. Removal of IAV also may promote increased turbidity and reduce predator success. Longfin smelt would not be as strongly affected by this action because they occur infrequently in the central and south Delta and only during the drier years, and the time they would be in this part of the Delta would be relatively shorter and would occur when turbidity is controlled more by storm flows than by IAV. Currently, the high turbidity in the winter/spring that cues upmigration in delta smelt results from high winter inflows. Results from one relatively large removal of egeria-dominated SAV showed a small increase in turbidity, but still below the levels critical to delta smelt (Hestir et al. 2010a). It is not yet known whether larger scale IAV removal will bring larger scale increases in turbidity.

Removal of IAV also may benefit smelt by allowing nearshore foodwebs to reestablish, which may increase local planktonic food supplies for delta and longfin smelt. In the absence of IAV, primary production would shift to phytoplankton and the foodweb it supports—see Appendix 5.E, *Habitat Restoration,* for discussion of foodweb changes.

In addition, because IAV can reduce the distance exported organic material travels down through the Delta, potentially reducing transport of food resources from the upstream ROAs (e.g., Cache Slough, Yolo Bypass, and South Delta) (Kneib et al. 2008), IAV control could improve transport of productivity.

Based on current data, the beneficial outcome is expected to be small.

Reduce Predation on Juvenile Salmon, Steelhead, and Splittail by Reducing Habitat for Nonnative Predatory Fish

The potential effects of IAV control on fish predator reduction are discussed in Section F.5.

Increase Rearing Habitat for Juvenile Salmon (All Races), Steelhead, and Splittail

Currently the dense beds of egeria-dominated SAV are believed to block access to suitable rearing areas for juvenile salmonids and splittail (California Department of Boating and Waterways 2006; National Marine Fisheries Service 2007; Interagency Ecological Program 2008). Dense SAV is present in areas that would be treated under the proposed conservation measure, such as channel margin habitat, and restored areas. Removal of IAV would restore suitable habitat conditions for juvenile salmonids. A similar effect would be expected on splittail, but because they rear over a larger area and the treated SAV areas would be a smaller portion of splittail habitat, the effect would not be as strong. The removal of SAV at restoration sites would maintain the intended benefits of those sites to juvenile salmonids and splittail.

Reduced Encroachment of Submerged Aquatic Vegetation into Delta Smelt and Longfin Smelt Spawning and Rearing Habitat

Removal of IAV, especially SAV from areas of the central and north Delta known seasonally to contain delta smelt larvae, may increase habitat use for spawning. Spawning is thought to occur on or over sandy substrates at subtidal elevations, and these are the areas where SAV is found. Although little is known of the spawning areas, the extent of overlap between shallow sandy areas suitable for spawning and current dense SAV stands or areas suitable for invasion by SAV has not yet been quantified. Longfin smelt are believed to spawn and rear in areas of the Delta west of the areas currently or potentially affected by SAV, so benefits to longfin smelt spawning and rearing habitat are unlikely.

Removal of SAV may increase the amount of habitat potentially available for delta and longfin smelt in nearshore habitats of the Delta. SAV beds physically occupy nearshore habitat that may be used by larval and juvenile smelt. Depending on how delta smelt use marsh edge and shallow-water habitat, the SAV removal may or may not have a substantial effect on larval and juvenile habitat use. If larval and juvenile delta smelt do use this type of habitat and this action successfully prevents SAV from spreading or occupying habitat restoration sites and making them unsuitable for delta smelt, this benefit may be substantial, given the amount of shallow tidal habitat that would be created by the Plan. A similar effect would be expected on longfin smelt, but because of the difference in distribution and timing, the effect would not be as strong.

F.4.3.1.2 Potential Risks and/or Detrimental Effects

Potential Adverse Effects of Herbicide Toxicity on Aquatic Life Zooplankton and Phytoplankton

DBW has been using herbicide treatments to control egeria since 2001 and water hyacinth since 1983. From the start, DBW researched several different herbicides, and adjuvants where required, and application protocols. To meet the requirements of the California Environmental Quality Act (CEQA), the NMFS Biological Opinion (BiOp), and National Pollution Discharge Elimination System (NPDES) permit, DBW was required to review and summarize the results of toxicology studies on phytoplankton and zooplankton for each herbicide proposed for use in the program. DBW also was required to comply with all restrictions on timing, application methods, and concentrations required to avoid or minimize potential adverse effects on aquatic life, including phytoplankton and zooplankton. Research and monitoring results are summarized in the second addendum to the environmental impact report (EIR) (California Department of Boating and Waterways 2006). In addition, DBW undertook and funded research on potential toxic effects of herbicide treatment. During and after herbicide treatments, DBW conducted extensive water quality monitoring to monitor herbicide concentrations at and downstream from the treatment sites for residue and toxicity. All chemicals used were U.S. Environmental Protection Agency (EPA)–approved, which meant that they had undergone extensive testing and research before being labeled for aquatic use. The herbicides studied and used were 2,4-D, glyphosate, diquat, and fluridone, and the adjuvant Agri-dex. In addition, experiments were conducted with the copper-containing Komeen, but it was not used in the control programs.

Based on DBW research and field observations, fluridone is considered the most effective treatment for egeria. Based on standard criteria used by the EPA, fluridone is classified as *Practically Nontoxic* to mammals and birds, and *Slightly Toxic* to *Moderately Toxic* to fish and aquatic invertebrates. Fluridone is a contact herbicide that produces its toxic effect in plants by inhibiting synthesis of carotenes. It is slow-acting, requiring a residence time of 6 to 8 weeks to be effective. Where flow rates do not allow long enough contact, multiple applications are made. The concentrations of fluridone used in the EDCP are10 to 20 parts per billion (ppb), which is at the low end of the labeled application rates, and are well below the level that is toxic to zooplankton and phytoplankton. For daphnids, one of the most sensitive zooplankton, the acute lethal concentration 50 (the concentration in water having 50% chance of causing death) (LC-50) values are 3.6 to 6.3 mg/L, and the chronic no-observed-effect concentration (NOEC) value is 0.1 mg/L. For aquatic algae, studies suggest that levels below 50 ppb have little or no adverse effect (summarized in U.S. Department of Agriculture [USDA] Forest Service 2008). Results from water quality monitoring during and after herbicide treatment in the Delta confirmed that fluridone concentrations have been maintained within the nonlethal range for aquatic invertebrates (California Department of Boating and Waterways 2006). The application of fluridone at the concentrations used by the EDCP therefore would not decrease zooplankton. The proposed CM13 would use protocols and treatment concentrations similar to those already developed by DBW and would treat a similar amount of acres, so the effects are expected to be similar to those observed by DBW.

Potential Toxic Effects of Herbicide on Covered Fish

Sturgeon

There are no toxicity data on fluridone effects on green sturgeon. The NMFS's BiOp for the EDCP included a comprehensive review of the research on toxicity effects of fluridone on sturgeon and salmonids, including potential lethal and sublethal effects, and analyzed the potential toxic effects on juvenile sturgeon from fluridone used at the approved application concentrations (National Marine Fisheries Service 2007). NMFS concluded that the concentrations of herbicide are low enough to prevent substantial direct mortality of fish, and although secondary, sublethal effects may adversely affect the suitability of the designated critical habitat for migration and rearing of listed fish; because the herbicide use under the EDCP is in small areas and concentrations would dissipate, widespread adverse effects were not anticipated (National Marine Fisheries Service 2007). Based on these findings, and because the proposed CM13 would use protocols and treatment concentrations similar to those already developed by DBW and would treat a similar amount of acres, widespread adverse effects from implementation of CM13 are not anticipated.

Salmonids

The effects of diquat and fluridone on juvenile salmonids are sublethal and cause narcosis, rheotropism, chemical interaction, and immunotoxicity. Exposure to these herbicides can increase their vulnerability to predation and can reduce their invertebrate prey. (National Marine Fisheries Service 2006.)

Delta Smelt and Longfin Smelt

The Aquatic Toxicology Laboratory of DFG conducted toxicology tests on larval delta smelt and larval Sacramento splittail for all the herbicides and surfactant used by DBW in the EDCP and WHCP (California Department of Fish and Game, Aquatic Toxicology Laboratory 2004). Exposure levels of herbicides and surfactant measured after herbicide applications were several orders of magnitude less than the 96-hour LC-50 for larval delta smelt and splittail, except for Komeen (a copper complex no longer used) and diquat. The concentrations of diquat measured in the Delta approached the LC-50 for larval Delta smelt and splittail, and as a result, diquat would not be used when larval fish are present. The study concluded that sublethal effects were unlikely because exposure levels are much less than acute toxic levels and the herbicides are relatively nonpersistent.

These results were supported by studies conducted by the Aquatic Pesticide Monitoring Program of the San Francisco Estuary Institute (SFEI) (Siemering 2005), which derived toxicity values for a range of aquatic species from peer-reviewed academic literature, EPA registration documents, and other government reports. For Delta smelt, the NOEC was 1.28 mg/L, or 1,280 ppb, several orders of magnitude greater than the maximum treatment concentrations used in the Delta (10–20 ppb), confirming that there is a favorable margin of safety. Toxicity values for the longfin smelt are expected to be similar, with a similar margin of safety.

Potential Adverse Effects of Submerged Aquatic Vegetation Control Treatments on Water Quality

Adverse effects on water quality could result from the death and decay of large amounts of treated vegetation that could increase detritus, producing particulate organic carbon (POC), and reduced DO. This effect was addressed in DBW's EIR, which summarized research findings and proposed avoidance and minimization measures, including measuring and monitoring DO pre- and post-treatment and postponing treatment or limiting the amount of acres treated if DO fell below specific levels.

Information on water quality effects of IAV treatment comes from the water quality monitoring conducted by DBW after herbicide treatment to control both egeria and water hyacinth. Results showed that potential adverse effects on DO caused by decaying egeria were reduced by the slow-acting nature of fluridone, which results in a gradual die-off of SAV over 30 to 60 days; in addition, the flow rates through treated areas were found to replenish DO (California Department of Boating and Waterways 2006). Similar results were found after water hyacinth treatment.

Based on these findings, and because the proposed CM13 would use protocols and treatment concentrations similar to those already developed by DBW and would treat a similar amount of acres, any increase in POC and reduction in DO caused by treatment is expected to be similar to those observed after previous control treatments, and would be localized and short-term. In addition, in the BiOp, NMFS (2007) concluded that fish are expected to move away from any areas with reduced DO.

Potential Changes in Predator-Prey Dynamics

There is some potential for displacement of nonnative predatory fish from treated areas to untreated areas, and removal of egeria may increase the foraging efficiency of striped bass. These changes have the potential to increase local predation on migrating salmonids in the short term until relative distributions of predators and prey equilibrate (National Marine Fisheries Service 2007). For more information, see the discussion in Section F.5.

Potential for Other Invasive Aquatic Vegetation to Colonize after Target Invasive Aquatic Vegetation Removal

A potential risk of IAV control is that successful removal of IAV may open the door to colonization by another invasive SAV species, especially if environmental conditions have been altered to the point where native species cannot thrive and other IAV species are already present. Indeed, Santos and coauthors (2011) suggest that earlier colonization of the Delta by Eurasian watermilfoil (*Myriophyllum spicatum*) may have facilitated the later invasion of egeria, a process termed *invasional meltdown* (Simberloff and Holle 1999). Targeted removal of egeria could benefit another invasive SAV species, such as Eurasian watermilfoil or curlyleaf pondweed, or the balance could shift toward native species. Factors such as environmental variables, species biology, competition, species presence and distribution, and even plant architecture may influence replacement dynamics after successful IAV removal.

In the Delta, the pool of species that could replace dense egeria stands includes native SAV species as well as nonnative species, some of which are known to be invasive or potentially invasive. Hydrilla, a highly invasive SAV species, is not known to be present in the Delta. Growth experiments have shown that hydrilla may outcompete egeria under many conditions (Mony et al. 2007); for example, egeria had lower growth rate at high alkalinity than hydrilla (Kahara and Vermaat 2003 and others cited therein), suggesting that egeria appeared to be less effective at using bicarbonate than hydrilla.

An extensive survey of SAV in the Delta conducted in 2007–2008 showed that SAV in the Delta is composed of a mix of native and nonnative SAV species, albeit strongly dominated by egeria (Santos et al. 2011). Nonnatives included some potentially invasive species, as rated by Cal-IPC (2011): Eurasian watermilfoil (rated high), curlyleaf pondweed (*Potamogeton crispus*; rated moderate), and Carolina fanwort (*Cabomba caroliniana*; not rated by Cal-IPC) (Santos et al. 2011). Native SAV species included coontail (*Ceratophyllum demersum*), Canadian waterweed (*Elodea canadensis*), longleaf pondweed (*Potamogeton nodosus*), sago pondweed (*Stuckenia pectinata*), and broadleaf sago pondweed (*Stuckenia filiformis*).

Environmental factors may influence succession because tolerances and responses to different environmental variables vary between species. For example, Canadian waterweed is known to be depth-tolerant (Nichols and Shaw 1986), and in the Delta, it had a higher biomass at greater depth (Santos et al. 2011). Additionally, like other native SAV species, it is less tolerant of higher water temperatures (Santos et al. 2011) and does not compete well with nonnatives that grow better at higher temperatures (Nichols and Shaw 1986). Three species in the Delta, Eurasian watermilfoil, curlyleaf pondweed, and Canadian waterweed, grew better at higher salinity levels (Santos et al. 2011).

Removal of FAV may improve habitat conditions for SAV: in a presentation aptly titled, “Better the devil you know than the devil you don’t: submerged aquatic weed invasions in South Africa,” Coetzee (2009) suggests that sites with dense nonnative FAV cover may be resistant to invasive SAV, but removal of FAV cover can allow nonnative SAV to invade. There is some evidence from the Delta that the successful removal of water hyacinth has created habitat for SAV, including egeria—surveys showed that 14% of the area cleared of water hyacinth became dominated by SAV or other FAV and emergent species (Santos et al. 2009). Removal of water hyacinth also could create vacant water surface that could allow a recent invader, South American spongeplant, to establish and spread.

In previous years, it appeared to be egeria that recolonized treated areas (California Department of Boating and Waterways 2006), but in 2007, the SAV species composition did shift to other species, including natives (Santos et al. 2009). Observations from the Delta also suggest that each year there are shifts in cover in both directions between SAV and water hyacinth on the order of 6% to 30%, suggesting that single-species management may not be the optimal approach (Santos et al. 2009).

F.4.3.2 Recreational Users Invasive Species Program (Conservation Measure 20)

Under *CM20 Recreational Users Invasive Species Program,* the BDCP Implementation Office will fund actions to reduce the invasion of nonnative invasive species into the Plan Area. Funding will be provided to implement the DFG Watercraft Inspection Program in the Delta.

One important component of an integrated invasive plant program is prevention, which incorporates regulatory authority, risk analysis, knowledge of introduction pathways, and inspections. Invasive aquatic plants such as egeria and hydrilla (not yet known to occur in the Delta) can be fragmented and spread by boats and trailers moving between watersheds (California Department of Fish and Game 2008). Controlling the introduction of such invasive aquatic plant species, or the further spread of any existing nonnative aquatic plant species, thereby would benefit aquatic natural communities in the Plan Area.

F.4.3.2.1 Benefits and Risks

The boat inspections will direct effort to one of the important routes by which IAV species are moved between water bodies. In addition, the inspections and related public education will inform the public on the threats posed by IAV and how to recognize them, thus increasing the level of vigilance.

F.4.4 Uncertainties and Research Needs

F.4.4.1 Uncertainties

Uncertainties of effects are related to both lack of knowledge, which can be addressed by research, and unpredictability, which results from the highly variable and complex nature of the Delta ecosystem.

F.4.4.1.1 Potential for Success

This discussion will review control efforts to date for egeria and water hyacinth in the Delta, and examples of other existing and potential IAV species to attempt to answer the question: Can IAV in the Delta be effectively controlled?

Egeria

The history of control efforts for egeria in the Delta and the increase of egeria-dominated SAV over the years were discussed in Section F.4.2.2.1. In summary, the early years of the DBW EDCP were limited by resources, rather than by biological or ecological factors, and coincided with the rapid expansion of egeria throughout the Delta at an annual growth of about 10–15%—the program appeared to be too little, too late and was not gaining ground against a rapidly expanding target. However, the success of the Franks Tract management focus in 2007–2008 shows that effective control of quite large areas is possible, and significant reductions in SAV cover were achieved, although this was offset by continuing spread elsewhere. However, there is a suggestion that egeria may be slowing down, perhaps because it is close to occupying most of the suitable habitat in the Delta.

Assuming a continued 10% annual growth rate, the acreage that would need to be treated to maintain the status quo would be about 1,000–1,500 acres per year, slightly less than the low estimate of the proposed treatment acreage under CM13, which at 1,679 acres, would represent a 17% reduction in the current acreage of SAV. The high estimate, 3,358 acres/year would represent a 34% reduction, which would make significant inroads into the current SAV acreage.

Water Hyacinth

The history of control efforts for water hyacinth in the Delta and its increase over the years were discussed in Section F.4.2.2.2. From a high of 1,000 acres in 1981, just before the DBW control program began, water hyacinth was reduced to an estimated 139 acres in 2008, and the program can be considered successful in controlling water hyacinth across the Delta (Santos et al. 2009; Baxter et al. 2010).

Hydrilla

The absence of hydrilla from the Delta now is a testament to the success of CDFA's aggressive Hydrilla Eradication Program, which is mandated to eradicate, not control, hydrilla in California. This approach was determined necessary to protect the state's water systems from the environmental and economic effects of this highly invasive species. After each hydrilla outbreak, a Hydrilla Science Advisory Panel is convened; these panels have always found eradication to be feasible (Akers 2010). To date, there have been 29 hydrilla introductions and 20 successful eradications; no new infestation have been found since 2005 (Akers 2010). The Hydrilla Eradication Program uses an integrated pest management, with manual removal, small-scale dredging, lining of water bodies, biological control, and aquatic herbicides.

One of the largest infestations in California is in Clear Lake, which is connected hydrologically to the Delta, and like the Delta has a high level of recreational boat use, so there is potential for hydrilla to spread to the Delta via both routes. Covering 739 acres of Clear Lake at its worst, after several years of herbicide treatment and intensive surveys, by 2010 only a handful of plants was detected.

Aware of the threat to the Delta (Leavitt 2002), and committed to early detection and rapid response, CDFA since the mid-1980s has conducted an annual survey of the Delta and lower reaches of tributaries for hydrilla. The surveys are extensive and thorough—larger waterways, such as OMR, major canals, and many of the major sloughs, are surveyed from motorboats; marinas, launch ramps, and some of the smaller channels and sloughs are surveyed by canoe, kayak, or airboat. No hydrilla has been detected.

The success of the hydrilla program shows that, given the legislative authority, sufficient and consistent resources, and effort, in partnership with several cooperating agencies and organizations, eradication of a highly invasive aquatic weed is possible.

South American Spongeplant

This potential invader first was detected in 2004 in the San Joaquin River in Fresno County and immediately was recognized to present a significant threat, similar to water hyacinth but with a higher ability to reproduce and spread (Akers 2010). Its ability to produce abundant seed that can remain viable for several years and tiny seedlings that are easily moved by water currents makes early detection and rapid response very important for this species, eradicating small infestation before they can reproduce and spread is vital. Monitoring and control have been aggressively implemented by giving responsibility for spongeplant to the Hydrilla Eradication Program. Since 2004, small infestations have appeared around the state. In late December 2007, a patch of spongeplant was found on the east edge of Decker Island on the Sacramento River. A winter storm appeared to have eradicated the patch, but it reappeared in 2009 and has been spreading slowly east and south.

Other Species

The combined knowledge, experience, and vigilance of the various agencies, research organizations, and weed control programs in and around the Delta—DBW, USDA-Agriculture Research Service (ARS), CDFA, Center for Spatial Technologies and Remote Sensing (CSTARS), and the Bay Area Early Detection Network (BAEDN), a partnership of regional land managers, invasive species experts, and concerned citizens—enable rapid detection and effective early response to any new Delta invader.

In addition, CM20 should be effective in preventing new IAV species from gaining a foothold in the Delta.

F.4.4.1.2 Overlap of Delta and Longfin Smelt and Invasive Aquatic Vegetation–Infested Areas

One of the uncertainties is the extent of overlap between the distribution of covered smelt species and the areas of dense IAV infestation. The central distribution of small delta smelt ranges from about 70 to 130 kilometers (km) from the Golden Gate from April through July and for large delta smelt, 75–100 km from May through July (Dege and Brown 2004). Larval and juvenile delta smelt have been collected from nearshore habitats, including marsh edge and offshore habitats in the low salinity zone (LSZ) (Grimaldo et al. 2004; Bennett and Burau 2011); however, other studies indicate that juvenile delta smelt are found predominantly in open channel areas and are not found near shore (Nobriga et al. 2005).

The distribution of longfin smelt is more westerly and occurs for a shorter time period; small longfin smelt are located about 60 to 90 km from the Golden Gate from April through May and large longfin are located 50 to 85 km from the Golden Gate from April through July (Dege and Brown 2004). Although longfin smelt use areas in the lower Sacramento and San Joaquin Rivers, they spawn earlier than delta smelt and do not remain in this part of the Delta nearly as long as do delta smelt (Nobriga et al. 2004). IAV occurs in less saline areas, e.g., upstream of the Antioch area (about 85 km from the Golden Gate). These distributional patterns indicate that removal of SAV would tend to have a stronger effect on delta smelt than on longfin smelt.

F.4.4.1.3 Overlap of Salmonids and Invasive Aquatic Vegetation–Infested Areas

Prioritization of areas for treatment can be improved with better understanding of the relative distribution and habitat use by juvenile salmonids in the Delta. Juvenile salmonids use the Delta both as a migration corridor and as rearing and foraging habitat. Mortality of juvenile salmon is high in Cache Slough (Perry and Skalski 2009), but that may be mitigated by IAV removal leading to decreased predator abundances. Extensive SAV infestations in main migration pathways likely increase predation risk. The Delta Passage Model (DPM) (see Appendix 5.C, *Flow, Passage, Salinity, and Turbidity*) and radio telemetry studies (e.g., San Joaquin River Group Authority 2011) could be used to identify important migration corridors or channel reaches with high losses. Consideration should be given to treating areas of high use by covered species and high risk for fish loss.

F.4.4.1.4 Post-Treatment Conditions

Foodweb

The effects on the foodweb of removing IAV are uncertain. Removal of dense IAV may change productivity or food availability for covered species. The productivity of egeria and its contribution to the foodweb as a primary producer in the Delta are largely unknown. It probably serves as a substrate for epiphytes that are part of the foodweb, and two of the amphipods that live in egeria are important food for native fish (Grimaldo et al. 2009), but because native fish do not use dense egeria beds, this food source is functionally unavailable. Water hyacinth in the Delta supports a distinct assemblage of invertebrates that lived epiphytically on the roots and leaves and provide food for fish (Toft 2000). Removal of water hyacinth would remove the habitat for these invertebrates. Toft

(2000) found differences in the invertebrate assemblages on water hyacinth and on a native FAV plant, water pennywort (*Hydrocotyle umbellata*), with water hyacinth supporting a higher density of a nonnative amphipod not prevalent in fish diets and water pennywort supporting a higher density of a native species of amphipod favored by fish. The research evidence suggests that native SAV and FAV species may support a higher proportion of native invertebrates that are favored by native fish. This suggests that a shift from nonnative to native SAV/FAV would change the invertebrate assemblage and therefore affect organisms higher up the foodweb.

Succession/ Replacement Dynamics

There is uncertainty about which aquatic plant species, native or nonnative, could colonize the newly treated habitat. Egeria is capable of reinvading treated areas (California Department of Boating and Waterways 2006).

Several native and nonnative SAV and FAV species are known to be present in the Delta. Native SAV species include coontail (*Ceratophyllum demersum*), longleaf pondweed (*Potamogeton nodosus*), sago pondweed (*Stuckenia pectinata*), and broadleaf sago pondweed (*Stuckenia filiformis*).Native FAV species include pennywort (*Hydrocotyle* spp.), waterfern or azolla, and duckweed. Nonnative species, most of which are known to have invasive potential as evaluated by Cal-IPC (2011), include parrotfeather (*Myriophyllum aquaticum*; rated high-alert); Eurasian watermilfoil (*Myriophyllum spicatum*; rated high), curlyleaf pondweed (*Potamogeton crispus*; rated moderate), and Carolina fanwort (*Cabomba caroliniana*; not rated by Cal-IPC) (Santos et al. 2011). A very recent invader, just at the point of becoming established in the Delta, is South American spongeplant (*Limnobium laevigatum*; rated high-alert by Cal-IPC) (Akers 2010).

