SJC-386

EXHIBIT TBI-4

# BEFORE THE STATE WATER RESOURCES CONTROL BOARD

WRITTEN TESTIMONY OF

CHRISTINA SWANSON, PH.D.
EXECUTIVE DIRECTOR AND CHIEF SCIENTIST
THE BAY INSTITUTE

# REGARDING FLOW CRITERIA FOR THE DELTA NECESSARY TO PROTECT PUBLIC TRUST RESOURCES: DELTA HYDRODYNAMICS

PREPARED FOR:

THE BAY INSTITUTE
AMERICAN RIVERS
ENVIRONMENTAL DEFENSE FUND
NATURAL HERITAGE INSTITUTE
NATURAL RESOURCES DEFENSE COUNCIL

# EXHIBIT 4: DELTA HYDRODYNAMICS

## Overall relevance of Delta hydrodynamics to public trust resources

*Summary points:*

- *Changes in Delta hydrodynamic conditions have caused direct species effects (entrainment), indirect species effects (predation, disruption of migration), and indirect ecosystem effects (water quality, residence time) on public trust resources.*
- *Delta hydrodynamic conditions, which are function of both in-Delta flow alterations and inflows, are generally expressed here as Old and Middle River flow conditions and export/inflow ratios..*

The Delta is the common migration corridor for all anadromous fishes produced throughout the Sacramento-San Joaquin watershed (including salmonids, sturgeon, splittail, and striped bass), spawning habitat for numerous estuarine species such as delta smelt and longfin smelt and, at least for a portion of their life spans, rearing habitat for all of these and other public trust resources. Upstream water management operations (e.g., storage, on-stream diversions) and the water export operations of the Central Valley Project (CVP) and State Water project (SWP) Delta pumps have substantial effects on flow conditions within the Delta as well as on Delta outflow (and inflows). Because most of the public trust resource species that rely on Delta outflow also use the Delta for key parts of their life cycles, in-Delta flows and hydrodynamic conditions have both direct and indirect impacts on all four aspects of viability aspects: abundance, productivity, spatial extent and diversity.

Current regulations and infrastructure capacity allow as much as 65% of the total freshwater inflow to the Delta to be diverted by the CVP and SWP pumps for much of the year (i.e., an Export:Inflow ratio, or E:I, of 0.65; SWRCB 2006) at rates of nearly15,000 cfs (although because of Army Corps of Engineers regulatory constraints, maximal export rates rarely exceed 12,000 cfs). Combined CVP and SWP export rates are regularly five to eight times higher than total San Joaquin River inflow to the Delta. During the past several decades, increases in export capacity, demand for exported water (including water transfers), and the capacity and availability of south-of-Delta storage (e.g., new surface and groundwater storage facilities) have increased the intensity of both upstream and in-Delta water management operations, with concurrent changes in a number of Delta hydrodynamic parameters known to affect public trust species and aspects of the Delta ecosystem that support them (see Exhibit 1).

It can be difficult to quantitatively evaluate or even distinguish the direct or indirect effects of Delta hydrodynamic conditions on abundance, survival, reproductive success, habitat quality and quantity, and other aspects of species viability for a variety of reasons. First, the Delta is a complex and highly altered environment in which the alteration in flows exerts both direct impacts (e.g., mortality of fishes at the pumps) simultaneously with indirect impacts on species (e.g., predation on fishes entrained into the central Delta by altered flows) and the ecosystem (e.g., the effect of altered flows on providing habitat conditions that favor establishment and success of non-native predators and "ecosystem engineers" like *Egeria*). Second, the effects of CVP and SWP water exports on the hydrodynamic environment to which the fish are exposed can be greatly modulated by other flow conditions, particularly inflows from the San Joaquin River and tidal conditions. The ranges of these other flow variables also tend to be much larger than the maximum range of the export variable (e.g., San Joaquin River inflows range from <1000 cfs to >33,000 cfs compared to export flows, which range from only ~1000 cfs to ~12,000 cfs).

Therefore, different scientific analyses use different metrics to examine the effects of Delta hydrodynamics on species and habitats. For example, many analyses investigate the effects of exports using variables that relate export rates to inflows, usually in the form a ratio such as the E:I ratio or the Vernalis flow:Export ratio. Others express the effects of exports in terms of the magnitude and direction of flows in channels leading to the export facility intakes, such as tidally filtered combined Old and Middle River flows (OMR flows).