There is some anecdotal evidence that native aquatic plants are able to colonize treated areas; for example, pennywort may colonize areas where water hyacinth has been removed or died back (Toft 2000), and sago pondweed may be able to reestablish quickly from tubers after herbicide treatment has killed other SAV species (Ruch and California Department of Boating and Waterways, Aquatic Weed Unit 2006; Santos et al. 2009). There is also evidence, however, that egeria may move into areas where water hyacinth has been removed (Santos et al. 2011).

Physical properties of the different species may affect how they interact. Coontail was the second most abundant species in the 2007–2008 survey, and was found to co-occur frequently with egeria. It grows entwined in the canopy of other species rather than anchored in the sediment—egeria may provide suitable anchoring structure, whereas the narrow-leaved native sago pondweed may not provide effective anchoring (Santos et al. 2011).

Sago pondweed is a native SAV species that forms beds in Suisun Marsh and the West Delta in conditions of higher salinity than the egeria-dominated SAV of the central Delta. Sago pondweed has an open canopy and filiform architecture and presents less resistance to flow than egeria and therefore is unlikely to reduce turbidity; in addition, it provides suitable habitat for native fish and does not harbor predatory fish. Research is being initiated into the factors that control its distribution and growth, especially the role of salinity in controlling the distribution of native versus nonnative SAV (Boyer 2010).

Turbidity

The amount of sediment reaching the Delta has decreased in the latter half of the twentieth century (Wright and Schoellhamer 2004; Cloern et al. 2011). This suggests that, despite removal of egeria, turbidity levels may not be increased to pre-infestation levels simply because overall sediment input is lower, and as a result, the desired state change from a low turbidity–high SAV state to a high turbidity–low SAV state may not be achieved.

Although there are no field experiments to demonstrate cause and effect, there are some recent data that directly address this point using measurements of turbidity before and after herbicide treatment to remove egeria in the Delta. Measurements of turbidity and SAV cover were taken at Franks Tract before and after the treatment of 3,000 acres in 2007 (Hestir et al. 2010a). Between 2006 and 2007, the data were equivocal, with a marked reduction in SAV but no corresponding increase in turbidity. However, between 2007 and 2008, there was a further reduction in SAV cover of an order of magnitude and a corresponding increase in turbidity, from 5.1 nephelometric turbidity units (NTU) to 8.3 NTU. This observation is an indication that SAV removal could result in an increase in turbidity, but the resulting turbidity did not reach the levels critical for delta smelt; for example, it does not reach the 12–15 NTU level that cues spawning migration (CALFED Bay-Delta Program 2009 cited in Hestir et al. 2010a).

Microcystis

One recently emerged uncertainty is the effect of SAV removal on blooms of blue-green algae (also called cyanobacteria), and especially the effect of herbicide treatments on the relationship between phytoplankton and *Microcystis aeruginosa* (microcystis). Microcystis is a cyanobacteria that produces a biological toxin called microcystin. Microcystis can reach very high densities ("algal bloom") in the Delta that may negatively affect phytoplankton, zooplankton, and covered fish species (Lehman et al. 2008, 2010; Ger et al. 2009; Acuna et al. 2011).

SAV removal could affect microcystis blooms primarily in three ways.

1. The relative toxicities of the herbicides to phytoplankton and microcystis could affect the relationship between the two.
2. The decay of large amounts of dead SAV/FAV has a short-term effect on water quality and nutrient balance.
3. In the long-term, the effect of SAV removal could affect microcystis through its effects on changes in water quality, particularly nutrient loads and ratios.

This discussion will focus on fluridone because currently it is the preferred herbicide in use in the Delta to control egeria, which is the main IAV species of concern at this time. Any other herbicide proposed for use would have to be analyzed with regard to its effects on phytoplankton and blue-green algae.

Experimental results are somewhat contradictory on the effects of fluridone on phytoplankton: several early studies showed that phytoplankton were unaffected by fluridone treatment, whereas others showed toxic effects on both phytoplankton and blue-green algae (reviewed in Struve et al. 1991). However, it appears that fluridone applied at the concentrations used in the Delta (typically 10–50 ppb) does not have an adverse effect on phytoplankton and blue-green algae or affect the phytoplankton community structure. If this holds true in the Delta, adverse effects on microcystis would not be expected.

The decay of large amounts of IAV after control treatment has the potential to cause substantial releases of nitrogen, carbon, and phosphorus, which could trigger rapid growth of microcystis. However, post-treatment monitoring in the Delta has shown that the treatments used to control egeria do not produce a sudden release of nutrients because of the slow effects of fluridone—egeria dies and decays slowly over the course of several weeks and nutrient releases therefore are gradual without adverse effects on water quality (California Department of Boating and Waterways 2006). Although shredding of water hyacinth in the Delta produced a large amount of decaying plant matter and short-term increases in nitrogen and phosphorus, local effects varied depending on site-specific hydrology and broader effects were limited (Greenfield et al. 2007). These results suggest that this effect of SAV control would not have adverse effects on water quality that would affect microcystis.

The changes in nutrient concentrations in the Delta, particularly elevated ammonium levels, that are thought to lead to conditions favorable to IAV (Feijoó et al. 2002) are also thought to favor microcystis (Glibert et al. 2011) and contribute to a decline in phytoplankton (Jassby et al. 2002). However, recent surveys in the Delta have shown that low water velocity and high water temperature were strongly correlated with the seasonal variation of microcystis cell density, leading Lehman and coauthors (2008) to suggest that "nutrient concentrations and ratios were of secondary importance in the analysis and may be of lesser importance to seasonal variation of the bloom in this nutrient rich estuary." Thus, to the extent that IAV removal, particularly SAV, would affect nutrient ratios, water velocity, and water temperatures, it seems possible that SAV removal would not have led to an increase in microcystis. An additional consideration is that the high photosynthetic activity in dense SAV beds leads to high pH, of which microcystis is more tolerant than phytoplankton is. Therefore, removal of SAV may alleviate high pH conditions that favor microcystis.

A synthesis of these various factors and how they interact to affect microcystis blooms awaits more detailed information. The factors affecting microcystis blooms, particularly nutrient balance, pH, salinity, water flow, and temperature, require further research.

F.4.4.2 Research Needs

F.4.4.2.1 Ecology and Biology of Invasive Aquatic Plant Species in the Delta

Knowledge of seasonal growth rates, phenology, reproduction, and resource allocation of the major IAV species of concern in the Delta provides guidance on the most effective methods and times of the year for control treatments, aiming to apply control methods when the plants' ability to recover is lowest. Recent and ongoing research on egeria (e.g., Pennington and Sytsma 2009) and water hyacinth (Spencer and Ksander 2005) have provided useful information in that regard—for example, knowing that egeria in the Delta has a secondary growth peak late in the season and does not die back in the Delta's mild water temperatures (Pennington and Sytsma 2009), surveys in the fall are effective in identifying concentrations of egeria to target in early spring treatments (Santos et al. 2011).

Continuing research on biological control is required to alleviate the concerns about toxicity effects of herbicide use. Biological control has been successful against water hyacinth, particularly in the southeast United States (Center et al. 2002). The CDFA released water hyacinth–eating weevils (*Neochetina eichhorniae* and *N. bruchi*) and a moth (*Sameodes albiguttalis*) at selected sites in the Delta. Only *N. eichhorniae* established but survived at densities too low to affect water hyacinth, in part because of cool winter temperatures (California Department of Boating and Waterways 2003), and perhaps because of pathogens; additional studies are needed to investigate whether they have been infected by a pathogen.

DBW recently began releasing the water hyacinth water hopper (*Megamelus scutellaris*) at three sites in the Delta (California Department of Food and Agriculture 2011). A fungus isolated from egeria in its native range, a species of fusarium, has shown promise in laboratory experiments but has not yet been tested under field conditions. USDA-ARS is evaluating the potential of a leaf miner (*Hydrellia* spp.) as a biological control agent for egeria in the Delta.

One of the risks associated with biological control is that the organism may attack closely related native species. The weevils prey on all members of the pickerelweed family (Pontederiaceae), but all but one species in California is nonnative, and the only native species, grassleaf mudplantain (*Heteranthera dubia*) does not occur in the Delta; the closest known occurrence is in Colusa County (Calflora 2012).

F.4.4.2.2 Performance/Efficacy Monitoring

Recent and current research should continue to investigate improved methods of surveying and measuring the extent of IAV infestations before and after herbicide treatment to provide fast and efficient survey over large areas. Methods that provide results quickly would be an important part of an adaptive management program that would track the effectiveness of each treatment and help to decide whether follow-up treatments were necessary. Recent innovations include the use of 2.8-meter resolution multispectral satellite imagery that can quickly provide estimates of the areal extent of egeria and water hyacinth over large areas of the Delta and sonar transducer surveys to assess the biovolume of egeria in the water column.

Post-treatment monitoring programs also should focus on two major areas relevant to the adverse effects of IAV on covered fish populations: turbidity and nonnative predatory fish.

In addition to measurements of water quality, monitoring should include surveys before and after treatment to determine the abundance and distribution of nonnative predatory fish. Sampling sites for a treated region should include vegetated areas to be treated (before and after), untreated areas, and nonvegetated sites to examine whether predatory fish population abundance and/or local distribution has changed.

Post-treatment monitoring should be designed to detect microcystis blooms and relate that to water quality and hydrodynamic parameters. Finally, long-term monitoring should track the development and succession of the aquatic plant community and the fish assemblage that develops following treatment.

F.4.5 Conclusions

The control of invasive submerged aquatic vegetation (Conservation Measure 13) should reduce predation mortality of covered fish species by removing habitat for predators and increasing turbidity.

IAV control should benefit covered fish species that use shallow-water habitats (habitats prone to IAV growth) like salmonids and splittail, but should have less effect on pelagic fishes like delta smelt and longfin smelt. Removal of IAV likely would improve conditions for delta smelt by removing the aquatic vegetation associated with a decrease in turbidity. Increased turbidity is associated with improved concealment for delta smelt to avoid detection from mainly visual predators like largemouth bass and striped bass. Turbidity in the Delta is lower than it was 30–40 years ago, and decreasing turbidity in the Delta has constrained the distribution of juvenile and possibly spawning delta smelt. The smelt probably avoid overly clear water and thereby reduce risk of predation, but it may be that smelt in too-clear water are eaten.

Control of IAV, and especially SAV, is expected to enhance natural community ecosystem functions by removing ecologically dominant invasive species. Dense SAV provides suitable habitat and cover for nonnative predatory fish, especially centrarchids that prey on juvenile salmon and steelhead. Predation on juvenile salmon, steelhead, and splittail in the migration corridor can be significant; for example, it is well-documented that juvenile Chinook salmon experience predation by largemouth bass lurking in SAV. Controlling invasive SAV is expected to reduce the population of nonnative predatory fish.

The control of invasive submerged aquatic vegetation (Conservation Measure 13) should increase food consumption by covered fish species.

Food consumption by delta smelt and longfin smelt larvae and juveniles is expected to increase because of the increased turbidity that would result from removing or reducing SAV. The delta smelt conceptual model indicates that the ability of delta smelt larvae and juveniles to see prey organisms in the water is enhanced by turbidity, and that delta smelt larvae require turbidity to initiate feeding—the larvae do not feed in water that is too clear. The role and importance of turbidity for longfin smelt feeding efficiency are not as well-known as they are for delta smelt. The amount of overlap between SAV treatment areas and delta smelt and longfin smelt food areas is uncertain and may be low; however, although areas currently occupied by SAV are not suitable for delta smelt, removal of SAV helps to restore suitable habitat conditions.

Control of IAV and the restoration of native aquatic plant communities in treated areas are expected to increase the quantity and quality of habitat suitable for some prey resources (such as crustaceans, annelids, mollusks, fish, and midges) important to green and white sturgeon.

Removal of dense stands of IAV is expected to increase food availability for delta and longfin smelt near treatment locations by increasing light levels below vegetation. Dense IAV blocks light penetration into the water column. IAV control allows greater light penetration in the water column, leading to greater phytoplankton productivity, which in turn leads to greater productivity of zooplankton that constitute prey for a variety of covered fish species, primarily smelts and juvenile salmonids. Dense IAV canopies reduce light penetration through the water column more than would the anticipated increases in water turbidity resulting from SAV removal, and as a result, it is anticipated that IAV removal would lead to an increase in phytoplankton productivity. SAV removal and control thus would lead to a net increase food availability for these covered fish species.

The control of invasive submerged aquatic vegetation (Conservation Measure 13) should increase the amount of spawning and rearing habitat for covered fish species.

Dense patches of SAV physically obstruct covered fish species' access to habitat for spawning and rearing. Removal of SAV is expected to increase the availability of freshwater spawning habitat for longfin smelt in the Delta (spawning occurs where average water temperatures are 10–12°C from mid-December to April). There is no indication, however, that the delta smelt population is limited by the amount of suitable spawning habitat area because they spawn throughout the Delta in different years. For river and Pacific lamprey, SAV removal is expected to increase the availability of suitable existing tidal mudflat and channel margins that support larval settlement and development. Removal of dense stands of egeria from channel edge and shallow-water habitats is expected to increase the amount of suitable rearing habitat for juvenile salmonids and splittail.

Funding efforts that prevent the introduction of new invasive species (CM20) would benefit covered fish species in the Plan Area. A key component of an integrated aquatic invasives program is prevention, which incorporates regulatory authority, risk analysis, knowledge of introduction pathways, and inspections. Specifically, efforts that prevent the transport of invasive species by requiring recreational boats to be properly cleaned, drained, and dried after leaving a water body that could harbor invasive plant species are considered beneficial.

The boat inspections will direct effort to one of the important routes by which IAV species are moved between water bodies. In addition, the inspections and related public education will inform the public of the threats posed by IAV and how to recognize them, thus increasing the level of vigilance.

F.5 Fish Predation

Although predation is a natural part of aquatic community dynamics, increased predation rates by nonnative fish species has been identified as a stressor for BDCP covered fish species, especially delta smelt (Baxter et al. 2008), steelhead (Clark et al. 2009; National Marine Fisheries Service 2009), and juvenile Chinook salmon (Good et al. 2005; Moyle 2002; National Marine Fisheries Service 2009). Elevated predation rates are a potential indirect effect of water diversion operations (Brown et al. 1996) and a potential hindrance to shallow-water habitat restoration (Brown 2003; Nobriga and Feyrer 2007). Modeling by Lindley and Mohr (2003) suggested that increases in the striped bass population could substantially reduce the population viability of winter-run Chinook salmon. Statistical modeling by MacNally and coauthors (2010) documented a weak negative relationship for largemouth bass and delta smelt. Delta smelt life cycle modeling also points to predation as a negative factor (Maunder and Deriso 2011) (see also Appendix 5.G, *Fish Life Cycle Models)*. The functional response of fish populations to predation pressure, however, is not easy to predict and is likely to vary depending on species and ecological context (Mather 1998; Durand 2008; Nobriga et al. 2011).

F.5.1 Ecological Effect Pathways

Predatory fish species of particular concern in the Delta are striped bass (*Morone saxatilis*), largemouth bass (*Micropterus salmoides*), and Sacramento pikeminnow (*Ptychocheilus grandis*). Nobriga and Feyrer (2007) found numerous invertebrate and fish taxa in the diets of these common species. At least 13 additional species of predatory fishes occur in the Delta (Table F.5-1.). Many of these species, including striped bass and largemouth bass, are nonnative. Striped bass and "black bass" (largemouth bass and other *Micropterus* species such as spotted and redeye bass) support important recreational fisheries in the Delta (Lee 2000; Conrad et al. 2010).

Table F.5-1. A List of Potential Piscivorous (Fish-Eating) Fish Species Reported from the Delta

Common Name	Scientific Name
Sacramento pikeminnow	*Ptychocheilus grandis*
Striped bass	*Morone saxatilis*
Largemouth bass	*Micropterus salmoides*
Smallmouth bass	*Micropterus dolomieu*
Spotted bass	*Micropterus punctulatus*
Redeye bass	*Micropterus coosae*
Black crappie	*Pomoxis nigromaculatus*
White crappie	*P. annularis*
Bluegill	*Lepomis macrochirus*
Green sunfish	*L. cyanellus*
Redear sunfish	*L. microlophus*
Warmouth	*L. gulosus*
Hybrid sunfish	*Lepomis* spp.
Brown Bullhead	*Ameiurus nebulosus*
White catfish	*A. catus*
American shad	*Alosa sapidissima*
Sources: Cavallo et al. in press; Miranda et al. 2010.	

Striped bass is a pelagic anadromous species that was introduced to the Delta in 1879. The Delta population is in major decline (Baxter et al. 2008), having collapsed from about 1.5 million fish in 2000 to about 500,000 fish in 2007 (California Department of Fish and Game 2012). The striped bass is the most broadly distributed and abundant large piscivorous fish in the Plan Area, although it tends not to use habitats occupied by aquatic vegetation (Nobriga and Feyrer 2007). The diet, both historically (1963–1964, before declines of delta smelt and Chinook salmon) and more recently (2001, 2003) is dominated by mysid shrimp, amphipods, threadfin shad, other striped bass, and infrequently Chinook salmon and smelt (Stevens 1966; Nobriga and Feyrer 2008). Striped bass is a generalist predator that can switch prey depending on predator size and prey availability, often focusing on more abundant or easily captured prey (Nobriga and Feyrer 2008). Striped bass and largemouth bass are known to prey on juvenile Chinook salmon, juvenile steelhead, delta smelt, and Sacramento splittail (Stevens 1966; Moyle 2002; Nobriga and Feyrer 2007, 2008). However, these covered species make up only a small proportion of these predators' overall diet. Inland silverside and threadfin shad, two common nonnative fishes in the Delta, occur more frequently in striped bass diets (Nobriga and Feyrer 2008).

Adult striped bass often congregate near screened diversions, feeding on concentrations of small fish, especially salmon. Striped bass are a major cause of mortality of juvenile salmon and steelhead near the SWP south Delta diversions (Clark et al. 2009).

Striped bass spawn in large, nontidal tributaries. Most spawning occurs in the Sacramento River, from above Colusa (about River Kilometer 195) to below the mouth of the Feather River (about River Kilometer 125). Spawning bass may be attracted to large outflows of agricultural return water from Colusa Drain. During wet years, spawning may take place in the Sacramento River portion of the Delta. In the San Joaquin River, successful spawning upstream of the Delta occurs mainly during years of high flow, when the large volume of runoff dilutes salty irrigation wastewater that normally makes up much of the river's flow. In years of lower flow, spawning occurs in the Delta itself. Because of interactions among these factors, there are two main spawning areas in the Delta: the Sacramento River from Isleton to Butte City and the San Joaquin River and its sloughs from Venice Island down to Antioch (Moyle 2002). After spawning, striped bass eggs and larvae are transported to the LSZ of the estuary by river currents. Striped bass that are 1 year old and older occur throughout the Bay-Delta and in adjacent freshwater and marine habitats.

Largemouth bass are a freshwater nearshore fish that cannot successfully reproduce in brackish water (Nobriga and Feyrer 2007). Largemouth bass were introduced to the Bay-Delta watershed in the late nineteenth century. Largemouth bass prefer warm, shallow waters of moderate clarity and beds of aquatic vegetation. Their numbers have increased recently, associated with expansion of IAV beds and increasing water clarity (Nobriga and Feyrer 2007; Conrad et al. 2010). Adult bass are solitary hunters that may either range widely or remain in a relatively restricted area centered around a submerged rock or branch (Moyle 2002). Nobriga and Feyrer (2007) concluded that largemouth bass may have the highest per capita effect on nearshore fishes, followed by striped bass and then pikeminnow. This estimate is based on the greater frequency and number of native fish in largemouth bass stomachs and their conversion to a fish diet at a small size (Nobriga and Feyrer 2007).

The native Sacramento pikeminnow is a freshwater fish, commonly associated with flowing-water habitats (Nobriga and Feyrer 2007). Long-term trends in Sacramento pikeminnow abundance are unknown, but the species is common in the Sacramento River basin (Nobriga and Feyrer 2007). The Sacramento pikeminnow is not a sought-after sport fishery in the Delta. There is, however, a bounty fishery in the upper Sacramento River to reduce predation by these fish on emigrating salmonids (Nobriga and Feyrer 2007). Large pikeminnows typically cruise about in pools during the day in loose groups of five to ten fish, although very large individuals may be solitary. Often by midday they become relatively inactive and return to cover, although some still cruise about, feeding on surface insects or benthos. The largest fish emerge from cover as darkness falls, entering runs and shallow riffles to forage on small fish. Peak feeding usually occurs in the early morning for smaller fish or at night for larger fish. Nighttime predation rates at Red Bluff Diversion Dam apparently were enhanced when lights on the dam made prey more visible (Vogel 2011).

Habitat structure and heterogeneity can affect opportunities for encounter and capture by predators. In open water habitats, striped bass are the most likely primary predator of juvenile and adult delta smelt. Other species, such as largemouth bass, are ambush predators that remain close to cover such as in-water structures or IAV.

As described in Section F.4, IAV beds appear to provide habitat that is more favorable to nearshore fishes such as largemouth bass and sunfish that also can take advantage of increased water clarity to find prey (Brown 2003; Nobriga et al. 2005; Nobriga and Feyrer 2007). In IAV-dominated habitats in the Delta, native fishes are very rare and nonnative fishes are dominant (Brown 2003; Feyrer and Healey 2003; Feyrer 2004; Grimaldo et al. 2004; Nobriga et al. 2004; Nobriga et al. 2005). Sunfish have increased in abundance since the 1980s, and the relative abundance of native fish has declined as Brazilian waterweed/egeria has expanded in the Delta over the past 25 years (Brown and Michniuk 2007). Largemouth bass are strongly associated with dense IAV beds and have increased in abundance and size in the Delta (Nobriga and Feyrer 2007; Conrad et al. 2010). The IAV beds have decreased turbidity, which could enhance prey capture by visual predators (Gregory and Levings 1998). Reduced turbidity may enhance foraging efficiency and reduce cover for delta smelt and other pelagic species (Nobriga et al. 2005). Research in other systems suggests visual predators hunt more successfully in clear water (Gregory and Levings 1998; Gadomski and Parsley 2005). Pelagic fishes, including many smelt species, experience lower predation risks under turbid water conditions (Thetmeyer and Kils 1995; Utne-Palm and Stiansen 2002; Horpilla et al. 2004). Some studies have shown decreased foraging rates at increasing turbidities (Sweka and Hartman 2003), while other studies show that changes in turbidity result in a change in the foraging activity of the predator as a mechanism to compensate for the more difficult prey detection, but this does not necessarily reduce feeding rates (Reid et al. 1999). The variability in these findings depends on the predator and prey species studied as well as the range of turbidities evaluated.