All of these metrics are highly correlated with each other. In the analyses described below, we use all of these various metrics to evaluate the multiple effects of Delta hydrodynamic conditions on the viability of public trust resources. However, to simplify the hydrodynamic criteria and better understand their interaction with Delta outflow and inflow criteria, we have transformed the results of our and others' research to express our recommendations in terms of OMR flows. We developed and use the following simple equations, derived from daily flow data from 1987-1994.

OMR (cfs) = -331-(0.767*exports, cfs) n=2823, $r^2$=0.903

OMR (cfs) = -1021-(10267*E:I), n=2823, $r^2$=0.544

OMR (cfs) = -1025-(0.817*exports)+(0.664*Vernalis), n=2823, $r^2$=0.943

We also use a simple conversion developed by Contra Costa Water District for comparison and validation.

OMR (cfs) = 0.5(Vernalis, cfs)-(exports, cfs)

OMR flows also vary substantially with spring and neap tides cycles, therefore these equations and resultant conversions of one Delta hydroynamic parameter into units of OMR flows should be considered simple, first order approximations of medium-term (i.e., monthly) average OMR flow conditions.

## Relationship between Delta hydrodynamics and abundance and productivity of public trust resources

*Summary points:*

- *The direct or indirect effects of Delta export pumping result in the loss of tens of millions to hundreds of millions of individual organisms belonging to public trust species each year, and have increased over time.*
- *Entrainment contributes significantly to the inability of salmon populations to achieve doubling objectives and other abundance targets.*
- *Export-related entrainment loss was as high as 40% of the total delta smelt population.*
- *Entrainment impacts on productivity are likely to be most significant for pelagic species when population levels are low and when inflows and outflows are low.*

Every year, millions of fish are entrained in the flow of water towards the export pumps and captured (or “salvaged”) at the SWP and CVP fish facilities (e.g., Foss 2004).

Actual numbers of fish entrained in the export flow and which experience direct mortality at the export facilities are much larger than the numbers of fish counted as salvaged for several reasons, including:

a) mortality of entrained fishes from predators in the approach waterways immediately upstream of the fish screen facilities, which ranges from the current value used to estimate loss of Chinook salmon, 75% pre-screen loss, to more than 99% for delta smelt for the SWP export facility (Gingras 1997; NMFS 2009; G. Castillo, USFWS, *unpublished*);

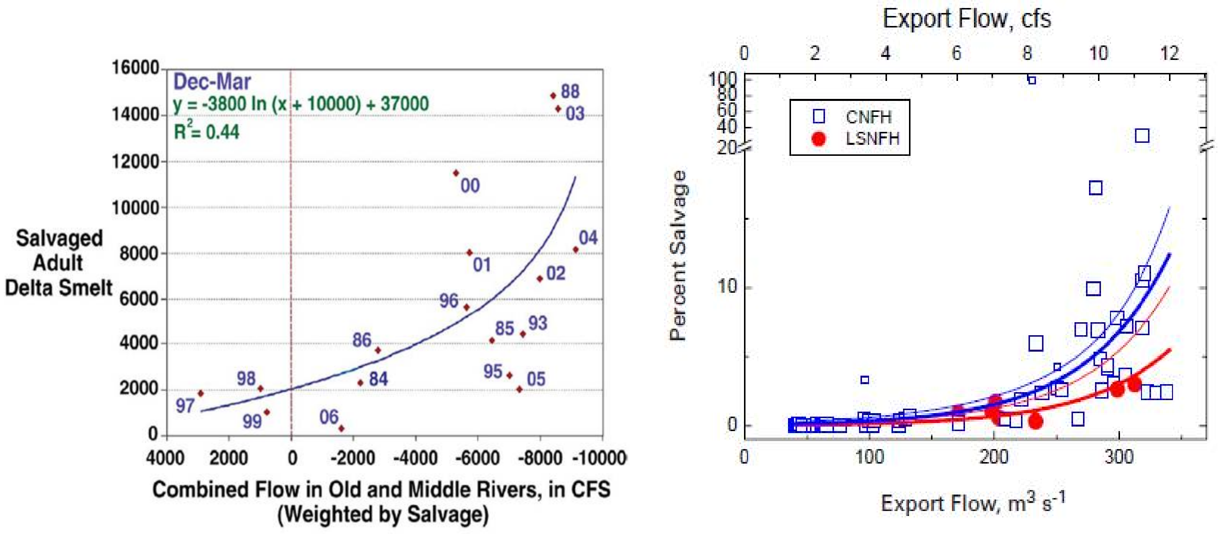
b) low efficiency of the fish screens and louvers intended to divert entrained fish into holding tanks for salvage (e.g., for species like delta smelt, more than 50% of the entrained fish pass through the louvers and not collected in the salvage tanks; USFWS 2008); and

c) incomplete counting and monitoring procedures (i.e., only fish larger than 20 mm in length are counted; loss of larval and young juvenile fish, life stages that have virtually no capability of escaping the hydrodynamic flow towards the pumps, is not adequately monitored or counted at the salvage facilities).

Thus, direct mortality to fish as it is currently measured is a substantial underestimate and is most likely in the tens to hundreds of millions of fish annually.

Mortality of fish attributable to indirect impacts of Delta hydrodynamics results from the adverse effects of altered Delta flows on habitat quantity and quality, water quality, predation by native and non-native predators, and/or migration delay or misdirection, and/or diversion of fish from their normal dispersal pathways to areas of the Delta where mortality is unnaturally elevated; Brandes and McLain 2001; Newman 2003; Newman 2008; Perry and Skalski 2008; NMFS 2009). It is difficult to precisely measure. In their review and synthesis of numerous studies investigating survival of salmonids through the Delta, NMFS (2009) estimated that, on average, 54% of salmonids died during their migration through the Delta (compared to an estimated 24% under unimpaired, or pre-development, conditions) (NMFS 2009; Table 6-33). Mortality was higher in drier years (67-88% mortality for critical and dry years) when the natural and anthropogenic reductions in inflow and combined with relatively higher exports to have greater impacts on hydrodynamic and environmental conditions compared to wetter years (17-39% for wet and above normal years). NMFS also reported that Delta mortality was higher in recent years (i.e., 1990 level of development) compared to a 1940 level of development, a clear indicator of the adverse impacts of increased water management operations in the Delta and upstream.

Most recent studies of the effects of Delta hydrodynamic conditions on resident and migratory fishes have focused on direct mortality (Baxter et al. 2008; Kimmerer 2008). A number of analyses have shown that the numbers of fishes salvaged at the export facilities are positively and directly related to exports rates (regardless of whether exports are expressed as export rates, E:I ratios or OMR flows) (Figure 1); Baxter et al 2008; Kimmerer 2008; USFWS 2008; Grimaldo et al. 2009; NMFS 2009). In general, simple correlative analyses to relate measured entrainment mortality in a given year and subsequent population abundance have found few consistent patterns or statistically significant relationships (Kimmerer et al. 2001; Kimmerer 2008; Grimaldo et al. 2009). This type of analytical approach has limited value for several reasons, including: a) very large, known measurement error for entrainment mortality data (see above); b) measurement error for population abundance indexes (which likely increases when abundance is low and the ability of surveys to detect fish is reduced); c) known significant effects of species' distribution on their vulnerability to entrainment into the south Delta export facilities (e.g., Kimmerer and Nobriga 2008); and d) large inter-annual variations in both environmental and biological conditions (e.g., the timing, amounts and patterns of inflows, fish movements). Basing criteria solely on these analyses will likely underprotect public trust resources.



Note: Data shown are for the period 1984-2007, excluding years 1987, 1989-92, 1994, and 2007 that had low (<12ntu) average water turbidity during Jan-Feb at Clifton Court Forebay.

**Figure S-8 – Relationship for the total number of adult delta smelt salvaged at the State and Federal fish facilities in the south Delta during the winter months of December through March with the combined, tidally averaged flow in Old and Middle Rivers near Bacon Island (*AVG_OMR*$_i$).**

**Figure 9.** Chinook salmon. Relationship of estimated proportional salvage of tagged smolts at the fish facilities, $P_S$, to export flow. Small symbols represent data based on six or fewer fish caught, which were not used in determining the line. Lines are from a generalized linear model with log link function and variance proportional to the mean ($p < 0.0001$, 57 df), with source of fish as a categorical variable. Thick lines are predictions for fish from each hatchery; thin lines are upper 90% confidence limits of the predicted mean values.