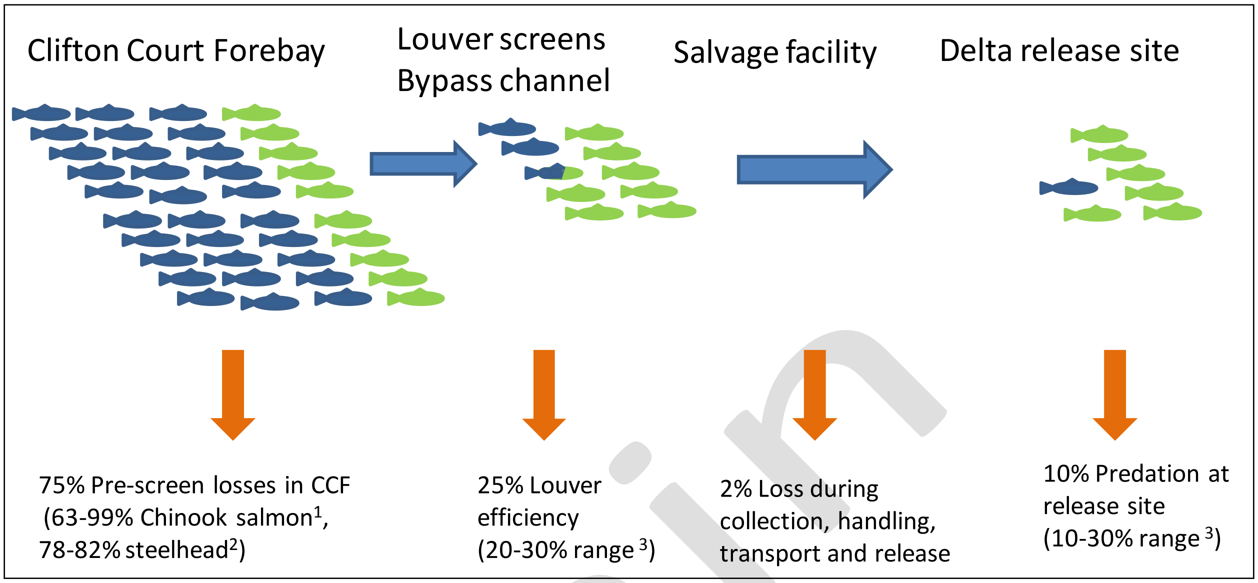
Habitat features that allow predators to forage more efficiently include structure, dark locations adjacent to light locations, and deep pools that allow them to hide and ambush their prey. Human-made structures (e.g., bank revetment, dams, bridges, water diversions, piers, wharves) can alter local flow patterns and provide habitat features that can both attract predators and disorient small fish such as juvenile salmonids and smelt (Stevens 1966; Decato 1978; Vogel et al. 1988; Garcia 1989). An extreme case of concentrated predation is seen at release points for salvaged fish, where large aggregations of piscivorous fish and birds gather to prey on the disoriented fish (Miranda et al. 2010). Predatory fish used floating debris trapped against pier pilings as cover and were observed darting out to feed on released salvage fish (Miranda et al. 2010).

Throughout the Sacramento River, the lower San Joaquin River, and the Delta, multiple locations are hot spots that attract high densities of predators. For example:

- Old structures in or hanging over Delta waterways, such as pier pilings or other human-made features (Vogel 2011).
- Abandoned boats.
- The deep hole downstream of the head of Old River in the San Joaquin River (Bowen and Bark 2010; San Joaquin River Group Authority 2011).
- Specific locations in Georgiana, Sutter, and Steamboat Sloughs (Vogel 2008).
- Release sites of salvaged fish from SWP/ CVP facilities (Miranda et al. 2010).

Operation of any diversion, including new diversions, may increase predation. Because of hydraulics around diversion structures, prey fish become disoriented (turbidity, light), and predators tend to aggregate at diversion locations (Kratville 2008). Few direct estimates of predation rates and effectiveness are available. Predation has been evaluated at Red Bluff Diversion Dam and the GCID intakes (Vogel et al. 1988; Vogel 2008).

Insights about predation can be drawn from studies of entrainment losses at the SWP south Delta facilities. These losses typically are ascribed to predation by striped bass (Figure F.5-1). Losses of tagged hatchery fish are high crossing the CCF. Studies of tagged fish documented losses of 63 to 99% of Chinook salmon juveniles and 74% of steelhead between the radial gates to the salvage facility (Clark et al. 2009; Gingras 1997). Mortality associated with collection, handling, transport in trucks, and release is estimated at 2% for Chinook salmon, which are usually juveniles or smolt-sized fish. Estimates of post-release predation are 10–30% of the salvaged fish released (National Marine Fisheries Service 2009). A pilot study of marked delta smelt had losses exceeding 90% across the CCF (Castillo et al. in review). Another study measured delta smelt mortality associated with collection, handling, transport, and release, ranging 13–22% for adults and 42–63% for juveniles (Morinaka 2010).



Sources: [1] Gingras 1997; [2] Clark et al. 2009; [3] National Marine Fisheries Service 2009.

Figure F.5-1. Predation Losses of Salmon and Steelhead at SWP South Delta Facility, from Clifton Court Forebay to Delta Release of Salvaged fish

F.5.2 Conceptual Models and Hypotheses

F.5.2.1 Conceptual Models

Predator-prey dynamics are influenced by many interacting factors that directly and indirectly influence prey encounter and capture probabilities (Mather 1998; Nobriga and Feyrer 2007; Lindley and Mohr 2003). Factors affecting the opportunity and magnitude of predation include habitat overlap between predator and prey, foraging efficiency by predators, energetic demands of predator, size, life stage, behavior, and relative numbers of predators and prey.

Fish tend to be opportunistic foragers that readily switch from one food species to another and/or concentrate their feeding in areas of greater abundance (Durand 2008). This type of foraging strategy is called Type III functional response to prey availability (*sensu* Holling). The functional response to abundance suggests that fish capitalize on highly abundant organisms and therefore tend not to limit annual recruitment, which makes it difficult to determine the role of piscivorous fish in controlling fish populations (Durand 2008).

Habitat structure and species-specific habitat use affect opportunities for predation. As illustrated by Brown (2003) for freshwater tidal wetlands, fish species composition and predator-prey interactions are strikingly different depending on the presence of SAV (Figure F.5-2 and Figure F.5-3).

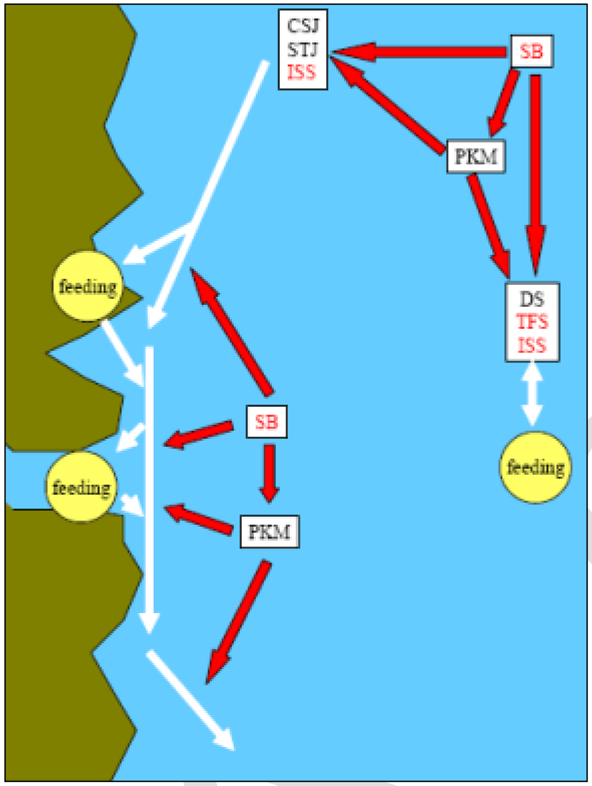


Figure F.5-2. Conceptual Model for Fish Habitat Use in Delta Tidal Wetlands without SAV

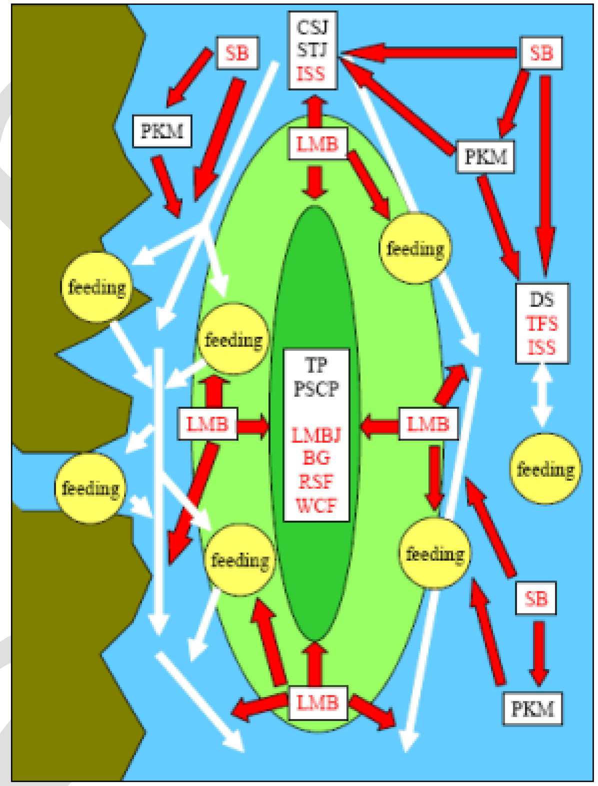


Figure F.5-3. Conceptual Model for Fish Habitat Use in Delta Tidal Wetlands with SAV

Note: Species codes in red indicate alien fishes. Red arrows indicate piscivory. White arrows indicate prey movements. Yellow circles represent feeding by prey fishes. Olive green represents emergent vegetation. Light green represents low-density SAV. Dark green represents dense SAV. Species codes: BG-bluegill; CSJ-juvenile Chinook salmon; DS-delta smelt; ISS-inland silverside; LMB-adult largemouth bass; LMBJ-juvenile largemouth bass; PKM-adult Sacramento pikeminnow; PSCP-prickly sculpin; RSF-redear sunfish; SB-adult striped bass; STJ-juvenile splittail; TFS-threadfin shad; TP-tule perch; WCF-white catfish.

Source: Brown 2003.

For this analysis of conservation measures, a simple conceptual model focused on three elements of predator-prey interactions (below) was used.

1. Abundance of predators.
2. Opportunities for predator-prey encounter.
3. Success and efficiency of prey capture.

Actions to reduce predation mortality of covered fish species therefore can be directed toward:

1. Reducing numbers of predators.
2. Reducing proximity and habitat overlap of predators and prey.
3. Reducing capture success by modifying habitat features that favor predators (e.g., cover elements) or increasing cover for prey (e.g., increasing turbidity for pelagic smelt).

Stressors and conservation actions were evaluated for their direct and indirect effects on these three factors (Figure F.5-4).

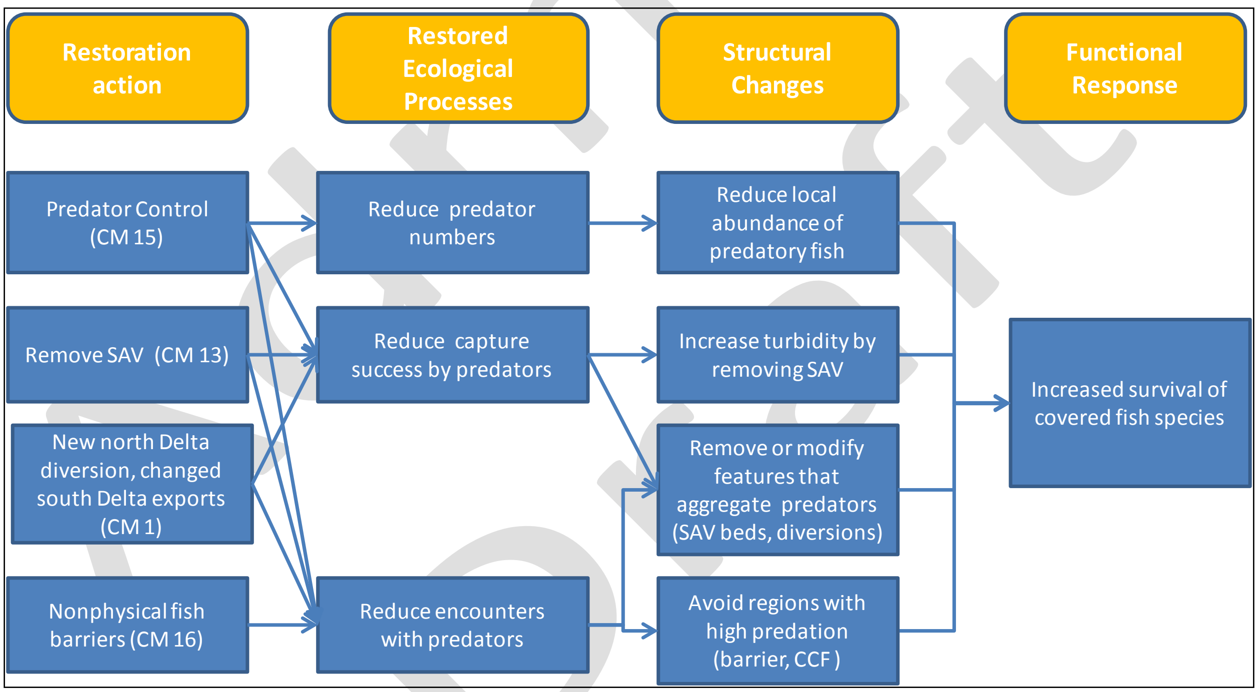


Figure F.5-4. Conceptual Model of Predation-Related Effects of BDCP Conservation Measures

F.5.2.2 Hypotheses about Predator Control

Activities that increase the risk of predation on covered fish species in the Delta include those following.

- Nonnative fish introductions.
- Alteration of natural flow patterns.
- The proliferation of human-made structures (diversions, abandoned structures, docks or wharfs, etc.).

- Changes in channel characteristics (the formation of deep scour pools) or water quality (turbidity).
- The regular release of salvaged fish at established sites.

The effectiveness of conservation measures in reducing predation losses and enhancing survival of covered fishes is evaluated according to the following hypotheses.

- Removing predatory fish at locations with high predator densities and/or localized high predation (predation hot spots) will locally reduce predation pressure.
- Removing or modifying features that aggregate predators near covered species will reduce encounter rates.
- Removing or modifying features that provide cover for predators will reduce capture success.
- Increasing cover or removing features that reduce cover (e.g., turbidity for smelt) for covered fish species will reduce capture success.
- Reducing predation losses will increase survival and contribute to enhanced populations of covered fishes.

More specifically, conducting localized predator control at hot spots in the Delta through a variety of control methods should reduce local predator abundance, consequently reducing the localized losses of covered fish species to predation, and increase their survival in the Delta. In addition, by documenting the abundance and type of predatory fish present at these sites, along with the relative threat to covered fish species, the BDCP Implementation Office should be able to design predator control methods that will reduce the effects of predators on covered fish species and monitor their effectiveness.

F.5.3 Potential Effects: Benefits and Risks

F.5.3.1 Chinook Salmon and Steelhead

F.5.3.1.1 Water Operations and Facilities (Conservation Measure 1)

Juvenile Chinook salmon and steelhead are exposed to predation as they migrate downstream and through the Delta. Steelhead are relatively less vulnerable because they migrate out as older, larger fish than Chinook salmon juveniles. Predation risk can be higher at water diversion facilities, especially at the CCF. Under existing biological conditions, exports at the south Delta facilities can alter flow patterns in the Delta, which can alter the migration pathway of juvenile Chinook salmon and steelhead toward the central and south Delta (details in Appendix 5.C, *Flow, Passage, Salinity, and Turbidity*) and increase entrainment at the south Delta facilities (details in Appendix 5.B, *Entrainment*).

Implementation of CM1 includes:

1. Installation and operation of new north Delta water diversion facilities with state-of-the-art fish screens.
2. Reduced pumping at the existing south Delta facilities.

The effects of each component on localized predation are analyzed separately below.

North Delta Diversions

The physical characteristics of structures such as water intakes can increase encounter rates and capture success by predators. Instream structures create areas of turbulence and lower velocity refuge habitat that attract predatory fish and/or concentrate or disorient juvenile salmonids (Vogel 1995, 2011). The new north Delta intake structures will be five separate intake structures located on-shore along the mainstem Sacramento River. Relative to other intake design alternatives, the proposed on-shore diversions have minimal structures in the main flow of the river. This will reduce areas where predators can aggregate and should reduce the risk of predation.

The bioenergetics model estimated consumption of juvenile salmon and steelhead by striped bass (Table F.5-2, Table F.5-3, Table F.5-4, and Table F.5-5). Assuming 133 striped bass per diversion intake (665 fish total for the five intakes), an estimated 61,509 juvenile Chinook salmon would be consumed in the early long-term (Table F.5-2) and 66,686 juvenile Chinook salmon would be consumed in the late long-term (Table F.5-4). This predation loss represents 0.08% of the juvenile fall-run and spring-run Chinook salmon population, 0.09% of the winter-run Chinook salmon population, and 0.22–.23% of the late fall–run Chinook salmon population (Table F.5-3 and Table F.5-5). Increased water temperatures (in warmer months or due to long-term climate change) are associated with higher metabolism of striped bass predators and thus increased consumption. However, model predictions of striped bass predation rates barely increase (range 0.0–0.01% of annual production) for the late long-term scenarios.

Table F.5-2. Annual Total of Juvenile Chinook Salmon (Number) Consumed by Striped Bass at North Delta Intakes in Early Long-Term with No Predator Control

Striped Bass per Diversion	Total Striped Bass	Spring-Run Chinook Salmon	Fall-Run Chinook Salmon	Winter-Run Chinook Salmon	Late Fall–Run Chinook Salmon
20	100	478	7,033	343	1,396
133	665	3,178	46,772	2,279	9,280
245	1,225	5,854	86,158	4,198	17,095

Table F.5-3. Percentage of Total Juvenile Chinook Salmon Consumed by Striped Bass in Early Long-Term with No Predator Control

Striped Bass per Diversion	Total Striped Bass	Spring-Run Chinook Salmon (%)	Fall-Run Chinook Salmon (%)	Winter-Run Chinook Salmon (%)	Late Fall–Run Chinook Salmon (%)
20	100	0.01	0.01	0.01	0.03
133	665	0.08	0.08	0.09	0.22
245	1,225	0.14	0.14	0.16	0.40

Table F.5-4. Annual Total of Juvenile Chinook Salmon Consumed by Striped Bass at North Delta Intakes in Late Long-Term with No Predator Control

Striped Bass per Diversion	Total Striped Bass	Spring-Run Chinook Salmon (No.)	Fall-Run Chinook Salmon (No.)	Winter-Run Chinook Salmon (No.)	Late Fall–Run Chinook Salmon (No.)
20	100	503	7,708	359	1,458
133	665	3,343	51,256	2,389	9,698
245	1,225	6,158	94,419	4,401	17,865

Table F.5-5. Percentage of Total Juvenile Chinook Salmon Consumed by Striped Bass in Late Long-Term with No Predator Control

Striped Bass per Diversion	Total Striped Bass	Spring-Run Chinook Salmon (%)	Fall-Run Chinook Salmon (%)	Winter-Run Chinook Salmon (%)	Late Fall–Run Chinook Salmon (%)
20	100	0.01	0.01	0.01	0.03
133	665	0.08	0.08	0.09	0.23
245	1,225	0.15	0.15	0.17	0.42

Implementing a predator control program at the north Delta diversions would reduce localized losses of juvenile Chinook salmon. Removing 20 striped bass (15%) near the north Delta intake structures (113 striped bass remain at each control structure [five structures] for a total of 565 striped bass) would result in a similar 15% reduction in total annual consumption of juvenile Chinook salmon to 52,259 in the early long-term and 56,658 in the late long-term. This may be a conservative estimate of predator removal benefits if targeted removal (e.g., electrofishing) is more effective at removing larger predators (which have higher consumption rates and capture efficiency) than the smaller, younger predators.

Like all piscivorous fishes that swallow their prey whole, striped bass become more efficient piscivores as they grow larger because they gain a size advantage over more and more individual prey. The rate of predation by striped bass on a particular prey item (e.g., juvenile salmon) is assumed to be proportional to the frequency of encounters with that prey type (Type III functional response). Therefore, it is estimated that many more fall-run Chinook salmon are consumed than winter-run or spring-run juveniles because they are more abundant. However, because salmon in the Delta are relatively rare, the functional response of striped bass to changing prey densities actually was based on data of threadfin shad.

South Delta Diversion Facilities

Reduction in the volumes and rate of water exported from the south Delta SWP and CVP export facilities will contribute directly to a reduction in the numbers of juvenile salmon and steelhead that would be at risk of entrainment and salvage. Expected outcomes based on reduced entrainment for the preliminary proposal compared to baseline conditions are described further in Appendix 5.B, *Entrainment.* Reduced pumping at the existing south Delta facilities is expected to result in the reduced entrainment and consequently reduced predation of covered fish species at the facilities.

Incremental losses of fish vary at different steps along the SWP and SVP screening process (Table F.5-6). The greatest losses are pre-screen losses in the CCF (75%, range 63–99%) and louver efficiency at the CVP Tracy fish Collection Facility (53% loss). Pre-screen entrainment loss at the CCF is the greatest effect (Gingras 1997; Clark et al. 2009; National Marine Fisheries Service 2009). Predation losses in the forebay have been estimated at 63–99% for salmon (Gingras 1997) and 74–86% for steelhead (Clark et al. 2009), based on studies of tagged hatchery fish.

Modifying post-salvage release activities, such as regularly changing release sites and timing, will benefit covered species that are successfully salvaged and survive transport, but those losses represent only a small fraction of the overall losses.

Table F.5-6. Overall Survival of Fish Entrained by the Export Pumping Facilities at the Tracy Fish Collection Facility and the John E. Skinner Fish Protective Facility

Estimate of Survival for Screening Process at the SWP and CVP[1]				
	SWP		CVP[2]	
	Percent Survival	Running Percent	Percent Survival	Running Percent
Pre-screen survival	25% [3,4] (75% loss)	25%	85%[5] (15% loss)	85%
Louver efficiency	75% (25% loss)	18.75%	46.8%[6] (53.2% loss)	39.78%
Collection, handling, transport, and release survival	98% (2% loss)	18.375%	98% (2% loss)	38.98%
Post release survival (predation only) [7]	90% (10% loss)	16.54%	90% (10% loss)	35.08%

Source: National Marine Fisheries Service 2009 (Biological Opinion).

Notes:

[1] These survival rates are those associated with the direct loss of fish at the state and federal fish salvage facilities. Please see the text for a more thorough description.

[2] These values do not incorporate the 45% of the operational time that the louvers are in noncompliance with the screening criteria. The actual values of the louver efficiency during this time are not available to NMFS. These values would determine the percentage of survival through the facility under real time circumstances.

[3] Prescreen loss for the SWP is considered to be those fish that enter Clifton Court Forebay that are lost to predation or other sources between entering the gates and reaching the primary louvers at the Skinner Fish Protection Facility.

[4] Estimates have ranged from 63 to 99% (Gingras 1997). Recent steelhead studies indicate a loss rate of approximately 78–82% (Clark et al. 2009).

[5] Prescreen survival in front of the trashbacks and primary louvers at the Tracy Fish Control Facility (TFCF) have not been verified, but are assumed to be 15%.

[6] Overall efficiencies of the louver arrays at the TFCF have been shown to be 46.8% (59.3% primary, 80% secondary). Recent studies indicate overall efficiencies during low-flow periods could be less than 35% (Bureau of Reclamation 2008). This value does not include periods when the louvers are being cleaned, where overall efficiency drops toward zero.

[7] Predation following release of salvage fish ranges from less than 10% to 30% according to DWR (2009). NMFS uses the lower estimate to give a conservative estimate of loss. Actual loss may be greater, particularly in the winter when the density of salvage fish released is low, and predators can consume a greater fraction of the released fish (Clark et al. 2009).

The reduction in predation loss attributable to reduced pumping under the BDCP conservation strategy can be estimated from the decrease in salvage compared to existing conditions. Estimates of total salvage were taken directly from Appendix 5.B, *Entrainment*. Assuming that predation is 75% at the SWP and 15% at the CVP facilities, predation losses are decreased by several thousand for steelhead and each race of Chinook salmon under CM1 in both the early and late long-term scenarios (Table F.5-7, Table F.5-8). This decrease in predation loss was compared with annual estimates of juvenile salmon population by race: 2.6 million winter-run juveniles; 3.2 million spring-run juveniles, and 55.2 million fall-/late fall–run juveniles (Table F.5-7). The population level of juvenile steelhead in the Central Valley is unknown at this point. Estimated predation losses at the south Delta facilities were decreased substantially under the PP in comparison to existing biological conditions for steelhead (55–58%) and fall-/late fall–run Chinook salmon (56–60%), and spring-run Chinook salmon (14–24%), but little changed for winter-run (–3% to 8%). In the context of the population for each race, however, these differences make up no more than 0.1% of estimated annual production for Chinook salmon (Table F.5-8).