**Figure 1.**
Relationships between OMR flows and salvage of delta smelt (left panel; from USFWS 2008, Fig.s-8) and exports and salvage of Chinook salmon (right panel, from Kimmerer 2008, Fig.9). Vertical red dashed line (right panel) shows an export rate of approximately 6500 cfs.

The most comprehensive and useful investigation of the effects of entrainment loss on population abundance was conducted by Kimmerer (2008), who examined loss of Sacramento basin Chinook salmon, a seasonal migrant, and delta smelt, a resident estuary-dependent species vulnerable to entrainment during both adult and juvenile life stages. For salmon, Kimmerer (2008) used data from multiple releases over multiple years of known numbers of tagged salmon. His results showed that the proportion of the salmon release group migrating through the Delta that was lost at the export facilities was significantly affected by and directly related to export rates: a larger proportion of Sacramento Basin outmigrating juvenile salmon were lost at the CVP and SWP export facilities when export rates were high then were lost when export rates were low. Furthermore, the relationship between export rates and loss was not linear but rather exhibited sharp increases in the proportion of the population lost when exports exceeded 6000-8000 cfs. Regarding salmon mortality, Kimmerer (2008:24) concluded:

> *From a population maintenance standpoint, the calculated loss rate at the export facilities would be a significant component of direct anthropogenic mortality. ... [T]his level of additional mortality at the export facilities may place constraints on the rate of*

> *recovery of the listed winter- and spring-run stocks, and on ocean harvest of stocks (such as the fall run) that are not listed. Furthermore, these constraints may grow for winter Chinook if export flows continue to be kept high in winter to reduce impacts in spring.*

For San Joaquin Basin Chinook salmon, there have been some direct investigations of the effects of Delta hydrodynamic conditions on population abundance, measured as the numbers of adult fish returning the San Joaquin Basin rivers 2.5 years after they migrating through the Delta as juveniles (CDFG 2005). These analyses have shown that hydrodynamic conditions, measured as the ratio of San Joaquin River inflow to the Delta (i.e., Vernalis flow) to exports, are directly and positively related to escapement.

Delta hydrodynamic conditions can affect productivity by reducing abundance and survival of specific life stages to levels where productivity is insufficient to reverse population declines. Impacts on productivity can be chronic, for example conditions that regularly cause mortality of a large enough fraction of the population beyond what it can absorb and maintain a stable population, or episodic, such as instances of catastrophic mortality resulting from a extreme entrainment event in which a large fraction of the population is lost and population abundance declines dramatically (e.g., viability assessment criteria described by Lindely et al. 2007). Both chronic and episodic mortality events have disproportionately severe impacts on populations that are already at low abundance. Conservation managers understood this episodic impact on endangered species even before it was quantified. For example, the USFWS Native Fishes Recovery Plan (USFWS 1995a) acknowledged that SWP and CVP pumping rates probably had a large impact on spring-run Chinook salmon outmigration success, particularly when Delta outflows were low. Thus, the Recovery Plan stated that:

> *Sacramento spring [C]hinook will be regarded as restored when [among other factors related to abundance and spatial distribution] the smolt survival rates between Sacramento and Chipps Island approach pre-project levels when the number of adults in the tributary streams is fewer than 5,000.*

The Native Fishes Recovery Plan made similar recommendations regarding the need to control anthropogenic sources of mortality in the Delta, particularly when populations were already depressed, for San Joaquin River fall-run Chinook salmon and Sacramento River fall-run Chinook salmon.

For delta smelt, Kimmerer's results indicated that export-related entrainment loss was as high as 40% of the total population in some years and probably has had an episodic effect on the species' population abundance and productivity (Kimmerer 2008; Grimaldo et al. 2009). In the early 2000s, the high proportions of the delta smelt population that were lost to entrainment coincided with sharp declines in population abundance, a finding consistent with the conclusion of researchers investigating the Pelagic Organism Decline (POD) that loss of fish to the pumps could be a cause of population declines in some years (Baxter et al. 2008). In particular, entrainment of larval fish (which is not measured by the CVP or SWP) may have substantial impact on certain species depending on the interaction of initial population size, Delta inflow, and export operations (Kimmerer and Nobriga 2008; see also sections below).

## Methods for developing Delta hydrodynamics criteria to increase abundance and/or productivity of public trust resources

*Summary points:*

- *Based on significant increased salvage when OMR flows were less than -2000 to -3000 cfs, OMR flows should be greater than -2000 cfs from October to June in all years to prevent significant Sacramento basin salmonid population impacts and contribute to meeting salmon abundance targets.*
- *In order to support the attainment of doubling goals for San Joaquin River salmonids, San Joaquin River inflow to export ratios should range from 1:1 to 4:1 (roughly equivalent to OMR flows of -2000 to +3000 cfs) from March to June as runoff increases.*
- *Based on significant increased salvage when OMR flows are negative, extreme susceptibility to the effects of reverse flows, and vulnerability to extinction risk from a one year life history, OMR flows should be greater than -1500 cfs from December to June in all years to prevent significant, potentially catastrophic delta smelt population impacts.*
- *Based on the strong correlation between decreasing Delta outflows and increasing longfin smelt entrainment, when outflows are low and the FMWT <500, positive OMR flows should be maintained in April and May to prevent longfin population impacts.*
- *Based on the significant relationship between San Joaquin River inflow – Delta export pumping ratios and the productivity of San Joaquin Chinook salmons, inflow – export ratios of no less than 1 to 1 (roughly equivalent to OMR flows of -1500 to -5000 cfs) should be maintained in all years.*

*Sacramento Basin Chinook salmon and steelhead:* To develop our recommendations for Delta hydrodynamic conditions and export rates consistent with meeting the needs of Sacramento Basin salmonids, we used information on the current status of the species, timing of juvenile salmonid migration through the Delta (Figure 1) and the analyses and results reported by Kimmerer (2008) and NMFS (2009) to examine the relationship between CVP and SWP export rates and/or OMR flows, salvage and survival to identify threshold levels that corresponded to high salvage or marked increases in salvage of juvenile salmon and steelhead (Figures 1, 2 3). Most of these analyses showed an exponential increase in salvage with increases in exports (or decreases in OMR) and we found that salvage generally increased sharply at combined export rates that were: a) greater than 6000 – 7000 cfs (Fig DH-A right panel; this export level corresponds to approximately -5000 to -6000 cfs OMR); b) OMR flows that were less than -2000 to -3000 cfs (Figure 2); and c) approximately 200 TAF per month at each facility (Figure 3; this export level corresponds to approximately 6500 cfs exports or -5500 cfs OMR).

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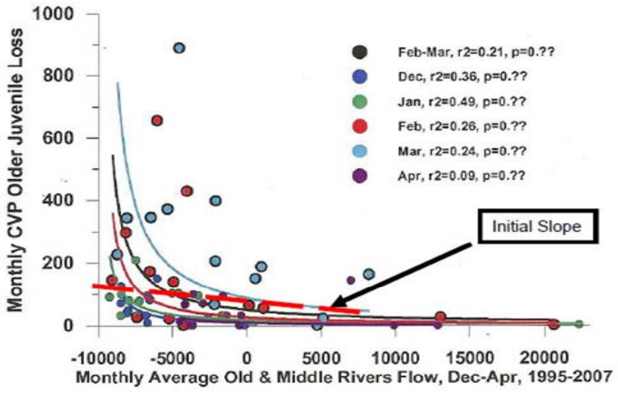

**Figure 6-65.** **Relationship between OMR flows and entrainment at the CVP, 1995-2007 (DWR 2008).**

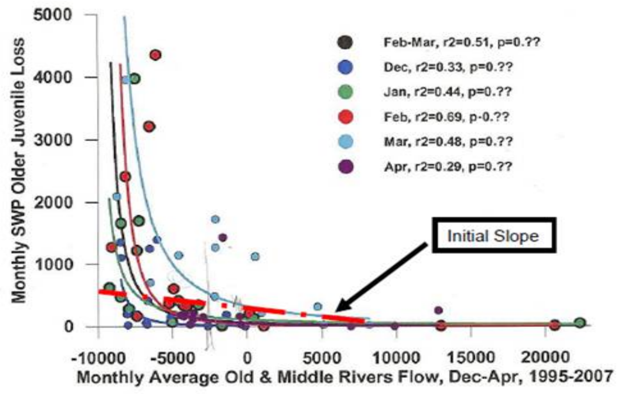

**Figure 6-66.** **Relationship between OMR flows and entrainment at the SWP, 1995-2007 (DWR 2007).**

**Figure 2.**
Relationships between OMR flows and loss of older juvenile salmonids at the CVP (upper panel) and SWP (lower panel). From: NMFS 2009.