Table F.5-7. Pre-Screen Losses of Salmonids at SWP and CVP South Delta Facilities

Species/Race	Existing Conditions ELT (EBC2_ELT)	Existing Conditions LLT (EBC2_LLT)	PP_ELT	PP_LLT
Steelhead	7,040	6,765	3,154	2,827
Fall-/late fall–run	4,711	4,564	2,080	1,815
Winter-run	20,321	20,474	20,879	18,770
Spring-run	30,678	29,944	26,389	22,839
Note: Based on assumption of 75% predation loss of salmonids in SWP and 15% predation loss in CVP.				

Table F.5-8. Reduction (Number and Percent) in Pre-Screen Losses of Salmonids at SWP and CVP South Delta Facilities under Existing Conditions and Preliminary Proposal[1]

Species/Race	Existing Conditions vs. PP_ELT	Existing Conditions vs. PP_LLT	% of Total Population (ELT)	% of Total Population (LLT)
Steelhead	3,886 (55%)	3,939 (58%)	Unknown	Unknown
Fall-/late fall–run	4,630 (56%)	7,475 (60%)	<0.1%	<0.1%
Winter-run	2,630 (-3%)	2,749 (8%)	0.1%	0.1%
Spring-run	1,585 (14%)	1,704 (24%)	<0.1%	<0.1%
Note: Based on assumption of 75% predation loss of salmonids in SWP and 15% predation loss in CVP.				

F.5.3.1.2 Habitat Restoration

Restored aquatic habitats are expected to support juvenile salmonids that migrate through or rear in the Delta by providing foraging habitat and cover. However, these habitats also may be used by predatory fish. The potential effects of the different types of aquatic habitat restoration are discussed qualitatively below. In general, predation risk for juvenile steelhead is expected to be lower than that for juvenile Chinook salmon because of their greater size and better swimming performance.

Yolo Bypass Fisheries Enhancement (Conservation Measure 2)

Yolo Bypass enhancement (CM2) to improve passage at the Fremont Weir and increase Yolo Bypass inundation would help reduce predation risk on migrating juvenile steelhead and Chinook salmon by providing a migration route with lower predation and entrainment risk (avoiding the north and south Delta diversions). Mortality, which occurs along the primary migratory routes for juvenile salmonids, is hypothesized to be the largest factor influencing Delta emigration success. Although concerns have been raised about stranding on the floodplain, juvenile Chinook salmon do not appear to be prone to stranding mortality (Sommer et al. 2005). The Yolo Bypass drains fairly efficiently, leaving little isolated area where stranding can occur. The exception is at water control structures, namely the concrete weir ponds at the Fremont and Sacramento Weirs.

There may be a potential for predators also to benefit from the Yolo Bypass restoration measures, but that risk likely is outweighed by the benefits to salmonids from the restoration measures. Feyrer and coauthors (2006) analyzed seasonally inundated floodplain habitat in the Yolo Bypass and found a much higher presence of juvenile salmon than predators like largemouth bass and striped bass, suggesting that Yolo Bypass restoration efforts likely will benefit salmon and steelhead more than nonnative fish predators. Even with stranding and predation losses in some places or some years, the risks may be offset by increased rearing habitat and food resources in other years (Sommer et al. 2001, 2005; Brown 2002). Survival of tagged juvenile salmon released in the Yolo Bypass and Sacramento River was somewhat greater for the Yolo Bypass release groups (Sommer et al. 2001).

Tidal Habitat Restoration (Conservation Measure 4)

Restored tidal wetlands are expected to increase food supply, benefitting rearing juvenile salmonids. Increased tidal habitats, especially along juvenile salmonid migration corridors, also might improve survival by providing refuge from predation. If restored subtidal areas are invaded by IAV, however, this could increase abundance of largemouth bass and hence increase predation losses of those juveniles exploiting the restored tidal habitat. However, Chinook salmon are most abundant when water temperatures are relatively low and largemouth bass metabolic and feeding rates are also low (Brown 2003).

Seasonally Inundated Floodplain (Conservation Measure 5)

Benefits and risks for Chinook salmon and steelhead in restored seasonally inundated floodplains in the Delta are expected to be similar to those observed in the Yolo Bypass. Seasonal floodplain restoration should be beneficial to juvenile salmonids by providing additional rearing habitat. Sommer and coauthors (2001) observed higher growth rates of juvenile salmon reared in the Yolo Bypass floodplains compared to salmon that remained the Sacramento River channel. Inundated floodplains provide a higher abundance of prey for juvenile salmon, leading to faster growth. As juvenile salmon become larger, survivorship increases, in part because of lower risk of predation. A 5-year study of fish abundance in restored floodplain habitat in the Cosumnes River found high abundance of centrarchids such as bluegill and largemouth bass in adjacent permanent sloughs (Moyle et al. 2007). These piscivorous predators typically spawn in main channel habitats, although juvenile centrarchids quickly moved into these seasonal floodplains as opportunistic feeders and adults occasionally spawned in temporary floodplain ponds. The restored Cosumnes River floodplain is inundated in winter and early spring, when juvenile Chinook salmon can use it, but drains by late spring before many nonnative warmwater species spawn (Moyle et al. 2007). Feyrer and coauthors (2006) observed much higher presence of salmon than predators in restored floodplains, which supports the concept that more restored floodplains in the Delta likely will provide a net benefit for salmonids.

Channel Margin Habitat (Conservation Measure 6)

Cover is an important habitat component for juvenile salmonids as they migrate through the lower Sacramento and San Joaquin Rivers and the Delta, serving in part as a means to avoid predators. Channelized, leveed, and riprapped banks common in the lower river reaches and sloughs of the Delta region offer little protection for covered fish species from either fish or avian predators.

Recovering channel margin habitats may contribute to a net improvement in survival if the recovered habitats contribute to increasing prey resource availability locally and regionally, improving migration habitat connectivity, and providing other benefits to migratory native fish while reducing habitat benefits for nonnative predators. Juvenile Chinook salmon and steelhead are expected to inhabit restored channel margin habitat and seasonal wetlands located along the Sacramento River as resting and foraging areas during their migration downstream. Cobbles and boulders on the banks can provide flow breaks that provide shelter and feeding stations for juveniles. Natural bank areas also have lower predator densities compared to riprapped channel margins (Michney and Hampton 1984; Cavallo et al. 2004).

Restoring natural river or slough channel banks is expected to benefit covered fish species by eliminating channel bank features (e.g., riprap) attractive to fish predators. However, a quantitative assessment is difficult because data is lacking on predator densities associated with restored channel margin habitat. Increased food availability resulting from habitat expansion is considered to be a benefit to juvenile salmon and steelhead, although the risk of predation may contribute to increased juvenile mortality. Shallow-water habitats also may provide a refuge from predation by larger pelagic fish such as striped bass, but also may harbor black bass if these areas become colonized with IAV (Nobriga and Feyrer 2007).

Riparian Habitat (Conservation Measure 7)

Riparian restoration could provide additional cover for both covered species and predators, depending on whether riparian vegetation is located at the land-water interface, where it could provide underwater structure (e.g., undercut banks, roots, woody debris) or direct shading.

F.5.3.1.3 Nonnative Aquatic Vegetation Control (Conservation Measure 13)

Control of IAV would reduce habitat that supports predatory fish in freshwater nearshore habitat. Largemouth bass, a very effective nearshore predator, recently has shown an increase in abundance and size in the Delta and is strongly associated with dense IAV beds (Nobriga and Feyrer 2007; Conrad et al. 2010). A decrease in IAV in the Delta should open up nearshore habitats used by juvenile salmonids for cover and rearing while reducing their encounters with piscivorous predators like largemouth bass. Dense IAV cover also has been associated with reduction of water turbidity in the Delta (Brown and Michniuk 2007). Removal of IAV may provide increased turbidity, which is associated with reduced hunting success of visual predators like largemouth bass and striped bass (Gregory and Levings 1998).

There is some potential that largemouth bass may move from areas of IAV removal and congregate even more densely in untreated areas, concentrating predation pressure in those remaining IAV areas. Removal of IAV may increase the foraging efficiency of pelagic predators like striped bass. These changes have potential to increase predation on migrating salmonids in the short term until a new equilibrium is reached (National Marine Fisheries Service 2007).

F.5.3.1.4 Predator Removal (Conservation Measure 15)

This action is expected to benefit covered fish species by reducing predation mortality at hot spots throughout the Delta. Targeted predator removal focused at identified hot spots in the Delta is expected to reduce local predator populations and increase survival of juvenile salmonids migrating through the Delta as well as delta smelt and longfin smelt. Removing or eliminating structural or hydraulic elements that attract and/or provide cover for predatory fish will reduce concentrations and predation effectiveness. Removing predators from release sites, modifying fish salvage activities, and reduced pumping at the existing CVP and SWP diversion facilities in the south Delta also are expected to benefit covered species.

The latest quantitative information that relates to striped bass predation on salmon is based on a predator diet study by Nobriga and Feyrer (2007). From this study, it is estimated that striped bass consume an average 0.01 juvenile salmon per day. Based on an average salmonid migration period of 150 days, it is possible to calculate a rough estimate for the effectiveness of a predator removal program. There is a high level of uncertainty associated with this type of analysis, but these estimates provide a basis for characterizing the general magnitude of the reduction of salmon loss to striped bass predation due to localized removal efforts.

Following are assumptions on the potential level of effort for a predator removal program.

- Daily (5 days per week) predator removal at the five proposed north Delta intakes during the October through June period removes 9,250 (10 fish per day * 5 days per week * 37 weeks * 5 sites = 9,250) striped bass from the system.
- Daily (5 days per week) predator removal at head of Old River during the October through June period removes 3,700 (20 fish per day * 5 days per week * 37 weeks = 3,700) striped bass from the system.
- Daily (5 days per week) predator removal at three sites in Georgiana Slough during the October through June period removes 5,550 (10 fish per day * 5 days per week * 37 weeks * 3 sites = 5,550) striped bass from the system.
- Daily (5 days per week) predator removal at a total of four sites in Sutter and Steamboat sloughs during the October through June period removes 7,400 (10 fish per day * 5 days per week * 37 weeks * 4 sites = 7,400) striped bass from the system.
- Weekly predator removal at each of the eight CVP/SWP salvaged fish release sites during the October through June period removes 5,920 (20 fish per day * 1 day per week * 37 weeks * 8 sites = 5,920) striped bass from the system.

Collectively, the efforts would remove roughly 32,000 Age-1 and older striped bass from the system annually. The feasibility of sustaining this presumed level of removal effort is unknown. Given the consumption rates above, this theoretically would reduce the number of juvenile salmonids lost to striped bass predation during the first year of full implementation by approximately 48,000 fish. Note that the above rough estimate does not take into account predation of salmonids by other predators besides striped bass, the fact that the highly mobile striped bass can quickly recolonize predator hot spots, or the size of the removed striped bass.

Results of a recent study by Cavallo and coauthors (in press) indicated that intensive, site-specific predator control could be an effective management strategy to enhance salmon survival through the Delta. However, benefits may be short-term and the effectiveness of repeated treatment remained unclear. Cavallo and coauthors (in press) applied the hypothesis that predator reductions and flow pulses would increase survival of emigrating juvenile Chinook salmon in the North Fork Mokelumne River. Applying a "before-after-control-impact" study design, they acoustically tagged juvenile fall-run Chinook salmon and removed predators from an "impact" reach of the river. Researchers conducted two separate predator removal treatments, set 1 week apart, by boat electrofishing on a 1.6 km reach of river. The researchers estimate a predator removal efficiency (of the fish predators vulnerable to electrofishing) of 91% (144 of 158) in the first removal treatment and 83% (497 of 601) in the second removal, with each removal treatment taking 1 day. This study provides valuable insight into how many predators realistically can be removed per day; however, the size and species composition of the removed predators are unknown. After targeted predator removal in the impact reach, researchers released paired groups of tagged juvenile salmon into impact and control reaches in consecutive days immediately following predator removal, and recaptured the tagged juveniles downstream. Despite generally encouraging results after the initial predator removal treatment in which there was 100% survival of juveniles, the researchers observed that there was no difference in survival after the second predator removal treatment compared to no predator removal. Presumably, the apparent benefit from initial predator removal might be undone through an influx of new predators to the treatment site. Sustained effort over time may be necessary to benefit juvenile salmon survival.

Daily predator removal treatments in the CCF are being proposed under CM15 to lower predation losses of entrained juveniles. However, achieving appreciable predator reductions in the forebay is expected to be more difficult because of the large area and continual influx of predators through the radial gates, not to mention the risk of incidental take of covered fish entrained into the CCF.

Predator removal programs implemented elsewhere have had mixed results. On the Colorado River, an investigation of nine predator removal programs showed removal programs failed to significantly improve the situation of native fish (six out of seven responses), with only a third of the programs resulting in a decrease in predatory fish numbers (Mueller 2005). Recolonization of the treated sites by predatory fish was typically rapid. Successful programs were limited to situations in an isolated water body that lacked predator recruitment from outside sources, and where targeted invasive species had low reproductive rates and were easy to capture.

In the lower Columbia River, a predatory pikeminnow control program was used over several years to reduce abundance of predatory fish greater than 250 mm by 10–20% over a sustained basis (Porter 2010). The program implemented a variety of techniques, including gill netting, angling, and sportfishing rewards. The project was moderately successful with indices of pikeminnow predation on juvenile Chinook salmon decreasing 44–95% in 1994–1996 compared to numbers from 1990–1993. The program also found no evidence that the reduction in pikeminnow abundance resulted in a compensatory response by smallmouth bass. Findings from the Columbia River program, however, showed that a sustained level of effort and harvest was required to maintain smaller predatory pikeminnow populations.

Predator control measures have a greater likelihood of success in smaller systems or in closed systems such as lakes. For example, predator removal was effective on Fossil Creek in Arizona, a small stream treated with a chemical piscicide (antimycin A) (Marks et al. 2010). The study used a before-after-control-impact design and snorkel surveys to compare the effects of both flow restoration and removal of nonnative fish. Results showed that removal of nonnative fish dramatically increased native fish abundance (Marks et al. 2010).

In general, predator removal is most successful in small, closed systems that can be thoroughly treated (often with a chemical piscicide) and where predators cannot recolonize the site (as in a lake). However, the Delta is neither small nor isolated from source populations of nonnative predators, which makes control an ongoing challenge.

One potential risk of localized predator removal is bycatch of steelhead or Chinook salmon during beach seining, gill netting, angling, electrofishing, and other capture methods. Likelihood of take is low because juvenile and adult salmonids generally do not congregate with predatory fish. In juvenile salmonids, except in very severe cases, electrofishing injuries heal and seldom result in immediate or imminent mortality (Snyder 2003). Striped bass monitoring at Knights Landing using fyke traps caught two adult steelhead in 16,100 hours; gillnetting on the lower Sacramento resulted in one steelhead mortality in 15,450 hrs. (Dubois and Mayfield 2009; Dubois et al. 2010). Hook and line removal of striped bass in the Carmel River Lagoon for 143 hours resulted in the capture of seven steelhead to 112 striped bass (California Department of Fish and Game 2010). Common hook and line injuries are damage to skeletal structure of the mouth, injury to gills, and secondary infections (National Marine Fisheries Service 2003). Adult salmonids caught in nets (fyke, beach seine, or gill nets) could suffer abrasions and stress from capture and handling. Juvenile salmonids could be gilled in nets and suffer from predation during capture (National Marine Fisheries Service 2003).

F.5.3.1.5 Nonphysical Fish Barriers (Conservation Measure 16)

Nonphysical barriers are designed to guide juvenile salmonid fish away from migration routes with low survival and high predation risk, such as the head of Old River and Georgiana Slough. Tools such as the DPM can be used to assess reach-specific mortality rates. This model incorporates studies of tagged juvenile smolts to estimate mortality in different reaches, presumably by predation losses (detailed in Appendix 5.C, *Flow, Passage, Salinity, and Turbidity*).

The physical structures of the nonphysical barrier, though, may attract piscivorous fish to the area and increase localized predation risks. Studies on the nonphysical barrier at the head of Old River indicate that the barrier is very effective at deterring salmon smolts from entering the Old River. However, many predators were attracted to a nearby deep scour hole immediately downstream on the San Joaquin River and a large in-water structure. In fact, while the nonphysical barrier deterrence rate was 81%, the predation rate was so high that the juvenile salmon survival rate was not statistically different whether the barrier was on or off (Bowen and Bark 2010).

Acoustic tagging studies have shed light on a predation hot spot at the scour hole downstream of the San Joaquin River and head of Old River (Bowen and Bark 2010;Vogel 2010, 2009; San Joaquin River Group Authority 2011). Bowen and Bark (2010) suggested that much of the gain accomplished by deterring salmon smolts from entering Old River was offset by heavy predation in the vicinity of the scour hole. In 2010, Bowen and Bark (2010) estimated a 23% predation loss rate in the reach at the head of Old River, while the Vernalis Adaptive Management Plan (VAMP) studies reported a 9% mortality rate in that reach (San Joaquin River Group Authority 2011). Vogel (2010) evaluated the movements of acoustic-tagged juvenile salmon released in the San Joaquin River and noted that some areas where relatively high numbers of transmitters were located tended to be in the vicinity of scour holes. Although substantial predatory fish activity and acoustic-tagged salmon (or transmitters) inside predators were believed to occur in the area of the scour hole just downstream of the head of Old River, the results of Vogel's study suggested that predatory fish did not reside in the scour hole for extended periods (Vogel 2010). Nonetheless, there may be risks associated with the installation of nonphysical barriers in that the benefits of deterrence by these highly efficient structures may be offset by predation at such geomorphic features as scour holes. The scour hole at the head of Old River is a proposed site for targeted removal of predators under CM15, possibly by purse seining.

An estimate of the expected level of predation at the nonphysical barriers can be based on predicted predator abundance from field surveys. This estimate is based solely on the size of in-water structures from the barrier itself and does not include other predator aggregations nearby, such as the scour hole at the head of Old River. The head of Old River nonphysical barrier being tested is 112 meters long (Bowen and Bark 2010). It is assumed that other nonphysical barriers are or will be of a size similar to the one at Old River. Estimates of predator abundance and predation rates were developed from fish screen studies conducted at GCID (Vogel 2008). Median predator abundance associated with the barrier would be 44 fish (predator density of 0.39 predator per meter of intake structure) with a median predation rate of 0.01 juvenile salmonid per day. Over the course of a 150-day smolt outmigration period, it was assumed that 66 juvenile salmonids are lost to predation annually at nonphysical barriers as a result of the increased holding habitat for piscivorous predators around the in-channel structures.

F.5.3.1.6 Nonproject Diversions (Conservation Measure 21)

Reduced entrainment of salmon and steelhead in unscreened nonproject diversions (e.g., small agricultural diversions) is discussed in Appendix 5.B, *Entrainment*. While fish may benefit from new screens that reduce entrainment at nonproject diversions, there may be some predation risk due to new structural components (e.g., screens, support beams, trash racks) necessary for the screen installations. Although most nonproject diversions are relatively small, they do require structural components (e.g., support beams, intake pipes) that could provide suitable cover or holding areas for predators. Consolidation and reduction of diversion intakes could reduce potential cover elements for predators.

Moyle and Israel (2005) evaluated a number of fish screen projects in the Sacramento–San Joaquin River system. Two studies suggested that some screens increased predation rates on juvenile Chinook salmon by providing holding areas for predatory fish, but Moyle and Israel (2005) found these inconclusive. While some screens may be detrimental because of predation on juvenile salmon, the effect of individual diversions is likely highly variable, depending on size and location. Insufficient information exists to support conclusions regarding the likelihood of predation associated with these structures.

F.5.3.2 Delta Smelt

F.5.3.2.1 Water Operations and Facilities (Conservation Measure 1)

Reduced exports in the south Delta will reduce the amount of water, and therefore the number of delta smelt, that will enter the CCF. Although the role of predation near the SWP and CVP south Delta pumping facilities in the dynamics of Delta fish populations is not well understood, delta smelt are likely to be highly vulnerable to predation in this area, where they are entrained and predators aggregate (Sommer et al. 2007; U.S. Fish and Wildlife Service 2008; Miranda et al. 2010), especially in the CCF. Predation in the forebay during the entrainment and salvage process is thought to contribute substantially to overall losses associated with the SWP export facilities. A pilot study of tagged delta smelt estimated pre-screen losses greater than 94% (Castillo et al. in review). Delta smelt face losses due to predation and handling even after they are salvaged at the fish facilities. Very few entrained smelt escape the high level of predation long enough to be released back into the Delta and survive. Therefore, reducing the number of fish entrained to the facilities would reduce the effect of predation on the delta smelt population.

Daily predator removal treatments in the CCF are proposed under CM15 and are expected to lower predation losses of entrained juvenile and adult delta smelt. However, predator removal in the forebay is expected to be difficult because of the large area, continual influx of predators through the radial gates, and incidental take of covered fish entrained into the forebay.

Entrainment and exposure to predation were calculated based on the OMR Proportional Loss model by Kimmerer (2008), which calculates smelt entrainment as a proportion of OMR flows. The numbers of delta smelt juveniles and larvae (Table F.5-9) and adults (Table F.5-10) entrained and therefore exposed to predation at the SWP and CVP facilities are substantially reduced in all water-year types under CM1 (PP_ELT and PP_LLT) compared to existing biological conditions (EBC2_ELT and EBC2_LLT). Average entrainment loss across all water-year types was reduced by 36–40% for larval and juvenile delta smelt, and 27–28% for adults (although the actual number of fish is low in both the EBC and PP scenarios). The reduction in entrainment was greater in wetter water-year types for both life stages and time scenarios (Table F.5-10). Because predation is high once smelt are entrained, a decrease in entrainment should reduce total predation losses by a large margin.

Table F.5-9. Average Estimated Change in Annual Proportional Loss of Juvenile and Larval Delta Smelt at SWP/CVP South Delta Export Facilities by Water-Year Type for the Six Study Scenarios, Using Estimates Based on Kimmerer (2008)

WY Type	EBC2 vs. PP_ELT	EBC2 vs. PP_LLT	EBC2_ELT vs. PP_ELT	EBC2_LLT vs. PP_LLT
All	-0.0388 (-39%)	-0.0462 (-47%)	-0.0334 (-36%)	-0.0353 (-40%)
Wet	-0.0459 (-51%)	-0.0507 (-56%)	-0.0433 (-49%)	-0.0456 (-54%)
Above Normal	-0.0426 (-40%)	-0.044 (-41%)	-0.0318 (-33%)	-0.0251 (-28%)
Below Normal	-0.03 (-27%)	-0.0418 (-38%)	-0.0243 (-23%)	-0.0332 (-33%)
Dry	-0.0381 (-34%)	-0.0524 (-47%)	-0.0323 (-31%)	-0.039 (-40%)
Critical	-0.031 (-40%)	-0.0344 (-45%)	-0.026 (-36%)	-0.0204 (-32%)

Table F.5-10. Average Change in Estimated Annual Proportional Loss of Adult Delta Smelt at SWP/CVP South Delta Pumps by Water-Year Type for the Six Study Scenarios

WY Type	EBC2 vs. PP_ELT	EBC2 vs. PP_LLT	EBC2_ELT vs. PP_ELT	EBC2_LLT vs. PP_LLT
All	-0.0246 (-28%)	-0.0266 (-30%)	-0.0233 (-27%)	-0.0233 (-28%)
Wet	-0.0493 (-64%)	-0.0476 (-62%)	-0.0473 (-63%)	-0.045 (-61%)
Above Normal	-0.035 (-38%)	-0.0366 (-40%)	-0.0346 (-38%)	-0.0355 (-40%)
Below Normal	-0.0191 (-20%)	-0.0194 (-21%)	-0.0177 (-19%)	-0.017 (-18%)
Dry	-0.0008 (-1%)	-0.0069 (-7%)	-0.0007 (-1%)	-0.0034 (-4%)
Critical	-0.0031 (-4%)	-0.0088 (-10%)	-0.0002 (0%)	-0.0015 (-2%)

The north Delta intakes should reduce entrainment of delta smelt, but there is the potential the structures associated with the facilities may attract fish predators. The predicted effect of predator removal around the new north Delta intakes is discussed below in Section F.5.3.2.4.