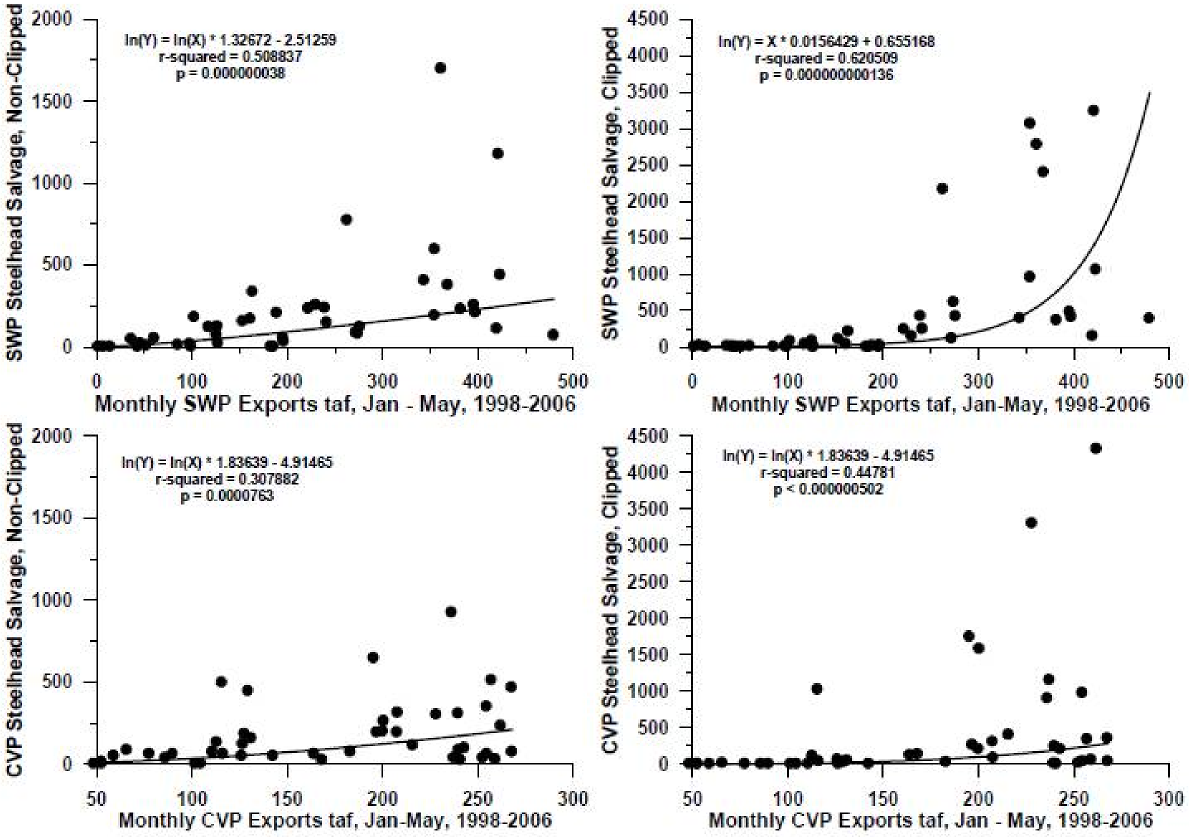

**Figure 6-72. Monthly steelhead salvage versus average exports, January through May, 1998 through 2006, at each facility; SWP and CVP (CVP/SWP operations BA figure 13-45).**

**Figure 3**
Relationships between monthly exports (as TAF) and salvage of juvenile steelhead (clipped and unclipped) t the CVP and SWP. From: NMFS 2009.

## Recommendation: Hydrodynamic criteria to increase abundance of public trust resources (Sacramento Basin Chinook salmon and steelhead)

Hydrodynamic conditions in the Delta should be managed to maintain OMR flows that are greater than -2000 cfs during the period from October-June in all years.

*San Joaquin Basin Chinook salmon:* Juvenile fall-run Chinook salmon migrating downstream along the lower San Joaquin River are particularly vulnerable to entrainment at the SWP and CVP pumps because the lower San Joaquin River is geographically closer to the export facilities than the Sacramento River and because one of the San Joaquin River's major distributaries, Old

River, flows directly past the pump intakes. We examined the relationship between escapement of San Joaquin Basin Chinook salmon and Delta hydrodynamic conditions, measured as the ratio San Joaquin River inflow (i.e., flow at Vernalis) and exports (VF:E ratio), that occurred 2.5 years earlier during the period when juveniles of the population cohort were migrating through the Delta (Figure 4). We found that population abundance (i.e., escapement) was directly and positively related to VF:E ratio: San Joaquin Basin Chinook salmon population abundance was higher when the VF:E ratio was high (i.e., San Joaquin River flows were higher than exports) during their juvenile outmigration period and low when juveniles migrated through the Delta under conditions of high experts relative to San Joaquin River inflows. For example, VF:E ratios that were greater than 1.0 during the spring consistently correspond to escapement numbers that were greater than 10,000 fish (e.g., escapement was >10,000 in 76% of years with VF:E ratios >1.0 during the juvenile outmigration 2.5 years earlier). In contrast, ratios below 1.0 produced salmon escapement levels greater than 10,000 in only 33% of years and corresponded to 80% of the years in which fewer than 2500 salmon returned to San Joaquin tributaries. We compared this relationship to salmon production objectives established by the SWRCB (and the CVPIA) to double salmon populations relative to their 1967-1991 average (the goal for salmon produced on the Stanislaus, Tuolumne and Merced Rivers is approximately 37,000 fish) and concluded that current Delta hydrodynamic conditions resulting from the combined effects of low San Joaquin River inflows and high export rates are almost always inadequate to provide conditions necessary to support or sustain San Joaquin Basin salmon population abundances or meet these objectives. We also concluded that only Delta hydrodynamic conditions with a VF:E ratios that were greater than 4.0 consistently corresponded to salmon abundance levels that approached the population abundance objectives for this species.

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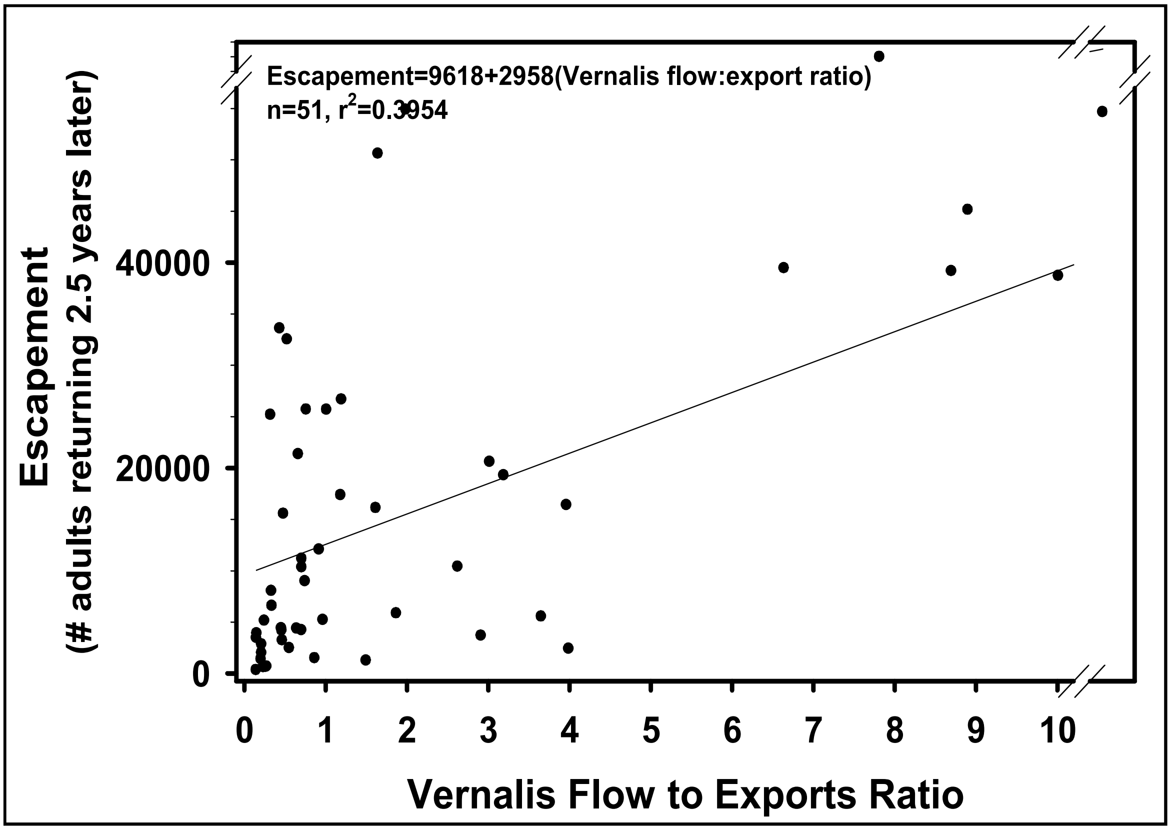