F.5.3.2.2 Habitat Restoration (Conservation Measures 2, 4, 5, 6, and 7)

Channel margin restoration will remove structures and riprap along levees in the Delta. These structures represent habitat that attract predators such as Sacramento pikeminnow or centrarchids. Larval and juvenile delta smelt have been observed in nearshore habitats, although they are found predominantly in open channel habitats (Nobriga et al. 2005). The importance of channel margin habitat for juvenile delta smelt rearing therefore is unknown. The effectiveness of channel margin restoration measures in reducing delta smelt predation also depends on whether these restored areas are invaded by nonnative IAV.

Tidal habitat restoration measures are not expected to notably reduce predation risk for delta smelt as these habitats are typically in shallow-water areas not associated with the pelagic nature of delta smelt.

F.5.3.2.3 Nonnative Aquatic Vegetation Control (Conservation Measure 13)

Removal of IAV likely would improve conditions for delta smelt by removing the aquatic vegetation associated with a decrease in turbidity. Increased turbidity is associated with improved concealment for delta smelt to avoid detection from mainly visual predators like largemouth bass and striped bass. IAV removal also should increase available shallow-water habitat for juveniles, although it is unknown how much juvenile delta smelt use these habitats. The effect on adult delta smelt is likely to be small, because adults are mostly pelagic and not likely to use shallow-water habitats typically associated with dense IAV. It is thought that spawning of delta smelt occurs over sandy areas at subtidal elevations, where SAV is known to occur. Removal of SAV therefore may increase the habitat available for spawning.

F.5.3.2.4 Predator Removal (Conservation Measure 15)

To the extent localized predator control efforts reduce the overall abundance of pelagic predators in the Delta occupied by delta smelt, it is expected that there would be some reduction in losses to predation, although very limited quantitative information is available regarding the current magnitude of delta smelt loss to predation. In general, delta smelt are most likely to benefit from actions that involve removal of migratory, pelagic predators (e.g., striped bass) from the system compared to other predator management actions for the reasons below.

- Some predator removal actions will occur upstream of smelt habitat.
- Removal of migratory, pelagic predators from anywhere in the system has the potential to reduce predation pressure on smelt because these predators are likely at some point to move into smelt habitat.
- Some anticipated actions will involve modifications to nearshore habitats, whereas smelt are more likely to inhabit open-water habitats and rarely associate with structures (Moyle 2002).

The only available quantitative information that relates to striped bass predation on delta smelt populations is from DFG (1999) and re-analysis of these data by Hanson (2009). DFG (1999) estimated that, based on the mean 1992–1994 abundance of Age-1 through Age-3+ striped bass (approximately 7 million) and the 1994 estimate of smelt abundance (approximately 5 million), striped bass annually consume 0.71 delta smelt per striped bass per year or roughly 250,000 individuals annually (about 5% of the delta smelt population). Hanson (2009), using similar data but different methods, estimated higher levels of striped bass predation on delta smelt (approximately

13% annually). There is a high level of uncertainty associated with both of these analyses (Hanson 2009). However, these estimates provide a basis for characterizing the general magnitude of the reduction in smelt loss to striped bass predation due to localized predator removal efforts.

The assumptions of theoretical level of predator removal effort are described earlier in Section F.3.5.1.4. Based on these estimates, it is presumed that roughly 32,000 Age-1 and older striped bass would be removed from the system annually. Given the consumption rates above, this theoretically would reduce the number of juvenile and adult smelt lost to striped bass predation during the first year of full implementation by approximately 22,000 fish.

There are several caveats to the above calculations on the effectiveness of predator removal. Striped bass in particular will be difficult to control locally because they are highly mobile and can quickly recolonize areas. Problems arising from rapid recolonization by mobile predatory species have been observed in previous predator removal programs (Mueller 2005; Cavallo et al. in press). Also the above hypothetical predator removal program assumes constant density of delta smelt at the predator removal locations during October–June. Because largemouth bass and striped bass are highly opportunistic feeders, their rate of predation on delta smelt will be proportional to the density of smelt present. Therefore, the benefits of predator removal for delta smelt will be realized only during the times delta smelt are present at those sites in appreciable numbers. The assumed consumption of delta smelt by striped bass may be overestimated, as delta smelt are currently less common than they were when the studies cited above were performed, and Nobriga and Feyrer (2007) did not observe littoral predators consuming any delta smelt. It is noted that the expected number of striped bass removed is small relative to the total population and annual fluctuations in the population, so the effect of removal on the population size of striped bass may not be discernible. Finally, the assumptions provided above regarding the number of striped bass that can be captured during daily removal efforts are speculative, but based on the best available information, professional judgment, and experience with past similar efforts. The numbers captured in practice likely will vary substantially with the methods employed, and according to the season and sampling conditions at the removal sites selected. A potential risk of localized predator removal is bycatch of delta smelt during electrofishing, fyke netting, or other capture methods meant to remove predators.

F.5.3.2.5 Nonphysical Fish Barriers (Conservation Measure 16)

Delta smelt are known to occupy areas in the Sacramento River upstream of Georgiana Slough and in the San Joaquin River upstream of the head of Old River, although they are found predominantly downstream of these areas. Nonphysical barriers in the Delta are not specifically designed to alter delta smelt migration routes; hence, they likely will not operate to deter smelt from entering parts of the Delta with high predation rates. Nonphysical barriers are typically operational only during the juvenile salmonid emigration period, which ends around May. Juvenile delta smelt emigration occurs mostly in May and June, so there may be limited overlap in timing with the juvenile salmonid migration. Delta smelt juveniles have only limited swimming ability, so it is unknown whether delta smelt have the escape ability to be deterred by and avoid the nonphysical barriers, especially in years with high flow rates. The in-water structures associated with these barriers may attract fish predators, increasing localized predation risk for delta smelt migrating past the barriers. The scour hole near the nonphysical barrier at the head of Old River is associated with high abundances of migratory striped bass predators. These nonphysical barriers and the scour hole at head of Old River may be targets of localized predator removal measures (CM15), which may help mitigate the predation risk to delta smelt.

F.5.3.2.6 Nonproject Diversions (Conservation Measure 21)

The extent that delta smelt are entrained in unscreened nonproject diversions (e.g., small agricultural diversions) along with the benefits and risks relative to entrainment associated with this conservation measure has been discussed in Appendix 5.B, *Entrainment*.

The primary risk associated with this conservation measure for delta smelt relates to:

1. The additional structural components (e.g., screens, support beams, trash racks) required for screening nonproject diversions, which may attract predatory fish.
2. The spatial distribution of nonproject diversions relative to the distribution of delta smelt.
3. The seasonal overlap of diversion operations and delta smelt distribution in the Delta.

F.5.3.3 Longfin Smelt

F.5.3.3.1 Water Operations and Facilities (Conservation Measure 1)

The potential benefits and risks for longfin smelt would be similar to those outlined above for delta smelt, although their magnitude may be reduced because longfin smelt occupy a smaller proportion of Delta habitat and for a shorter proportion of their life history.

Entrainment improves in wetter years, but worsens in drier years under CM1. Most entrainment of longfin smelt though occurs in the drier water-year types (refer to Appendix 5.B, *Entrainment*). Entrainment of longfin smelt, especially in the CCF, may be associated high predation losses. No quantitative assessment of the rate of predation loss for longfin smelt in the forebay has been conducted, but it is assumed to be similar to the high loss experienced by juvenile and adult delta smelt. It was presumed that predation loss of juvenile and adult longfin smelt was 75% and 15% at the SWP and CVP facilities, respectively. The amount of change in predation loss of longfin due to changes of entrainment under CM1 is shown in Table F.5-11. Entrainment in the early long-term for juvenile longfin smelt is increased but relatively unchanged for late long-term. Entrainment for adult longfin smelt is virtually unchanged under CM1. Changes in predation losses are low, because total entrainment of longfin smelt in the south Delta export facilities is small.

Table F.5-11. Total Predation Losses of Longfin Smelt under Conservation Measure 1

Longfin smelt	Existing Conditions ELT (EBC2_ELT)	Existing Conditions LLT (EBC2_LLT)	CM1 ELT (PP_ELT)	CM1 LLT (PP_LLT)	EBC2_ELT vs. PP_ELT	EBC2_LLT vs. PL_LLT
Juvenile	97	99	113	97	-16	-2
Adult	1	1	0	0	-1	-1
Note: Based on assumption of 75% predation loss of juvenile and adult longfin smelt in SWP and 15% predation loss in CVP.						

Longfin smelt are not expected to be affected by the north Delta intakes and hence not affected by the potential increase abundance of predators around the intake structures. Recent abundance and distribution survey data are not available for this region for longfin smelt, but previous studies indicate that this species is rarely distributed upstream of Rio Vista on the Sacramento River (Moyle 2002), although this may change in the future because of climate change.

F.5.3.3.2 Habitat Restoration (Conservation Measures 2, 4, 5, 6, and 7)

Because of longfin smelt preference for deeper waters, shallow-water habitat restoration is not expected to affect longfin smelt predation risks. Only a relatively small proportion of the juvenile population may use the shallow-water habitats in Cache Slough, Suisan March, and Yolo Bypass targeted for restoration (Moyle 2008). For the small number of juveniles that do rear in the areas, the risk of predation greatly depends on whether these habitats become recolonized by IAV and hence predators like largemouth bass.

F.5.3.3.3 Nonnative Aquatic Vegetation Control (Conservation Measure 13)

The effect of IAV removal on predation risk for longfin smelt is expected to be similar to that for delta smelt. Longfin smelt are found predominantly in deeper water habitats and do not commonly occupy shallow waters where IAV is found. For the small proportion of juveniles that do inhabit these shallow areas, removal of IAV likely will reduce presence of largemouth bass and hence reduce predation effects on longfin smelt. Removal of IAV is predicted to increase turbidity in the Delta, which should increase cover for longfin smelt for concealment from piscivorous predators.

F.5.3.3.4 Predator Removal (Conservation Measure 15)

The benefits and risks to longfin smelt from predator removal measures are expected to be similar to the effects predicted for delta smelt (Section F.3.5.2.4).

F.5.3.3.5 Nonphysical Fish Barriers (Conservation Measure 16)

Nonphysical barriers in the Delta are intended to guide juvenile fish away from migration routes with low survival and high predation risk, such as the head of Old River in the southeastern Delta and Georgiana Slough in the north Delta. Locations currently under consideration for the installation of nonphysical barriers are not likely to overlap the spatial distribution of juvenile and adult longfin smelt, which rarely are found upstream of Rio Vista or Medford Island (Moyle 2002) in the western and central Delta, respectively. Therefore, benefits are considered negligible at best. In addition, nonphysical barriers are not specifically designed to alter longfin smelt migration routes; hence, they likely will not operate to deter smelt from entering parts of the Delta with high predation rates. However, the structures associated with nonphysical barriers may attract fish predators, increasing the predation risk for longfin smelt that might encounter them. These barriers may be a target of localized predator removal measures (CM15) that may help mitigate the predation risk to longfin smelt.

F.5.3.3.6 Nonproject Diversions (Conservation Measure 21)

The extent of longfin smelt entrainment in unscreened nonproject diversions (e.g., small agricultural diversions) is discussed in Appendix 5.B, *Entrainment*.

The predation-related effects of this conservation measure for longfin smelt relate to the number and infrastructure of nonproject diversions.

1. The additional structural components (e.g., screens, support beams, trash racks) required for screening nonproject diversions, which may attract predatory fish.
2. The spatial distribution of nonproject diversions relative to the distribution of longfin smelt in the Delta.

3. The seasonal overlap of diversion operations and longfin smelt distribution in the Delta.

F.5.3.4 Sacramento Splittail

F.5.3.4.1 Water Operations and Facilities (Conservation Measure 1)

Juvenile and subadult splittail have been observed in fish salvage operations at both the SWP and CVP fish salvage facilities. No studies have been performed, however, to assess the vulnerability of juvenile and subadult splittail to predation in the CCF. Based on their size, it has been assumed for purposes of this effects assessment that splittail would be vulnerable to predation in a manner similar to that observed for juvenile salmon, striped bass, and steelhead (Gingras 1997; Clark et al. 2009). Therefore, the risk of predation mortality in the CCF is assumed to be approximately 75%, and the risk of predation associated with the CVP trash racks is assumed to be 15%. After splittail are salvaged at the export facilities, they experience predation by piscivorous fish and bird predators at the salvage release locations in the Delta. *CM15 Predator Control* will increase the number of release sites from four to eight and remove debris near salvage release sites monthly from October through June to reduce the predation loss of salvaged splittails and other fish once released.

Juvenile splittail would be vulnerable to increased predation mortality in the vicinity of the proposed north Delta intake locations during their emigration from upstream spawning habitats on the Sacramento River such as the Sutter Bypass. Splittail do not appear to be a substantial part of the diet of striped bass around the Sacramento River reach where the proposed north Delta intakes would be sited. Results of striped bass diet studies conducted by Thomas (1967) showed that no splittail were observed in the striped bass sampled. Stevens (1963) also conducted diet studies on striped bass in the reach of the Sacramento River upstream of Rio Vista and found splittail in the diet of striped bass. However, he reported only 1.4% of the striped bass stomachs that contained food had splittail, representing 1% of the diet of striped bass in July. Splittail were not observed by Stevens in the diet of striped bass in other months of the year. For purposes of this effects analysis, it is assumed that juvenile splittail would be vulnerable over a 4-month period in the late spring and summer (April–July) when, on average, nearly all juvenile splittail emigrate. Predator control measures (CM15) are being proposed for the north Delta sites to reduce the risk of predation on splittail and other covered fishes.

The bioenergetics model developed by Loboschefsky and Nobriga (2010) was used to estimate predation of splittail at the north Delta intakes. The methods for this bioenergetics approach for determining splittail predation loss are the same as those for the juvenile salmon bioenergetics analysis, except that splittail abundance and splittail fork length estimates were calculated on a monthly average instead of weekly. Under the assumption of 133 striped bass per intake (total of 665 striped bass at north Delta intakes), 198,835 splittail are consumed by striped bass in the early long-term and 212,119 splittail are consumed in the late long-term with no predator control. If predator control under CM15 was effective at removing 15% of the predators around the north Delta intakes (only 565 total predators instead of 665), the number of splittail consumed would decrease to 198,835 in the early long-term and 212,119 in late long-term (Table F.5-12). The effect of a 15% predator removal may be understated, if targeted removal is more effective at removing larger, more piscivorous fish predators than the smaller, younger predators.

Table F.5-12. Number of Sacramento Splittail Consumed by Striped Bass at North Delta Intakes with and without Predator Control (15% Removal)

Striped Bass Numbers		Splittail Consumed (Estimated Number)				Reduction in Splittail Predation losses	
Estimated per Diversion	Total	Without Predator Control		With Predator Control			
		ELT	LLT	ELT	LLT	ELT	LLT
20 (low)	100	29,900	31,898	25,415	27,113	4,485	4,785
133 (med)	665	198,835	212,119	169,010	180,301	29,825	31,818
245 (high)	1,225	366,275	390,745	311,259	332,054	55,016	58,691

F.5.3.4.2 Habitat Restoration (Conservation Measures 2, 4, 5, 6, and 7)

The effect on splittail predation risk from proposed habitat restoration is unknown, but the general effect is expected to be similar to that for salmon and steelhead. Both juvenile and adult splittail are known to readily occupy shallow-water habitats; therefore, the efforts to restore shallow tidal habitats, seasonal wetlands, and channel margins likely will be beneficial to the species. However, if these restored areas are recolonized by IAV, splittail may suffer increased predation risks from predators like largemouth bass.

All life stages of splittail on the Yolo Bypass floodplain are vulnerable to predation from catfish, centrarchids, and birds, but the high turbidity often found on the floodplain may reduce predation risk (Sommer et al. 2008). The risk to splittail in restored shallow-water tidal zones and floodplains depends on how readily piscivorous predators use these areas (see Section F.5.3.1.2 for benefits and risks to Chinook salmon and steelhead). Feyrer and coauthors (2006) analyzed seasonally inundated floodplain habitat in the Yolo Bypass using rotary screw traps and found striped bass in only 22% of samples and largemouth bass in 12% of samples. Most of the occurrence of striped bass in the Yolo Bypass occurred in June, by which time most covered juvenile fishes have migrated from the area. Chinook salmon and splittail represented 79% of all individuals collected in the intentionally inundated floodplains, suggesting that floodplain habitat restoration benefits native fish species like splittail more than nonnative fish predators (Feyrer et al. 2006).

F.5.3.4.3 Nonnative Aquatic Vegetation Control (Conservation Measure 13)

Benefits and risks from CM13 are assumed to be similar to the effect for Chinook salmon (see Section F.2.4.1.2) based on the similar size of juvenile splittail and salmonids in the Delta.

Removal of IAV would be expected to benefit splittail by reducing habitat for predators.

F.5.3.4.4 Predator Removal (Conservation Measure 15)

Anecdotal observations indicate that recreational anglers have collected and used splittail as bait to catch striped bass. Similarly, golden shiner, a fish similar in size and body shape to a juvenile splittail, commonly are used as bait to catch both striped bass and largemouth bass. It has been presumed, therefore, that splittail are actively consumed by bass species.

Nobriga and Feyrer (2007) surveyed the diet of striped bass, largemouth bass, and pikeminnow in the Delta and reported that splittail were present in only three out of 608 predators sampled (0.5%). While it is reasonable to suspect predation of splittail does occur in the Delta, there is low certainty of its significance to the species. While predator removal may reduce the level of predation losses of splittail, the benefit of this action to the population is not known. There is also the potential to initiate a compensatory release of other species of predatory fish, if only certain predators such as largemouth bass and striped bass are targeted for removal. Targeted removal of predatory fish large enough to prey on listed species could fail to reduce total predation losses of listed fishes in the Delta as other non-targeted piscivorous fish populations increase in size. A potential risk of localized predator removal is bycatch of splittail during electrofishing, fyke or gill netting, or other capture methods meant to remove predators.

F.5.3.4.5 Nonphysical Fish Barriers (Conservation Measure 16)

The benefits of the installation of nonphysical barriers to Sacramento splittail are unknown. Although nonphysical barriers are constructed and operated mainly with salmonids in mind, splittail also are likely to be deterred by the nonphysical barriers based on their hearing ability and strong swimming ability as young juveniles. During wetter years, splittail may migrate up the Sacramento and San Joaquin Rivers beyond the northern and southern boundaries of the Delta and therefore are likely to encounter the nonphysical barriers at the head of Old River and Georgiana Slough. Although nonphysical barriers likely will be operated to coincide mainly with the juvenile salmonid emigration period, juvenile splittail outmigration to the Delta is most likely during April–August (Moyle 2002). Therefore, the first months of the juvenile Sacramento splittail migration to the Delta overlap the main juvenile salmonid outmigration period. If nonphysical barriers are effective at deterring splittail from areas with high mortality rates, such as Georgiana Slough, the risks of predation for juvenile splittail are reduced. The nonphysical barriers have the potential to attract predatory fish, which often hold around underwater human-made structure. Therefore, there is a slightly increased risk of predation for juvenile splittail in the area immediately around the nonphysical barriers.

F.5.3.4.6 Nonproject Diversions (Conservation Measure 21)

The extent to which Sacramento splittail are entrained in unscreened nonproject diversions (e.g., small agricultural diversions), along with the benefits and risks relative to entrainment associated with this conservation measure, has been discussed in Appendix 5.B, *Entrainment*.

The primary risk associated with this conservation measure for Sacramento splittail relates to:

1. The additional structural components (e.g., screens, support beams, trash racks) required for screening nonproject diversions, which may attract predatory fish.
2. The spatial distribution of nonproject diversions relative to the distribution of Sacramento splittail in the Delta.
3. The seasonal overlap of diversion operations and Sacramento splittail distribution in the Delta.

F.5.3.5 Green and White Sturgeon

F.5.3.5.1 Water Operations and Facilities (Conservation Measure 1)

Reduced exports in the south Delta from the construction of the north Delta intakes, which would be expected to reduce the number of sturgeon exposed to predation at the south Delta facilities, may reduce net entrainment of green and white sturgeon. Increased presence of predators around the north Delta intakes may increase predation loss of juveniles emigrating downstream to rear in the

Delta. Juvenile sturgeon begin to emigrate at a small size and may be small enough still to be preyed upon by piscivorous fish as they pass by the north Delta facilities. Juvenile sturgeon grow very rapidly early in their development. Green sturgeon juveniles reach up to 30 cm the first year and exceed 60 cm in the first 2–3 years (Nakamoto et al. 1995). Their larger size and protective bony plates (scutes) make them much less vulnerable to predation.

F.5.3.5.2 Habitat Restoration (Conservation Measures 2, 4, 5, 6, and 7)

The creation of permanent tidal brackish habitat in Suisun Marsh would create permanent year-round rearing habitat for juveniles of both species of sturgeon. Once these habitats become fully established, they are expected to provide highly productive food and refuge habitats. Because of their salinities, these habitats would be expected to provide some refuge from black bass. Also, because younger juvenile sturgeon are less tolerant of saltwater, juveniles that occupy these brackish habitats are likely larger and have developed armored bony plating to substantially reduce predation vulnerability. Predator control measures (CM15) may serve as a modest benefit to protect small juvenile sturgeon that can be vulnerable to predation risks, but benefits can be expected to be limited as sturgeon can quickly outgrow the hunting ability of the piscivorous commonly fish found in the Delta.

F.5.3.5.3 Nonnative Aquatic Vegetation Control (Conservation Measure 13)

The effect of IAV removal on predation risk for sturgeon is expected to be low. Larval and juvenile sturgeon inhabit the lower reaches of the Sacramento River, San Joaquin River, and the Delta (Stevens and Miller 1970), where they tend to concentrate in deeper areas of the estuary with soft mud and sand substrate (Moyle 2002); these areas generally lack IAV and would not be areas targeted for IAV removal. Sturgeon grow rapidly and can quickly outgrow the size range where predation could occur (Nakamoto et al. 1995). Sturgeon also have protective scutes, making them unappealing to predators even at a young age.

F.5.3.5.4 Predator Removal (Conservation Measure 15)

Little is known about predation of juvenile sturgeon in the Delta. Sturgeon grow rapidly in their first year of development and grow protect bony plating at an early age. For example, white sturgeon juveniles rearing in the Delta reach 18–30 cm fork length in their first year (Moyle 2002). Likewise, young green sturgeon grow quickly in their first year, probably reaching 30 cm (12 inches) in their first year (Kohlhorst and Cech 2001). Because of their rapid growth early in their development (Nakamoto et al. 1995), the period in which juvenile sturgeon are vulnerable to piscivorous fish predators in the Delta likely is limited.

Studies in the Columbia River basin show predation of very young juvenile sturgeon by northern pikeminnow and prickly sculpin is quite common in upstream reaches (Miller and Beckman 1996). Based on information from the Columbia River, it is presumed that predation of juvenile sturgeon in the upper reaches of the Sacramento River basin is likewise common by Sacramento pikeminnow and prickly sculpin. If most of the predation of juvenile sturgeon occurs in the upper Sacramento River basin, predator control measures in the Delta may have little effect on reducing total juvenile sturgeon predation losses. Sturgeon are benthic feeders which may limit their encounters with pelagic predators like striped bass.

One potential risk of localized predator removal is bycatch of green and white sturgeon during beach seining, gill netting, angling, electrofishing, and other capture methods. Sturgeon tend to reside in deepwater areas and should be protected from electrofishing, but they would be more susceptible to injury because of their large size. Striped bass monitoring by DFG at Knights Landing using fyke traps caught four adult green sturgeons in 16,100 hours; gill netting on the lower Sacramento resulted in the capture of two green sturgeons in 15,450 hours (Dubois and Mayfield 2009; Dubois et al. 2010). Adult sturgeon are not susceptible to being caught using artificial lures commonly used to catch striped bass but would be susceptible to baited hooks. Injuries to sturgeon would be similar to those experiences by salmonids discussed above. Adult sturgeon in deep water should be able to avoid most types of nets. Adult sturgeon caught in nets (fyke, beach seine, or gill nets) could suffer injuries similar to salmonids.

F.5.3.5.5 Nonphysical Fish Barriers (Conservation Measure 16)

The effect on sturgeon from predation associated with the construction of nonphysical barriers is unknown. Green sturgeon are not known to spawn currently in the San Joaquin River, although they may have historically (Moyle 2002; Beamesderfer et al. 2007). White sturgeon still spawn in the lower San Joaquin River, although likely only in wet years (Moyle 2002; Beamesderfer et al. 2007). Therefore, the level of interaction of sturgeon juveniles with the Old River nonphysical barrier is likely to be minimal. Both green and white sturgeon are known to spawn upstream in the upper Sacramento River basin (Moyle 2002), and emigrating juveniles likely will encounter the Georgiana Slough barrier. Nonphysical barriers are likely to attract piscivorous predators hiding among the physical structures of the barrier and may create an increased predation risk for small sturgeon juveniles. Sturgeon are not deterred by the sounds and lights of the barrier, in part due to their lack of specialized hearing structures and swimbladders, and therefore would not be deterred from entering areas of the central Delta associated with high predation. Additionally, the head of Old River and Georgiana Slough nonphysical barriers have been designed to allow passage of sturgeon under the barrier structure.

F.5.3.5.6 Nonproject Diversions (Conservation Measure 21)

The extent that sturgeon are entrained in unscreened nonproject diversions (e.g., small agricultural diversions), along with the benefits and risks relative to entrainment associated with this conservation measure, has been discussed in Appendix 5.B, *Entrainment*.

The primary risk associated with this conservation measure for sturgeon relates to:

1. The additional structural components (e.g., screens, support beams, trash racks) required for screening nonproject diversions, which may attract predatory fish.
2. The spatial distribution of nonproject diversions relative to the distribution of sturgeon in the Delta.
3. The seasonal overlap of diversion operations and sturgeon distribution in the Delta.

F.5.3.6 Lamprey

F.5.3.6.1 Water Operations and Facilities (Conservation Measure 1)

Lamprey have been observed in fish salvage operations at both the SWP and CVP fish salvage facilities. Because of the difficulty in distinguishing between juvenile Pacific lamprey and river lamprey, salvage data do not differentiate between the two species. Approximately 79% of lamprey salvage between 1993 and 2004 at state and federal facilities occurred during January and February (refer to Appendix B, *Entrainment*). Previous diet studies (Stevens 1966; Nobriga and Feyrer 2007) did not find a single Pacific or river lamprey in the gut of striped bass, largemouth bass, or Sacramento pikeminnow, despite examining thousands of predator guts (9,197 striped bass, 320 largemouth bass, and 322 pikeminnow combined in the two studies). However, the sampling periods of these studies (Stevens 1966: February–November; Nobriga and Feyrer 2007: March–October) did not generally overlap peak lamprey migration periods. Therefore, it is reasonable to assume that predation of lamprey occurs in the Delta, although there is low certainty of the effect that predation has on the species.

No studies have been performed to assess the vulnerability of lamprey to predation in the CCF as a consequence of fish salvage operations. Reduced exports from the south Delta will reduce the total number of lamprey entrained at the export facilities, but the proportion of entrained lamprey lost to predation is expected to remain the same under CM1. Lamprey are expected to experience increased predation in the Sacramento River due to the construction of the north Delta export facilities, although the certainty is very low.

F.5.3.6.2 Habitat Restoration (Conservation Measures 2, 4, 5, 6, and 7)

Although there is low certainty regarding their behavior in the Delta, lamprey macropthalmia likely use the Delta primarily as a migration corridor, as evidenced by low catches in beach seines in back sloughs and higher catches in beach seines in mainstem sampling (U.S. Fish and Wildlife Service unpublished data). Only a small proportion of the proposed habitat restoration will be located along major migration corridors, such as the mainstem Sacramento and San Joaquin Rivers, in the West and South Delta ROAs. Therefore, lamprey are presumed not to spend large amounts of time in restored tidal marsh or floodplain habitat. Assuming tidal marsh and floodplain restoration sites will be designed properly to avoid simply creating new habitat for nonnative predators, habitat restoration will result in a small reduction in exposure of lamprey macropthalmia to predators using this habitat, and therefore, a small benefit to lamprey macropthalmia, with low certainty regarding this conclusion. If restored habitats are recolonized by IAV, the benefit of habitat restoration for lamprey in terms of predation may be reduced because of the increased presence of piscivorous largemouth bass.

F.5.3.6.3 Invasive Aquatic Vegetation Control (Conservation Measure 13)

As noted above, lamprey appear to use the Delta primarily as a migration corridor. IAV removal along main migration corridors could have some benefits similar to those assumed for juvenile Chinook salmon by reducing local abundances of centrarchids. However, there is high uncertainty regarding microhabitat use by migrating lamprey and their exposure to predators associated with IAV.

F.5.3.6.4 Predator Removal (Conservation Measure 15)

It is reasonable to assume that predation of lamprey could occur in the Delta, although there is low certainty of the effect that predation has on the species. For this analysis, it is assumed that this predation rate during the months when lamprey are in the Delta is similar to that of Chinook salmon. A potential risk of localized predator removal is incidental bycatch of lamprey by practices such as electrofishing.

F.5.3.6.5 Nonphysical Fish Barriers (Conservation Measure 16)

Effects on lamprey species from predation associated with the construction of nonphysical barriers are unknown. River and Pacific lamprey both are known to inhabit reaches of the Sacramento and San Joaquin River basins upstream of the Delta, so they will encounter the nonphysical barriers at Georgiana Slough and the head of Old River. The nonphysical barriers are likely to attract piscivorous predators hiding among the physical structures of the barrier. Unlike salmon, lamprey are not deterred by the sounds and lights of the barrier, and therefore are not deterred from entering areas of the Delta associated with high predation.

F.5.3.6.6 Nonproject Diversions (Conservation Measure 21)

The extent to which lamprey are entrained in unscreened nonproject diversions (e.g., small agricultural diversions) along with the benefits and risks relative to entrainment associated with this conservation measure, has been discussed in Appendix 5.B, *Entrainment*.

The primary risk associated with this conservation measure for lamprey relates to:

1. The additional structural components (e.g., screens, support beams, trash racks) required for screening nonproject diversions, which may attract predatory fish.
2. The spatial distribution of nonproject diversions relative to the distribution of sturgeon in the Delta.
3. The seasonal overlap of diversion operations and sturgeon distribution in the Delta.

F.5.4 Uncertainties and Research Needs

F.5.4.1 Uncertainties

F.5.4.1.1 Water Facilities and Operation (Conservation Measure 1)

Despite a good understanding of what flow levels entrain salmon into the central Delta and to what extent north Delta diversions affect flow patterns, there is still uncertainty regarding overall effects of the new diversions on predation. Uncertainty exists relative to:

1. The degree to which predators will aggregate at north Delta intakes.
2. The magnitude of losses due to predation at these facilities.
3. The amount of predation losses in the central Delta and any changes due to reduced flow downstream of the new north Delta intakes, which could affect movement of juvenile salmonids.

Uncertainty also exists with estimates of predation and mortality at the south Delta facilities (Gingras 1997; Clark et al. 2009; Castillo et al. in review). These estimates often are based on studies of tagged hatchery juvenile salmonids, which may be more vulnerable to predation than wild fish.

F.5.4.1.2 Habitat Restoration (Conservation Measures 2, 4, 5, 6, and 7)

Uncertainties associated with habitat restoration activities revolve around the extent that habitat restoration activities create predator habitat or encourage predator concentration in areas used by covered fish species. The uncertainty regarding a beneficial outcome is high because data do not exist to estimate the fraction of salmonid fishes that are expected to be lost to predators as a result of changing flow and/or habitat conditions. The lack of data on how different bypass flows would affect shallow-water habitat, travel time, and flow splits adds to the uncertainty.

F.5.4.1.3 Invasive Aquatic Vegetation Control (Conservation Measure 13)

While removal of IAV beds has a high likelihood of locally reducing opportunities for predation by removing habitat favored by largemouth bass, it is unclear whether control efforts would be at a sufficient scale to increase turbidity, which provides cover for smelt.

F.5.4.1.4 Predator Control (Conservation Measure 15)

Efforts to reduce predation opportunities, such as eliminating structures and conditions that aggregate predators near covered fish species, have a greater likelihood of success than predator removals. The extent that predator control in the Delta can improve survival of covered fish species is unknown relative to existing biological conditions in the Delta. Uncertainties exist regarding both (1) the effectiveness of predator removal and (2) the response by predator and prey populations.

Actions to remove predators have a high degree of uncertainty. Removal efforts may not capture a large enough fraction of the local predator population to sufficiently reduce consumption of covered fish species. Capture success is likely to vary depending on predator size, species, and local habitat conditions. The durability of reductions is uncertain because predators are likely to move back into the area and some species, like striped bass, are highly mobile. There is a lack of strong evidence on the benefits of predator removal. Examples from predator control efforts elsewhere, such as the Columbia River (Porter 2010) and Colorado River (Mueller 2005), suggest that efforts must be sustained to achieve any benefits.

Another significant area of uncertainty regards the response of fish populations to predator reduction. The untested hypothesis of a control program is that predation by striped bass and largemouth bass regulates populations of salmon, steelhead, and smelt and that other predators play a minimal role. Estimates of predation pressure are variable and rough because of uncertainties regarding rates of predator-prey encounters, abundance of predators and prey, and other life history factors that affect capture and consumption (e.g., size and structure of local predator population, bioenergetics).

Uncertainty about expected outcomes is high because data are lacking or limited to estimate the fractional increase in covered fish populations resulting from predator control actions such as focused predator removal and structure removal or modification. The magnitude of the prey species' response to a predator reduction program is difficult to predict. Models suggest that predators could affect prey numbers (e.g., Lindley and Mohr 2003), but these estimates are not necessarily proven. Striped bass and largemouth bass are generalist predators, and predation pressure on a single prey species may not be high. Thus, the magnitude of the prey species response to reduced predator population size is difficult to predict. Removal of predators could trigger a compensatory response by other predators or by more favored prey species such as threadfin shad, juvenile striped bass, and inland silverside (*Menidia beryllina*). Silversides may compete with delta smelt for copepod prey and may prey on eggs or larvae (Bennett and Moyle 1996).

Assumptions regarding manipulation, alteration, and management of predator/prey interactions are uncertain. Therefore, conservation measures that rely on control of predator species might be regarded with uncertainty until proven otherwise.

F.5.4.1.5 Nonphysical Fish Barriers (Conservation Measure 16)

The effectiveness of nonphysical barriers and their interaction with predators is based on limited testing; thus, outcomes for salmonids remain uncertain.

Uncertainties associated with nonphysical barriers and other fish population factors revolve around the degree to which these activities create predator habitat, encourage predator concentrations in localized areas occupied by covered fish species, and/or influence their migration patterns through or in the Delta.

Tools such as the DPM, which uses extensive datasets on salmon survival through various Delta migration routes, could be improved or modified to better quantify the effects of predation at nonphysical barriers. Although constrained to an analysis of the effects on salmon, the DPM could add a barriers component or a submodel could be presented as a stand-alone. The baseline condition would be the number of salmon that would die without the barrier in place because they were routed down Georgiana Slough; the contrast is the number that would die with the barrier in place.

F.5.4.1.6 Nonproject Diversions (Conservation Measure 21)

Two studies, prompted by indications that some screens increased predation rates on juvenile Chinook salmon by providing holding areas for predatory fish, were found to be inconclusive (Moyle and Israel 2005). While some screens may be detrimental because of predation on fish species of concern, the effect of individual diversions on these species is likely highly variable, depending on size, location, type (retractable of not retractable), and timing of diversion (seasonal use). Whether there are detrimental effects of screening, including increased predation on species of concern, there simply is not enough information currently available to support a conclusion. Therefore, there is considerable uncertainty regarding the effect of nonproject diversion screening on predation rates on covered fish species.

F.5.4.1.7 Fish Species

Delta Smelt

Very limited quantitative information is available regarding the current magnitude of smelt loss to predation. To the extent localized predator control efforts reduce the overall abundance of pelagic predators in the system, smelt would be expected to experience some reduction in loss to predation. However, it is expected that the effect of local predator reduction efforts generally would provide a minor to negligible benefit to the overall delta smelt population. Localized predator control measures would reduce predation locally but may not have a discernible effect on the overall populations of striped bass. As striped bass are mobile predators, these efforts would provide some minor benefit, but these benefits would not be expected to be of the same level as in the immediate area of removal.

The estimated number of delta smelt lost to predation mentioned above may not reflect current consumption rates, as delta smelt are currently less common than they were when the studies upon which the estimate was based were performed. In addition, Nobriga and Feyrer (2007) did not observe littoral predators consuming any delta smelt. Whether the removal efforts described above produce year-over-year cumulative reductions in overall striped bass abundance will depend on any compensation response in the striped bass population. However, the number of striped bass removed represents only a small fraction of the total number of striped bass, and therefore the removal program may not actually have a discernible effect on smelt numbers.

Another uncertainty involves whether reducing local abundances of predators like striped bass and largemouth bass results in predatory releases of other smaller piscivorous fish like silversides. Such a response could result in a situation where total predation loss of covered fish by striped bass and largemouth bass is reduced, but compensated for by other piscivorous fishes. The effect of predation control measures focused around SWP and CVP pumping facilities and around fish salvage release sites for Delta smelt populations is also not yet known.

Longfin Smelt

Uncertainties of effects on longfin smelt associated with predator control would be similar to those described for delta smelt, although they may be somewhat reduced because longfin smelt occupy a smaller area in the Delta.

Another uncertainty of predator removal is whether a compensatory response will occur. Decreases in delta smelt mortality from predation on juveniles by striped bass can be subject to compensation from other sources.

Chinook Salmon

Juvenile Chinook salmon are expected to inhabit restored channel margin habitat located along the Sacramento River as resting and foraging areas during downstream migration. Many of the covered fish, such as juvenile Chinook salmon, steelhead, splittail, and sturgeon, use shallow-water habitat for juvenile rearing and foraging. Shallow-water areas also attract and provide habitat for a variety of native and nonnative predatory fish, including striped bass, largemouth bass, bluegill, sunfish, Sacramento pikeminnow, white catfish, and others (Brown 2003; Nobriga and Feyrer 2007). How created shallow-water habitat develops can affect to what extent different fish species use these areas. For instance, shallow Delta habitat dominated by egeria appears to provide mainly rearing habitat for centrarchid and other nonnative fish species potentially at the expense of native fishes (Brown 2003; Feyrer and Healey 2003; Grimaldo et al. 2004; Nobriga et al. 2005; Brown and Michniuk 2007). Grimaldo and coauthors (2000) reported high rates of predation mortality for tethered juvenile Chinook salmon in shallow-water habitats both with IAV (predation rate 95%) and without vegetation (79% predation rate). In addition, it was thought that at certain pikeminnow hot spots a removal rate of 10 to 20% could reduce their predation on juvenile salmonids by 50% (Porter 2010).

There are no reliable abundance estimates for steelhead, and very little research has looked at juvenile steelhead vulnerability to predation. As a result, many of these gaps in knowledge are filled using Chinook salmon as a model for steelhead. Although Chinook salmon and steelhead juveniles are similar in many aspects, using predation rates on Chinook salmon juveniles as a model for steelhead is largely an unproven method.

Uncertainty also exists regarding the effect that restored shallow-water habitat will have on steelhead populations. Colonization of the restored aquatic habitat by nonnative invasive submerged aquatic plants as well as colonization by predatory fish such as striped bass, largemouth bass, pikeminnow, and others may reduce estimated benefits. Although increased access to intertidal and subtidal habitat in the western Delta has been identified as a net benefit to steelhead, there is uncertainty associated with the quantitative magnitude of net benefits associated with the design, habitat suitability, food production, and resulting increases in juvenile growth rates and survival associated with expansion of channel margin aquatic habitat in the western Delta (Brown 2003).

Another uncertainty to predator removal is whether a compensatory response will occur. Decreases in steelhead mortality from predation on juveniles by striped bass can be subject to compensation from other sources.

Sacramento Splittail

The extent of predation on splitttail by nonnative predators is unknown. As discussed above, it is reasonable to suspect predation of splittail does occur in the Delta, but there is low certainty of its importance to the species. Several Plan conservation measures have the potential to affect predation on splittail, including habitat restoration, changes in lower Sacramento River flow, and north Delta intake structures.

Anticipated flow reductions may result in little change on predation on juvenile splittail in drier years but could result in a substantial increase in predation in wetter years. The north Delta intakes will provide new habitat for piscivorous fish such as striped bass, resulting in increased predation on juveniles. The increases could be substantial; however, this conclusion is highly uncertain because the actual predation rates by striped bass and other Delta piscivores on splittail are unknown. Overall, the conservation measures to control predators and removal of IAV could result in minor reductions in predation with respect to predation on splittail, but the magnitude of effects is uncertain.

Another uncertainty to predator removal is whether a compensatory response will occur. Decreases in splittail mortality from predation on juveniles by striped bass can be subject to compensation from other sources.

Green and White Sturgeon

There are no reliable abundance estimates for green or white sturgeon in the Delta.

The predation rate on juvenile sturgeon is largely uncertain, but it is probably low because of their exterior armor and large size even as juveniles.

F.5.4.2 Research Needs

Understanding of predator-prey interactions in the Delta and the elements key to the relationship needs to be improved. Even if predator control at hot spots is shown to be effective, it will be necessary to evaluate the effect of such control at the scale of the estuary in order to determine whether predator control is beneficial to specific fish populations.

In addition, even if the exact predation rate on covered fish species is known, knowing total mortality rates for covered fish species and their population's compensatory responses is necessary to put the predation rate into any kind of meaningful context . Therefore, research is needed to establish the relevance of predation on covered fish species population dynamics.

Tools such as the DPM, which uses extensive datasets on salmon survival through various Delta migration routes, could be improved or modified to better quantify the effects of predation at localized hot spots, physical and nonphysical barriers, and habitat restoration sites. Although constrained to an analysis of the effects on salmon, the DPM might add components, or submodel presented as a stand-alone, addressing localized predator control, barriers, or restoration actions.

In addition, more studies similar to the before-after-control-impact design used by Cavallo and coauthors (in press) are needed and could be focused on currently known local hot spots for predation, such as the scour hole at the head of Old River. These types of studies would provide critical information regarding the success of predator control activities, especially those related to localized predator control. A similar type study could be considered for the CCF to determine whether predator control in the forebay does in fact reduce predation loss there.

Some covered species research needs are listed below.

- What is the extent of predation pressure on smelt eggs and larvae by native and nonnative predators?
- What is the extent of predation pressure on smelt juveniles and subadults by native and nonnative predators?
- What is the significance of turbidity relative to predation on smelt in the Delta?
- Will predator removal activities result in release of other native or nonnative predators or competitors?
- What is the degree of predation/competition in floodplains on native covered fish species by nonnative species?
- What is the relative effect of different predators, both predatory fish and others animals such as birds, in restored habitats?
- Is there potential for cascading effects that could affect community structure?
- More information is needed regarding the current effect of nonproject diversions on covered fish species, including predation occurrence at these sites and the predation rate(s) on covered fish species.
- While it is expected that the effect of individual diversions vary, depending on size, location, type and use (seasonally, intermittent, etc.), research is needed to document this in the Delta.
- Intensive before and after studies are needed at nonproject diversion sites, documenting predator occurrence and predation rates on covered fish species.
- What is the relative importance of predation mortality on total mortality rates of covered fish species?
- More detailed analyses of predator abundances associated with human-made structures is needed.
- What is the rate of incidental take of covered species when practicing predator removal programs (i.e., bycatch)?

After further study, more information regarding the importance of predation on covered species may be better understood, and effective predator management programs can be developed.

F.5.5 Conclusions

Predation is a natural ecosystem process. In the Delta, however, there is considerable uncertainty and lack of understanding as to what constitutes a balanced predator-prey relationship. Nevertheless, there are certain situations regarding fish predation in the Delta that are considered important enough to pursue through the BDCP conservation strategy. These include:

1. Localized predator hot spots.
2. Predator attraction to new structures (e.g., new diversions, nonphysical barriers).
3. Predator attraction to restored habitat sites.
4. The significance of IAV as predator habitat.
5. The attraction of predators to the numerous, relatively small nonproject (agricultural) diversions in the Delta.

Implementation of the water and facilities conservation measure (Conservation Measure 1) would decrease predation on covered fish at the south Delta facilities although predation at the new north Delta facility will occur.

At the south Delta CVP and SWP facilities, losses due to predation have been estimated at 75% for salmonids in the SWP CCF and 15% for the CVP facilities, and exceeding 90% for delta smelt at the CCF. Once the north Delta facility is operating, reduced pumping at the south Delta facilities is expected to result in the substantially reduced entrainment and consequently reduced predation of covered fish species at the facilities. Based on studies of tagged fish released at the CCF, these estimates of predation at the south Delta facilities may be conservative.

The construction of the north Delta export facilities on the Sacramento River likely will attract piscivorous fish around the intake structures. Bioenergetics modeling (modified from Loboschefsky and Nobriga) of striped bass abundance and consumption rates was used to estimate predation losses of juvenile Chinook salmon, steelhead, and splittail. While losses of Chinook salmon and steelhead are predicted to be substantial (thousands), the population level effect is minimal (less than 1%) compared to the annual production estimated for the Sacramento Valley. The BDCP bioenergetics model likely overestimates predation of juvenile salmon and splittail because of simplified model assumptions (e.g., perfect capture efficiency by all size classes of striped bass).

Some of the benefits associated with implementation of habitat restoration measures (Conservation Measures 2, 4, 5, 6, and 7) could be offset by an increase in predation by centrarchid fishes if these areas are colonized by invasive aquatic vegetation; control of invasive aquatic vegetation (Conservation Measure 13) and removal of predators in "hot spots" (Conservation Measure 15) should minimize this effect.

If restored habitats become recolonized by IAV, they could provide potential habitat for predatory species. As such, predation risks would increase as largemouth bass become more prevalent in those areas. Fish predators use seasonal wetlands, although warmwater species such as centrarchids typically spawn later in the year when covered fish have already started to emigrate. Habitat design and maintenance to discourage use of the restored areas, including removal of IAV, should minimize this effect. Additionally, these restored areas may be targeted for predator removal during key occurrence of covered species in these areas, which may also reduce this effect.

Removal of predatory fish at targeted localized hot spots (Conservation Measure 15) would reduce predation on covered fish species for short periods in these areas.

Predatory fishes such as striped bass and largemouth bass prey on covered fish species and can be locally abundant at predation hot spots. Adult striped bass are pelagic predators that often congregate near screened diversions, underwater structures, and salvage release sites to feed on concentrations of small fish, especially salmon. Striped bass are a major cause of mortality of juvenile salmon and steelhead near the SWP south Delta diversions (Clark et al. 2009). Largemouth bass are nearshore predators associated with beds of IAV.

Targeted predator removal at hot spots would reduce local predator abundance, thus reducing localized predation mortality of covered fish species. Predator hot spots include submerged structures, scour holes, riprap, and pilings. Removal methods will include electrofishing, gill netting, seining, and hook and line. Predator removal measures will be highly localized. As such, they would not appreciably decrease Delta-wide abundances of predatory game fish. Additionally, intensive removal efforts inadvertently could result in bycatch and take of covered species in localized areas.

The benefits of targeted predator removal are likely to be localized spatially and of short duration unless efforts are maintained over a long period of time, but could be key to reducing predation during important migration or other periods. Removal of predators even at a localized scale will be difficult to achieve and maintain without a substantial level of effort. Highly mobile predators like striped bass can rapidly recolonize targeted areas within a matter of days, implying that predator removal will need to be conducted at frequent intervals when covered species are migrating. Overall Delta-wide benefits of focused predator removal are uncertain.

Efforts to reduce fish predation (Conservation Measure 15) have inherent uncertainties at the population scale.

The overall benefit for covered fishes at the population scale is uncertain because (1) local predator controls may not appreciably reduce the size of populations of fish predators Delta-wide and (2) there are uncertainties surrounding the cause and effect relationships between Delta predators and prey that make it difficult to predict the role of piscivorous fish in controlling the size of fish populations Delta-wide (Durand 2008). Predator-prey dynamics are influenced by many interacting factors that directly and indirectly influence prey encounter and capture probabilities (Mather 1998; Nobriga and Feyrer 2007; Lindley and Mohr 2003), such as habitat overlap between predator and prey, foraging efficiency by predators, energetic demands of predator, size, life stage, behavior, and relative numbers of predators and prey. Fish are opportunistic foragers that readily switch from one food species to another to capitalize on highly abundant organisms and therefore tend not to limit annual recruitment.

Nonphysical fish barriers (Conservation Measure 16) could reduce fish predation by deterring covered fish from predation hot spots.

Nonphysical barriers at the head of Old River and at Georgiana Slough are designed to deter juvenile salmonids from entering certain reaches of the Delta associated with poor survival. These barriers operate by using strobe lights and speakers to deter juvenile fish, with a bubble curtain designed to contain the noise and form a wall of sound. Salmon, steelhead, and splittail are expected to be effectively deterred. Sturgeon and lamprey are not expected to be deterred by the presence of the barriers. Delta smelt may be deterred to some extent, although weak swimming as young juveniles decreases their ability to avoid the barriers. Longfin smelt are distributed too far west in the Delta to encounter the nonphysical barriers. There may be a slight risk of predation related to the underwater structures associated with nonphysical barriers that may attract fish predators. If needed, targeted predator removal activities would be implemented in these areas.

Consolidation and screening of nonproject diversions (Conservation Measure 21) in the Delta will have an unknown effect on fish predation.

Much of the effect will depend on where in the Delta these nonproject diversions are, how/when they are operated, the size/extent of submerged structure associated with them, and how they will be modified. Installation of fish screens and other structures intended to reduce entrainment losses of covered fish actually may attract additional predators and increase localized predation risks.

F.6 Invasive Mollusks

F.6.1 Ecological Impact Pathways

F.6.1.1 Overbite Clam *Corbula amurensis*

The overbite clam *Corbula amurensis* (formerly *Potamacorbula amurensis*) was introduced to San Francisco Bay in 1986 from Asia, likely as larvae transported in ballast water, and spread rapidly throughout the estuary (Carlton et al. 1990). *Corbula amurensis* (*Corbula*) is abundant in the Carquinez Strait, San Pablo Bay, Suisun Bay, Grizzly Bay, and into the western Delta (Thompson 2000; California Department of Water Resources 2010b, 2010c). *Corbula* has displaced some members of the previous benthic community and is now a dominant component in some areas of the bay (Nichols et al. 1990).

Benthic invertebrate monitoring by DWR documented the highest *Corbula* densities in Grizzly Bay and Suisun Bay during summer or fall. For example, peak densities approached or exceeded 29,000 clams per square meter in 2008 and 2009 (California Department of Water Resources 2010b, 2010c). Abundance of *Corbula* declines each winter, likely due to increased predation pressure by diving birds and with high freshwater outflows (Poulton et al. 2002). Densities in Suisun Marsh vary among the sloughs (O'Rear and Moyle 2008, 2009). The vast majority of captures were in Goodyear and lower Suisun Sloughs (California Department of Water Resources 2001; Schroeter et al. 2006; O'Rear and Moyle 2008, 2009). *Corbula* densities were lower in Denverton Slough, located in upper Suisun Marsh, a narrower channel where salinity was lower and substrate was coarser material (O'Rear and Moyle 2009).

Corbula is a dioecious (sexes are separate), broadcast-spawning bivalve with external fertilization. It grows to around 2–3 cm in length. It is usually white, tan, or yellow with no markings on the external valves. *Corbula* burrows into sediments, leaving one half to two thirds of its shell exposed above the sediment to feed (National Introduced Marine Pest Information System 2012). *Corbula* spends most of its 2–3 year life in the sediment and spends about 3 weeks in the water column during its larval dispersal phase.

Juvenile *Corbula* clams become reproductively active at about 5 mm in length (Parchaso and Thompson 2002) which can occur within 2 months of recruitment. *Corbula* live 2–2.5 years at most locations and commonly reproduce twice a year but can continuously reproduce if conditions permit. Recruitment variability is a function of the availability of adults to produce larvae and site-specific environmental conditions.

Physiological tolerances of *Corbula* are summarized in Table F.6-1. Adult *Corbula* can tolerate weeks of exposure to salinities ranging from 0 to 35 ppt, but long-term survival is highest at salinities from 5 to 25 ppt (Nicolini and Penry 2000). All life stages appear to be euryhaline; fertilization occurs in a somewhat narrower range (5 to 25 ppt), but developmental stages between 12-hour ciliated blastula and adult can tolerate 2 to 30 ppt (Nicolini and Penry 2000). Additionally, gametes, embryos, and larvae of *Corbula* can tolerate step increases in salinity of at least 10 ppt, although rapid changes appear to reduce larval growth (Nicolini and Penry 2000).

Successful maintenance and expansion of the distribution of *Corbula* are facilitated by transport of the embryos and larvae with water currents after reproduction. Recruitment of the species into the northern portions of the estuary, including the reach from San Pablo Bay to the Lower Sacramento River (Peterson and Vayssieres 2010), is dependent on timing; spring outflow can prevent upstream migration even when salinity conditions are favorable. The ability of the clam's larval stage to tolerate a wide range of salinity and relatively large step changes may increase its ability to recruit successfully into estuary habitat (Nicolini and Penry 2000).

Table F.6-1. Habitat Requirements of Invasive Mollusks

Habitat Attribute	**Present in Delta (Clams)**		**Not Currently Present in Delta (Dresseinid Mussels)**	
	Corbula amurensis	***Corbicula fluminea***	***Quagga mussel***	***Zebra mussel***
Salinity tolerance	5–25 ppt fertilization 2–30 ppt larvae 5–25 ppt adult optimum ≥0.01–35 ppt adult tolerance (Nicolini and Penry 2000)	<2ppt larvae; ≤10 ppt adults (Aguirre and Poss 1999)	≤4–6ppt adults tolerance, less at higher temperatures (Cohen 2008)	≤2–4ppt at 3–12°C ≤1 ppt at warmer (Mackie and Schloesser 1996)
Temperature	8–23°C in Delta 0–28°C in native distribution (Cohen 2011)	2–30°C (Aguirre and Poss 1999)	4–27°C (Cohen 2008)	6–30°C (Cohen 2008).
pH	Greater densities at higher pH (tested at pH 7.2–8) (Glibert 2011)	pH 5.5–8.3 (Vidal 2002)		pH 7.4–9.4 larvae (Sprung 1993)
Substrate	Mud, sand, peat, and clay substrates. Does not recruit on hard substrates (Baxter et al. 2010)	All types used, but prefer intermediate size (Thorp 2010)	Found on hard substrates and deep, soft sediments (Wilson et al. 2006)	Prefer hard substrates, especially artificial ones (Mackie and Schloesser 1996).
Depth	Found intertidally, but most at subtidal depths (Carlton et al. 1990). Found at depths up to 30 meters	Found at wide range of depths (Thorp 2010); limited by anoxia	Common to 30 meters, possible up to100 meters	Common to 15 meters, possible up to100 meters
Dissolved oxygen	High tolerance of hypoxic conditions (McEnnulty 2001)	Relatively intolerant of low DO at high water temperatures (20–30ºC) compared to other bivalves (McMahon 1979)	Likely tolerant of hypoxic conditions based on their presence at deep depth (McMahon 1996)	Relatively intolerant of anoxic conditions, but adults can survive for short periods of time
Diet	Bacteria, phytoplankton, microzooplankton (e.g., *copepod nauplii*). Phytoplankton is dominant carbon source (Greene et al. 2011).	Bacteria, phytoplankton. Maximum prey size 20–20 µm (Way et al. 1990)	Phytoplankton, microzooplankton (Kissman et al. 2010)	Phytoplankton, microzooplankton (Kissman et al. 2010)

Corbula establishment occurred following a wet 1986 and expanded during the 1987–1994 drought. Peterson and Vayssieres (2010) examined DWR benthic monitoring data over 27 years at four locations in the estuary (San Pablo Bay, Grizzly Bay, Lower Sacramento River, and Old River) and found that benthic assemblage composition varied with salinity and hydrology but was not strongly associated with physical habitat attributes such as substrate. The invasion of *Corbula* in the Delta has coincided with increases in nutrient concentrations and shifts in nitrogen-to-phosphorus ratios (Baxter et al. 2010; Glibert 2010). Specifically, nitrogen-to-phosphorus (DIN:TP) ratios have increased over time, and *Corbula* abundance is strongly positively correlated with DIN:TP ratios over the long term (Glibert 2010). There is also evidence of a strong long-term positive relationship between pH and *Corbula* abundance, and *Corbula’s* pelagic larval stage appears to exhibit accelerated rates of calcification in summer when temperature and pH are elevated (Glibert et al. 2011). These adaptations may allow *Corbula* to outcompete other species during droughts or under dry conditions (Glibert et al. 2011), and when discharge of ammonia and ammonium from wastewater treatment plants results in ammonium toxicity for other species (Ballard et al. 2009). Glibert and coauthors (2011) have hypothesized that shifts in X2 position, changes in nutrient ratios, and habitat characterized by higher salinities and DIN:TP ratios may facilitate further expansion of *Corbula* distribution in the Bay-Delta.

The invasion of *Corbula* has dramatically altered the benthic and planktonic community by decreasing phytoplankton abundance and decreasing species richness (Kimmerer et al. 1994; Peterson and Vayssieres 2010; Baxter et al. 2010). *Corbula* is a highly efficient filter feeder that can alter foodweb dynamics at multiple levels (Kimmerer 2006; Greene et al. 2011). During summer when biomass is high, these clams potentially can filter the water column (vertical turnover) in Suisun Bay in about 2–4 days in shallow waters and deeper channels in about 4–8 days (Greene et al. 2011). This high consumption has drastically reduced phytoplankton blooms in the lower estuary and has caused major declines in the abundance of many planktonic invertebrates, including copepods (a primary prey item for delta smelt) (Kimmerer et al. 1994; Kimmerer and Orsi 1996; Moyle 2002). The invasion of *Corbula* has greatly reduced the phytoplankton bloom in summer in Suisun Bay (Alpine and Cloern 1992). Much of the decline in summer phytoplankton has been in diatom biomass, and the linkage between this decline and the introduction of *Corbula* is strong, with minor influences of freshwater flow and temperature (Jassby et al. 2002; Kimmerer 2005). Although production remains low (Jassby 2008), phytoplankton production has recovered to some extent in the Delta since the mid-1990s. At the same time, no trend has been apparent in phytoplankton in Suisun Bay, even though grazing by *Corbula* remains a factor. The zone of depleted chlorophyll has extended well beyond the geographic distribution of the clam (Pereira et al. 1992) because chlorophyll produced in Suisun Bay is no longer available to be delivered to upstream locations through tidal sloshing (Kimmerer and Orsi 1996; Jassby et al. 2002). The decline in phytoplankton biomass in the upper estuary, including the lower Sacramento and San Joaquin Rivers (Cloern and Jassby 2006), has led to food limitation (Mueller-Solger et al. 2002). Scientists hypothesize that export of phytoplankton production from the estuary is helping to maintain the Bay's zooplankton (Baxter et al. 2010).

While *Corbula* relies heavily on phytoplankton, it also consumes ciliates, microflagellates, bacteria, particulate matter, and zooplankton (Werner and Hollibaugh 1993; Kimmerer et al. 1995; Kimmerer 2006; Greene et al. 2011). Since the appearance of *Corbula* in 1986, populations of zooplankton in the brackish Delta have been significantly reduced (Durand 2008). *Corbula's* effect on zooplankton is a function of both direct grazing on larval stages (microzooplankton such as copepod nauplii) and the indirect effects of competition for phytoplankton (Durand 2008). As a result, *Corbula* has eliminated much of the plankton available for native planktivores, such as delta smelt and longfin smelt, and diverted much of the estuary's production to the benthos (Winder and Jassby 2010; Baxter et al. 2010). Detritus-borne bacteria may support the microbial loop of the Delta food web and may be grazed on directly by *Corbula*. Bacterioplankton feeds into the microbial loop, being used directly by rotifers and ciliates, which in turn are consumed by zooplankton and a number of filter-feeding and planktivorous fish (Durand 2008). Although microzooplankton may not be a major component of the diet of these clams, *Corbula* consumption of bacteria and phytoplankton can disrupt this important trophic intermediary to higher trophic levels (Greene et al. 2011). (See Appendix 5.E, *Habitat Restoration,* for additional discussion regarding habitat productivity.)

Studies of metabolic response suggest that *Corbula* may have a disproportionately higher demand than other species. Activity of enzymes involved in osmoregulation were positively correlated with salinity, suggesting that *Corbula* experiencing higher salinities increase their metabolic rates to support greater osmoregulation and compensate by increasing their filter-feeding rate (Paganini et al. 2010).

Bivalves such as *Corbula* can increase water clarity by filtering fine particles, transporting organic matter from the water column to the sediment, altering physical habitat structure, and facilitating the spread of other species (Vanderploeg et al. 2002). However, Kimmerer (2006) noted that *Corbula* in the San Francisco Estuary had no significant impact on water clarity, which is principally controlled by the concentration of mineral particles (Jassby et al. 2002).

Documented consumers of *Corbula* include Dungeness crab (*Cancer magister*) (Carlton et al. 1990; Stewart et al. 2004), Sacramento splittail (Deng et al. 2007), white sturgeon (Urquhart and Regalado 1991; Kogut 2008), and diving ducks such as surf scoters (*Melanitta perspicillata*) and greater and lesser scaup (*Aythya marila* and *A. affinis*) (White et al. 1989; Urquhart and Regalado 1991; Linville et al. 2002). The position of *Corbula* in the sediment makes them more available to predators than the deep-burrowing bivalve that previously dominated the northern estuary (*Macoma petalum*, previously known as *Macoma balthica*). The caloric content of the two bivalves is similar (Richman and Lovvorn 2004).

One concern for consumers is *Corbula's* propensity to accumulate contaminants, which can bioaccumulate through the food chain to toxic levels. *Corbula* bioaccumulates selenium (Brown and Luoma 1995; Stewart et al. 2004; Lee et al. 2006), heavy metals (Brown and Luoma 1995), hydrocarbons (Pereira et al. 1992), butyltins (Pereira et al. 1999), and pesticides (Gale et al. 2003).

Selenium bioaccumulation is of particular concern. Lemly (2002) found that concentrations of selenium greater 3 micrograms per gram (μg/g) dry weight (dw) in the diet of fish (e.g., invertebrate prey) resulted in deposition of elevated selenium concentrations in developing eggs. Selenium concentrations greater than 5–10 μg/g dw (whole fish tissue) (Lemly 2002) or 15 μg/g dw (fish liver) were associated with deformities (teratogenesis) or reproductive failure (Stewart et al. 2004). Stewart and coauthors (2004) measured selenium concentrations in invertebrates and fish from San Pablo Bay and Suisun Bay. Mean selenium concentrations in invertebrates (toxicity threshold 10 μg/g dw) varied, with crustaceans around 2 μg/g dw, zooplankton about 5 μg/g dw, but *Corbula* around 11 μg/g dw. Selenium levels in fish liver were near or exceeded the toxicity threshold of predators (15 μg/g dw) for Sacramento splittail (about 13 μg/g dw) and white sturgeon (about 25 μg/g dw), with higher concentrations in larger, older individuals. Selenium levels also are elevated in diving ducks that consume *Corbula* (White et al. 1989; Urquhart and Regalado 1991; Linville et al. 2002).

F.6.1.2 *Corbicula fluminea*

The Asian clam *Corbicula fluminea* was first documented in the San Francisco estuary in 1945 and is presently one of the most widespread and abundant mollusks in the Delta (Hanna 1966). Broad shifts in salinity effectively determine the complementary ranges of the two invasive bivalves within the estuary, with *Corbicula* residing primarily in fresh water and *Corbula* in marine to brackish water (Durand 2008) (Table F.6-1). The major limitation on *Corbicula's* distribution is likely to be salinity. *Corbicula* typically is found in habitats with salinities less than 2ppt, mostly due to the physiological constraints of juveniles. Once established, adult clams can withstand salinities of

10 ppt and greater. *Corbicula* currently exist within most freshwater areas in the Delta and river channels east of Suisun Bay (Cohen and Carlton 1995; California Department of Water Resources 2010b). In Suisun Marsh, *Corbicula* occurs in Montezuma Slough upstream of the salinity control gates and in the upper reaches of Suisun Slough in all years. In the central Delta, *Corbicula* achieves high abundance and biomass in Franks Tract and in its surrounding sloughs (Lopez et al. 2006). *Corbicula* is also common in the sloughs surrounding Mildred Island but very sparsely distributed inside of Mildred Island (Lopez et al. 2006). *Corbicula* has been reported by the U.S. Geological Survey (USGS) and DWR in other flooded islands, including Big Break, Liberty Island, and Sherman Island. Peak *Corbicula* densities can exceed 3,000 clams per square meter in the lower Sacramento River (August 2008; California Department of Water Resources 2010b) and about 1,500 in the lower San Joaquin River (October 2009; California Department of Water Resources 2010c).

Corbicula has a patchy distribution that is not well understood but may be a function of water velocity, depth, and predation rates from birds and fish (Durand 2008).

Corbicula can tolerate low pH and emersion from the water for significant periods of time and has the ability to alter metabolic rate during periods of low food availability (Ortmann and Grieshaber 2003). *Corbicula* is highly tolerant of turbid conditions (Way et al. 1990), and their ability to exit the sediment during poor water quality conditions and be carried down-current gives them an extra option for survival. *Corbicula* can adapt to a wide range of conditions. Their high filtration rate, high net assimilation rate (excluding respiration), high fecundity, and high juvenile dispersal rate allow *Corbicula* to expand their distribution and to rapidly re-invade an area following extirpation. *Corbicula* are adapted to live in both high energy and low energy environments. Once settled, adults can burrow quickly in active sedimentary environments because of their high metabolic rate (McMahon 2002).

Corbicula is a shallow burrowing species that can live on solid substrates (e.g., riprap, concrete) by attaching to the substrate with their byssal threads until they exceed 14 mm in length when their byssus disappears. *Corbicula* can live in all water depths, all substrate types including concrete and peat, and can be found in egeria and tule beds. This species can occur in permanently inundated and tidally exposed habitats where they can withstand multiple days of exposure. *Corbicula's* ability to move into and attach to all substrates has enabled them to invade and live in newly disturbed and anthropogenically altered habitats when other bivalve species are not capable of doing so (McMahon 1991). In the Chesapeake Bay, *Corbicula* abundance has been correlated with nitrogen pollution, with abundance declining coincident with reductions in anthropogenic nitrogen loads to the system (Glibert et al. 2011).

Corbicula is viviparous (produce live young), releasing benthic pediveliger larvae or planktonic veligers that become benthic within 48 hours (Eng 1979). Adult clams are found with mature eggs year around, and they are believed to have two reproductive periods per year, one in spring and the other in fall. Individuals can self fertilize their eggs (Kraemer and Galloway 1986) allowing single individuals to potentially establish new populations. Juvenile clams become reproductively active around 6–10 mm in length (Kraemer and Galloway 1986), which can occur within a few months of recruitment. *Corbicula* is presumed to live 3–4 years, although some hypothesize they can live longer.

Corbicula are highly efficient suspension feeders that filter phytoplankton and bacteria from the water column. *Corbicula* are not as efficient as *Corbula* in terms of filtration rates, but they still can quickly filter out shallow water bodies when in sufficient densities. In shallow-water areas such as

Franks Tract, dense populations of *Corbicula* collectively can filter the entire water column in less than a day (Lucas et al. 2002). They can limit phytoplankton abundance from accumulating in shallow-water areas of the Delta. *Corbicula* also can reduce their metabolic rate by 90%, allowing them to persist even in periods and areas of low food availability (Ortmann and Grieshaber 2003). *Corbicula*, like *Corbula*, likely affect zooplankton populations by reducing the abundance of primary producers (Durand 2008), although this link has not yet been clearly established.

Corbicula provide food for benthic feeding fishes such as sturgeon, splittail, redear sunfish, and catfish and are one of the most commonly identified benthic organisms in fish stomachs collected from the Delta (Gleason 1984; Herbold and Moyle 1989). *Corbicula* can bioaccumulate pesticides and trace metals such as selenium (Lee et al. 2006).

F.6.1.3 Zebra Mussels and Quagga Mussels

Two species of dreissenid mussels, zebra mussels (*Dreissena polymorpha*) and quagga mussels (*D. bugensis*), are not currently present in the Delta. However, their rapid spread and negative ecological effects, as observed in other ecosystems (Benson et al. 2012; Cohen 2008; Kissman et al. 2010), merit evaluation of their invasion potential for the future.

Zebra mussels and quagga mussels are among the most significant biological invasions into North America (Benson et al. 2012). Zebra mussels first were documented in California in January 2008 at San Justo Lake, a reservoir in San Benito County (U.S. Geological Survey 2011). Quagga mussels have been found since 2007 in multiple reservoirs in southern California that receive raw water from the Colorado River (U.S. Geological Survey 2011).

Zebra mussels colonize hard substrates, and quagga mussels colonize both hard and soft substrates and colonize deeper than zebra mussels. These mussels can reach extraordinary densities and are notorious for their biofouling capabilities in water supply pipes, boats, and other submerged structures. Both species are prodigious water filterers that can remove substantial amounts of phytoplankton, microzooplankton, and suspended particulate matter from the water (Kissman et al. 2010). Mussels can bioaccumulate contaminants. The potential effects of these species would be similar to those of *Corbula* in those areas where mussels could become established.

The invasion risk of zebra/quagga mussels depends on salinity, calcium, and alkalinity (pH) (Whittier et al. 2008; Cohen 2008; Claudi and Prescott 2011). Zebra/quagga mussels are predominantly freshwater, but they can tolerate salinity up to 5 ppt (Spidle et al. 1995). North American populations of zebra mussel can tolerate salinity up to 4 ppt (Benson et al. 2012). Other studies suggest limiting values of 2–10 ppt to assess zebra mussel distribution (reviewed by Cohen 2008). Quagga mussels are less tolerant of salinity than zebra mussels. Calcium is considered a key limiting factor, required for basic metabolic function as well as shell building (Whittier et al. 2008).

The invasion risk of zebra/quagga mussels in the Delta has been evaluated by DFG (Cohen 2008) and DWR (Claudi and Prescott 2011). Cohen (2008) used salinity and calcium to evaluate invasion risk at six locations in the Delta (Sacramento River at Delta, Rock Slough, Old River Intake, CCF, Old River at Tracy Road Bridge, and San Joaquin River at Antioch Ship Channel). Cohen (2008) selected maximum salinities of 6 ppt for zebra mussels and 4 ppt for quagga mussels. Calcium is required for shell calcification of larvae at settlement.

Salinity is typically less than 1 ppt at these locations. A review by Cohen (2008) suggested calcium concentrations of 12–28 mg/L as a limiting threshold. Calcium (range 6–33 mg/L), not salinity, appeared to be the limiting factor. Areas deemed to have insufficient calcium (<12 mg/L) included Sacramento River at Delta, Rock Slough, and Old River Intake. Calcium concentrations exceeded 28 mg/L at Old River at Tracy Road Bridge, and San Joaquin River at Antioch Ship Channel. CCF is moderately vulnerable because of intermediate calcium levels.

Claudi and Prescott's (2011) risk assessment focused on the relationship of calcium and alkalinity (Table F.6-2). They hypothesized that pH above 8 may facilitate survival at sites with marginal calcium concentrations, such as Barker Slough, San Joaquin River near Vernalis, and CCF (Claudi and Prescott 2011). This does not account for possible fluctuations in calcium and alkalinity. Given the limited knowledge of survival of dreissenid populations under marginal conditions of calcium and pH, predictions of survival at these locations are uncertain (Claudi and Prescott 2011).

Table F.6-2. Conditions of Calcium and pH Hypothesized to Support Dreissenid Mussels

	Calcium Concentration		
pH level	**<12 mg/L**	**12–15 mg/L**	**>15 mg/L**
<7.3	Unable	Unable	Unable
7.3–7.8	Unable	Potentially able	Potentially Able
>7.8	Unable	Potentially able	Able
Source: Claudi and Prescott 2011.			

F.6.2 Conceptual Model and Hypotheses

F.6.2.1 Conceptual Model

The conceptual model for evaluating effects of invasive mollusks includes consideration of:

1. Factors limiting recruitment, distribution, and abundance (salinity).
2. Competition by invasive clams with covered fish species for planktonic food resources.
3. Bioaccumulation of contaminants in consumers of clams.

Salinity is a limiting factor for the establishment and distribution of *Corbula* and *Corbicula* (Peterson and Vayssieres 2010). Because the adults are not mobile, it is the larval life stage that can be transported with currents and become established if conditions are suitable. *Corbula* larvae have a broad range of salinity tolerance (2 to 30 ppt) (Nicolini and Penry 2000), but they require salinity greater than 2 ppt to successfully recruit. Conversely, *Corbicula* require salinities less than 2 ppt to for recruitment, although adults can tolerate salinities up to 10–13 ppt.

While this assessment considers the effect of BDCP program actions on salinity and compares the distribution of threshold salinity levels with potential restoration areas, it should be acknowledged that a variety of factors that are not well understood influence whether an area actually is colonized.

Hypotheses for evaluation include:

- Salinity distribution is likely to limit recruitment and establishment of *Corbula* (require >2 ppt) and *Corbicula* (require <2ppt).
- Calcium concentrations and pH may affect potential recruitment and establishment of zebra/quagga mussels in the future.

- Grazing by invasive mollusks is contributing to food limitation for planktivores such as delta smelt and longfin smelt.
- Grazing by invasive mollusks may reduce foodweb benefits from habitat restoration.
- Selenium bioaccumulation may negatively affect benthic foragers such as Sacramento splittail and sturgeon.

F.6.2.2 Potential Direct and Indirect Effects on Covered Species

F.6.2.2.1 Delta Smelt

Reduced food availability in the Bay-Delta estuary has been identified as one of the major stressors to delta smelt (Resources Agency 2007) (see also Appendix 5.E, *Habitat Restoration*). Extensive grazing by large populations of *Corbula* has drastically reduced phytoplankton blooms in the lower estuary and has affected population dynamics of calanoid copepods, a primary prey item for delta smelt (Kimmerer et al. 1994; Kimmerer and Orsi 1996; Winder and Jassby 2010; Baxter et al. 2010). The foodweb benefits of tidal wetland restoration could be reduced if *Corbula* invade the restored areas and grazes the aquatic productivity. *Corbula* also contribute to increased water clarity, which negatively affects delta smelt by reducing cover from predators and impairing feeding efficiency.

The effects of *Corbicula* in lower-salinity (<2 ppt) regions of the Delta are expected to be similar to those of *Corbula*. This would tend to affect food resources for adult delta smelt during the winter and spring when they migrate east into the Delta, and for larval delta smelt in spring and summer before they are transported to the western Delta regions that typically have salinity greater than 2 ppt.

F.6.2.2.2 Longfin Smelt

Effects are similar to those for delta smelt, but not as severe because longfin smelt do not spend as much time rearing in areas invaded by *Corbula*, such as Suisun Bay, or *Corbicula*, such as the central Delta and Cache Slough. However, Rosenfield and Baxter (2007) identified a decline in the survival of longfin smelt between Age-1and Age-2 that may be the result of a decline in the abundance of prey items following establishment of *Corbula* (Appendix 5.E, *Habitat Restoration*)

F.6.2.2.3 Steelhead and Chinook Salmon

Juvenile salmonids typically feed on zooplankton and insect larvae while in the Delta. . Juvenile Chinook salmon, for example, were found to rely predominantly on zooplankton and chironomids, with some amphipods derived from littoral sources while in the Delta (Grimaldo et al. 2009). The abundance of zooplankton and aquatic insect larvae are highly dependent on the availability of phytoplankton, the base of the aquatic foodweb. Because *Corbula* feeding rates on phytoplankton likely surpass the growth rate of phytoplankton, the foodweb benefits of tidal wetland restoration could be reduced if *Corbula* or *Corbicula* invade the restored areas. However, foodweb benefits derived from floodplain restoration areas are not expected to be diminished; the risk of invasion in floodplain restoration areas is low because of the seasonality of inundation. Salmon consumption of benthic clams like *Corbula* is likely low, limiting the exposure of salmonids to bioaccumulated selenium.

F.6.2.2.4 Sacramento Splittail

There is some indication that splittail are food-limited given that their growth rates declined following the invasion of *Corbula* and the collapse of *Neomysis* due to high rates of grazing by *Corbula* (Freyer et al. 2003) (see also Appendix 5.E, *Habitat Restoration*). Splittail generally feed on benthic invertebrates in areas of slower currents (Moyle 2002). Since the *Corbula* introduction in 1986, clams have been a dominant food item in older splittail (Feyrer et al. 2003). Clams expanding into restored areas could increase benthic food resources for splittail but would likely reduce zooplankton resources and could increase exposure to contaminants. *Corbula* are known to bioaccumulate toxic levels of selenium. Splittail collected from Suisun Bay have been documented with deformities typical of selenium toxicity (Stewart et al. 2004). (See Appendix 5.D, *Contaminants*, for additional information about selenium effects on covered fish species.)The reduction of standing phytoplankton biomass in the Delta due to the high filter-feeding rates of *Corbula* and *Corbicula* can negatively affect higher trophic levels in the foodweb (Greene et al. 2011). Reduced phytoplankton may have overall foodweb effects, reducing the abundance of prey on which splittail feed. Splittail also are known to rear in tidal wetlands. Restored tidal wetlands are intended to increase rearing habitat and improve food resources for splittail. However, restored tidal wetlands also may be exploited by the opportunistic *Corbula*, reducing the foodweb benefits anticipated by the restoration actions.

F.6.2.2.5 Sturgeon

Introduced *Corbula* and *Corbicula* are now the principal food of white sturgeon (Stewart et al. 2004; Israel et al. 2009). Israel and Klimley (2008) note that *Corbula* has replaced native mollusks and shrimp as food for green sturgeon.

While the consumption of *Corbula* helps reduce predation pressure on zooplankton, which are important in the diets of other fish species, the accumulation of selenium in high concentrations by *Corbula* and subsequently passed on to sturgeon is a concern. Because of their high filtration efficiency, *Corbula* can accumulate selenium concentrations above threshold levels at which toxic effects have been observed in other fish species (Lemly 2002). Dietary selenium in high concentrations can adversely affect sturgeon survival, activity, and growth (Tashjian et al. 2006). (See also Appendix 5.E, *Habitat Restoration*, for additional discussion.)

White sturgeon in San Pablo Bay and Suisun Bay have been found to have high levels of selenium in their livers (range 5–40 µg/g dw, mean 24 µg/g dw), above the 15 µg/g dw toxicity threshold for potential deformities and impaired reproduction (Stewart et al. 2004). Green sturgeon likely face similar risk.

F.6.2.2.6 Pacific Lamprey and River Lamprey

Corbula and *Corbicula* have little or no effect on Pacific lamprey and river lamprey that migrate through the Delta. Returning adults do not feed during their spawning migration. The diet of macropthalmia (the life stage that migrates from rivers to the ocean) is poorly understood, but it seems unlikely that these jawless fishes consume hard-shelled mollusks. It is unclear whether macropthalmia feed on zooplankton that could be diminished by clam grazing.

F.6.3 Potential Effects: Benefits and Risks

F.6.3.1 Water Operations Conservation Measure 1

Water operations (CM1) that affect salinity gradients could affect the recruitment and distribution of *Corbula* in the western Delta and *Corbicula* in freshwater habitats. For example, if the LSZ of X2 moves upstream in the Delta during the *Corbula* larval recruitment period, that could increase opportunities for *Corbula* to recruit further into the central Delta. Conversely, this could reduce available habitat for *Corbicula,* which requires more freshwater conditions (<2 ppt).

Corbula is more abundant in San Pablo Bay during wet years but more abundant in Grizzly Bay and Suisan Bay in dry years (Peterson and Vayssieres 2010). In general, assemblages of brackish benthic species such as *Corbula* shift downstream in years with high Delta outflow, and upstream during years with low Delta outflow (Peterson and Vayssieres 2010). Wet years in Suisun Bay are characterized by a higher percentage of reproductive individuals, while higher rates of reproductive individuals in San Pablo Bay occur in dry years (Parchaso and Thompson 2002). The higher rates of reproduction in Suisun Bay in wet years may be linked to increased transport of phytoplankton food resources from upstream Delta reaches.

The effect of BDCP water operations was evaluated by modeling the amount of potential habitat suitable for recruitment (square kilometers [km^2] area greater than 2 ppt) (Figure F.6-1) and habitat availability over time (percent exceedance) (Figure F.6-2). The amount of area suitable for *Corbula* with the Plan (PP_LLT and PP_ELT) during the first 30 years (exceedance frequency 60%) would be similar to EBC1 and greater than EBC2_ELT and EBC2_LLT. Slightly more habitat would be available during the early years under PP_ELT than PP_LLT. For the drier 40% of the period of record, all scenarios would provide similar amounts of potential *Corbula* recruitment habitat.

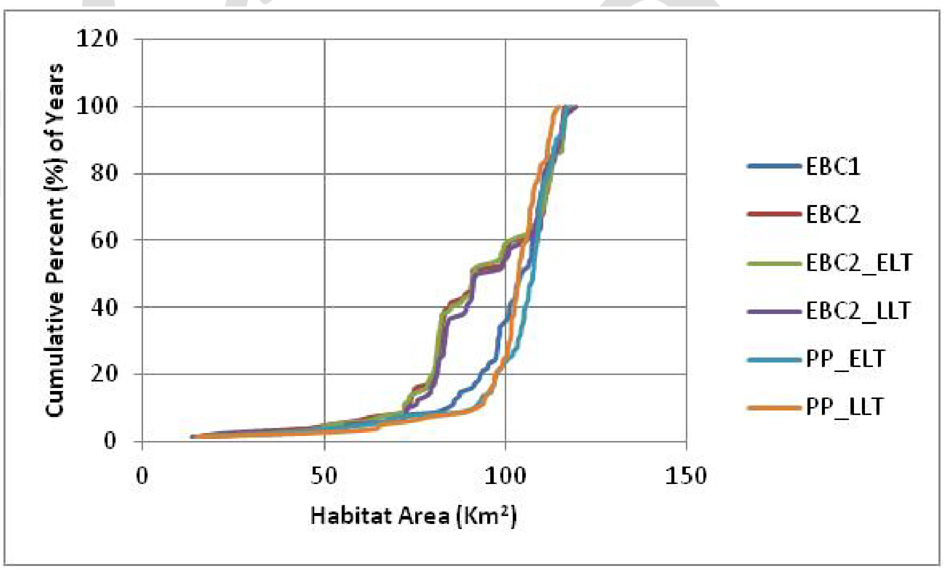


Figure F.6-1. Habitat Area Available for Recruitment by *Corbula* Larvae, Based on X2 Position

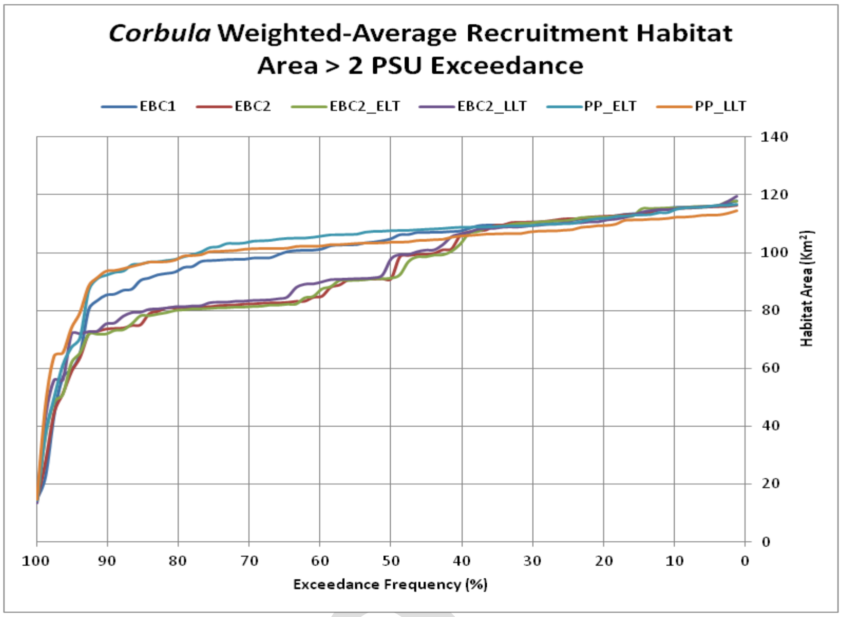


Figure F.6-2. Exceedance Frequency for Habitat Area Available for Recruitment by *Corbula* Larvae, Based on X2 Position (2 ppt = 2 practical salinity units [PSU])

This simple analysis, however, fails to capture the complex situation of invasive clams in the Delta. First, larval recruitment of *Corbula* can occur nearly year-round among the groups of adult *Corbula* at Chipps Island, Grizzly Bay, and San Pablo Bay, although it predominantly occurs in summer and fall. Therefore, any short periods with more upstream X2 positions can allow *Corbula* to expand their distribution. Adult *Corbula* would be able to persist at salinities down to 0.1 ppt. Furthermore, natural variation in climatic factors such as drought would facilitate further expansion of *Corbula* eastward irrespective of flow operations under the BDCP conservation strategy. Seasonal *Corbula* abundance declines in winter-spring, possibly due to winter outflow conditions or to increased predation by diving birds (Poulton et al. 2002). Furthermore, adult *Corbula* can persist at salinities down to 0.1 ppt.

Finally, *Corbicula* would be capable of colonizing new habitat that is too fresh for *Corbula* recruitment, such as Cache Slough, East Delta, and South Delta ROAs. *Corbicula* is already present in many of these regions. The effects of *Corbicula* on planktonic food resources may be slightly less than those of *Corbula* because these freshwater clams are not as powerful filter-feeders and they have a more patchy distribution and lower densities.

F.6.3.2 Aquatic Habitat Restoration (Conservation Measures 4, 5, 6)

Aquatic habitat restoration actions are designed to increase the area, diversity, and connectivity of habitats available to enhance food resources and support covered fish in the Delta. Restoration areas are distributed across the Delta: the Sacramento River and northern Delta at Cache Slough, the Cosumnes and Mokelumne Rivers in the eastern Delta, the San Joaquin River in the southern Delta, the western Delta, and Suisun Marsh. Habitat types include tidal wetland (CM4), channel margin aquatic habitat (CM6), and seasonally inundated floodplain (CM5). The expected foodweb benefits of increased productivity are discussed in further detail in Appendix 5.E*, Habitat Restoration*.

Aquatic restoration under BDCP will create new benthic habitat that may be colonized by *Corbula* or *Corbicula*, depending on the salinity regime. Physical and biological interactions can enhance or constrain the success of restoration in meeting conservation goals (Lopez et al. 2006). Some physical features that favor invasive species could be controlled, such as water depth, and location and dimension of levee breaks that determine residence time and circulation pathways (Lopez et al. 2006). Biological processes, such as the extent of potential colonization, are frequently indeterminate. If invasive clams become established, their vigorous filter feeding could take up an indeterminate portion of the expected phytoplankton and microzooplankton. Invading clams likely would constrain but not eradicate foodweb benefits. The greater patchiness in *Corbicula* distribution makes it more difficult to predict the extent of potential *Corbicula* expansion and impact.

Because salinity is a significant factor in clam distribution, understanding the likely salinity regime in different ROAs will guide evaluation of risk from clams. Suisun Bay is a stronghold of *Corbula*, but distributions within Suisun Marsh vary. *Corbula* may be able to establish in restored areas where salinities are greater than 5 ppt (e.g., Goodyear and lower Suisun Sloughs), while other areas farther into the marsh (i.e., Denverton Slough) could continue to resist invasion (O'Rear and Moyle 2008, 2009).

Moving eastward, at Chipps Island *Corbula* were found consistently in the spring, regardless of whether it was a drought year (e.g., 1988) or wet year (e.g., 1995) (California Department of Water Resources 2001b). The extent of *Corbula* in the fall months varies more substantially and is dependent on Delta outflow. In the fall of 1995, a wet year, *Corbula* populations moved westerly in response to higher freshwater flows, to around Chipps Island (California Department of Water Resources 2001b). In drier fall months, such as in 1990, *Corbula* was detected in the downstream reaches of the Sacramento and San Joaquin Rivers (Hymanson 1991). Downstream reaches of the Sacramento and San Joaquin Rivers are most likely vulnerable to invasion from larval recruits originating from the population in the Chipps Island channel. Recruitment from the Chipps Island population occurs mostly in the fall months. In drier years, there is the risk of larval *Corbula* recruiting to upstream reaches and continuing to persist through wet years.

The West Delta ROA appears to be the current upstream limit of *Corbula* distribution. This ROA may become vulnerable to *Corbula* during dry years, when more easterly X2 position allows recruitment farther upstream. A small restoration area on the west end of Hotchkiss Tract is also at the upstream end of *Corbula* distribution and should be free of *Corbula* during most years except years with poorer than usual outflow. Upstream restorations areas planned at Cache Slough, Yolo Bypass, east Delta, and south Delta are well upstream of the salinity tolerance of *Corbula,* and therefore *Corbula* is not likely to occur in those ROAs.

As noted above, however, *Corbicula* is likely to invade restored areas too fresh for *Corbula*. This includes Cache Slough, the east Delta, and south Delta.

The relative effect of benthic grazing on phytoplankton may vary with habitat depth (Lucas et al. 1999b; Lopez et al. 2006). As the water column becomes shallower, benthic filter feeders have greater access to phytoplankton in the overlying water (Lucas et al. 1999b). Lopez and others (2006) evaluated the hypothesis that phytoplankton biomass, production, and pelagic energy flow vary with habitat depth. They measured phytoplankton productivity, nutrients, tidal transport, and *Corbicula* densities in a variety of "shallow" aquatic habitats (Franks Tract mean depth 2.5 meters, Mildred Island mean depth 5 meters) and their adjacent deep channels, including Franks Tract and Mildred Island. The habitat provided by these two flooded islands is deeper than much of the shallow habitat expected under the Plan. Phytoplankton biomass and production were consistently low in habitats colonized by *Corbicula*. Their grazing rates were, on average, eight times higher than zooplankton grazing rates in those colonized habitats. Lopez and others (2006) concluded that fast transport and fast *Corbicula* grazing are the key processes leading to the decorrelation between phytoplankton growth rate and biomass distribution. Phytoplankton biomass provides no information about these governing processes, so biomass alone is a weak indicator of the ecological value of aquatic habitats. Whereas shallow pelagic systems routinely functioned as net sources of phytoplankton biomass, this trend was not true when accounting for losses to *Corbicula* grazing. Despite higher phytoplankton growth rates in shallow habitats, consumption by *Corbicula* rendered nearly all colonized shallow habitats phytoplankton sinks (Lopez et al. 2006). *Corbicula* distribution was inexplicably patchy, which implies high uncertainty in the outcomes of creating new aquatic habitat (Lucas et al. 2002).

F.6.3.3 Recreational Users Invasive Species Program (Conservation Measure 20)

Under *CM20 Recreational Users Invasive Species Program,* the BDCP Implementation Office will fund actions to reduce the invasion of nonnative invasive species into the Plan Area. Funding will be provided to implement the DFG Watercraft Inspection Program in the Delta.

A key component of an integrated aquatic invasives program is prevention, which incorporates regulatory authority, risk analysis, knowledge of introduction pathways, and inspections. While no feasible control measures are known for eradicating well-established invasive mollusks such as *Corbicula* and *Corbula,* prevention of further invasions is critical to avoid further stress to the Delta ecosystem.

Two of the most invasive aquatic species known, zebra mussels and quagga mussels, have not yet invaded the Delta. If these arrive, they likely would become established in more freshwater locations (e.g., East Delta ROA, Cache Slough ROA) and would exacerbate the negative impacts already imposed by *Corbula* and *Corbicula*. These two dresseinid mussels could be introduced as veligers persisting in boats transported from infested waters that retain moisture in live wells or bilges, or as adults attached to boats and trailers (California Department of Fish and Game 2008). To prevent transport, boats must be properly cleaned, drained, and dried after leaving a water body that could harbor mussels or mussel larvae (California Department of Fish and Game 2008). Controlling the introduction of additional invasive mollusks, or the further spread of any existing nonnative mollusk species, would benefit aquatic natural communities in the Plan Area.

F.6.4 Uncertainties and Research Needs

Understanding of the distribution patterns and foodweb dynamics of invasive mollusks has advanced thanks to long-term monitoring of benthic invertebrates (e.g., California Department of Water Resources 2001; Peterson and Vayssieres 2010; O'Rear and Moyle 2008) and recent and ongoing studies of foodweb dynamics and invasives, as synthesized for the Pelagic Organism Decline (Baxter et al. 2010). Management in the face of invasive mollusks would benefit from further investigation of constraints that limit transport, settlement, and establishment. Observed distribution of clams such as *Corbicula* can be patchy, which implies high uncertainty in the outcomes of creating new aquatic habitat (Lucas et al. 2002). Basic measurements such as salinity and temperature tolerance as co-variables, low oxygen tolerance, and feeding rates relative to water temperature are needed to improve assessments of temporal and spatial distribution.

The role of nutrients in facilitating *Corbula* expansion also has been hypothesized (Glibert et al. 2011), but the mechanism of the potential relationship is unknown. Further research on *Corbula* response to different nutrient variables is warranted. Nutrient variables could include concentrations, forms (e.g., ammonium, inorganic and organic phosphorus), and ratios (DIN:P). *Corbula* response variables of interest could include metabolism (filtering and consumption rates, e.g., Paganini et al. 2010), larval recruitment success, and comparison of distribution patterns with nutrient measurements in the field.

A critical uncertainty is whether areas with high primary productivity (e.g., Suisun Bay) can accumulate high phytoplankton biomass despite the presence of *Corbula* (Surface Water Ambient Monitoring Program [SWAMP] 2010). Based on relationships between the introduction of *Corbula* and the accumulation of phytoplankton biomass, there has been the assumption that the grazing effect of *Corbula* limits the accumulation of phytoplankton biomass regardless of the rate of primary production. However, in the 2010 SWAMP study a bloom did occur when *Corbula* were present and in the same concentrations as previous years. (Taberski et al. 2010.)

Monitoring of the benthic community at existing and restored habitats will be critical to detect any invasion and evaluate trends in benthic community composition. DWR's Generalized Random Tessellation Stratified (GRTS) study is an example of a design to monitor and analyze the Delta benthos. This 5-year (2007–2011) study sampled benthos each May and October at 175 sites (50 fixed, 125 variable sites) from San Pablo Bay to Stockton, and lower Cache Slough to CCF. GRTS data are being evaluated (K. Gehrts pers. comm.).

Although *Corbula* has successfully invaded the San Francisco Bay estuary, it is not yet documented at other eastern Pacific Rim locations. Possible explanations include physiological constraints in other locations, not yet introduced (ballast water at ports has been typical path of invasion), or not yet detected. Evaluation of conditions at uninvaded ports may be informative.

Another uncertainty is the effect that bioaccumulation by clams has on benthic consumers, such as splittail and sturgeon. While selenium bioaccumulation has been documented (e.g., Stewart et al. 2004; Lee et al. 2006), less is known about how bioaccumulation of heavy metals, pesticides, and hydrocarbons by *Corbula* affects its consumers at a population level.

F.6.5 Conclusions

The combined effect of water operations (Conservation Measure 1) that Increase the amount of habitat with salinity greater than 2 ppt compared to EBC2 and increased tidal habitat from restoration (Conservation Measure 4) may facilitate recruitment and expansion of *Corbula,* and result in reductions in food benefits described in Appendix E, *Habitat Restoration.*

Water operations that affect salinity gradients could affect the recruitment and distribution of *Corbula* in the western Delta and *Corbicula* in freshwater habitats. For example, if the lower end in the salinity zone of X2 moves upstream in the Delta during the *Corbula* larval recruitment period, that could increase opportunities for *Corbula* to recruit farther into the central Delta. Conversely, this could reduce available habitat for *Corbicula*, which requires more freshwater conditions (<2 ppt). These invasive clams have the potential to reduce food produced in and exported from the ROAs.

Funding efforts that prevent the introduction of new invasive species (Conservation Measure 20) would benefit covered fish species in the Plan Area.

A key component of an integrated aquatic invasives program is prevention, which incorporates regulatory authority, risk analysis, knowledge of introduction pathways, and inspections. Specifically, efforts that prevent the transport of invasive species by requiring recreational boats to be properly cleaned, drained, and dried after leaving a water body that could harbor invasive mollusk species are considered beneficial.

While no feasible control measures are known for eradicating well-established invasive mollusks such as *Corbicula* and *Corbula,* prevention of further invasions is critical to avoid further stress to the Delta ecosystem.

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F.7.1 Personal Communications

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