**Figure 4**
The relationship between abundance of San Joaquin Basin Chinook salmon (escapement) and Delta hydrodynamic conditions (Vernalis Flow to export ratio) measured their juvenile outmigration period 2.5 years earlier. The

## Recommendation: Hydrodynamic criteria to increase abundance of public trust resources (San Joaquin River Chinook salmon)

Hydrodynamic conditions in the Delta should be managed to maintain a March – June VF:E ratio that is greater than 4.0 in 40% of years, greater than 3.0 in 60% of years, greater than 2.0 in 80% of years and greater than 1.0 in 100% of years. These VF:E ratios are similar to those required by NMFS in their 2009 Biological Opinion for the protection of endangered San Joaquin Basin steelhead. Integrating these Delta hydrodynamic recommendation expressed in terms of VF:E with our recommendations for San Joaquin River inflows (i.e., Vernalis flows; see Exhibit 3); these recommendations roughly correspond to OMR flows for the March – June period that are greater than -2000 cfs in 100% of years and, for 80% of years, range from 0 cfs to substantially positive OMR flows (e.g., OMR flow greater than 3000 cfs in wetter years).

*Delta smelt:* Delta smelt are exposed to Delta hydrodynamic conditions and vulnerable to entrainment in the Delta export facilities as maturing adults during their winter upstream migration to freshwater spawning habitat in the upper reaches of the Delta and as larvae and young juveniles during the late winter and spring period when they move downstream through the Delta to low salinity habitat, usually located west of the confluence of the Sacramento and San Joaquin Rivers (Figure 1). Delta smelt are also smaller than juvenile salmonids transiting the Delta: all larvae and juveniles smaller than 20 mm in length are inadequately monitored and are not counted at the export facilities and large proportions of larger and older fish slip through the inefficient louver screens rather being diverted into holding tanks for salvage. In addition, delta smelt are also physically delicate and most studies suggest that virtually all entrained fish collected in salvage holding tanks at the export facilities do not survive (USFWS 2008).

Because of their small size, weak swimming abilities and behavioral tendencies to move with flow, delta smelt are particularly vulnerable to adverse Delta hydrodynamic conditions and entrainment at the export facilities. Further, because of their single year life span and limited geographic range, the species is particularly vulnerable to extinction from a catastrophic mortality event. Finally, because of the species' current critically low population abundance, it is already at high risk of extinction and even modest levels of mortality resulting from adverse Delta hydrodynamic conditions and export operations could result in extinction or prevent or delay recovery of the species to sustainable population levels. Simple correlative analyses (e.g., Kimmerer 2008) suggest that export effects are of greatest concern when inflows and outflows are low, but given the limitations and errors in the entrainment mortality data and the precarious status of this species, we recommend hydrodynamic flow criteria be developed for all years.

We used information from several studies to develop recommendations for Delta hydrodynamic conditions and export operations that are necessary to support the needs of this public trust species, including: a) analyses of entrainment loss by Kimmerer (2008); b) salvage v OMR flow relationships developed by USFWS and several other investigators (Baxter et al 2007; USFWS 2008); c) results of particle tracking model simulations for entrainment risk relative to export flows and E:I ratios (Kimmerer and Nobriga 2008); and d) results of analyses of delta smelt survival and hatching data by Drs. W. Bennett and J. Hobbs (reported by Baxter et al. 2008). We found that: a) Kimmerer reported that entrainment loss of delta smelt as a proportion of the total population exceeded 20 – 40% in some years and was related to OMR flows, with high proportions of the delta smelt population lost when OMR flows were highly negative (Figure 5)**;** b) the numbers of delta smelt salvaged was significantly related to OMR flows with salvage first increasing when OMR flows become negative and reaching the highest levels at OMR flows less than -5000 cfs; (Figure 1, left panel); c) entrainment risk for larval and juvenile smelt increased with increases in the E:I ratio in all regions of the Delta, with 100% of particles in the southern Delta entrained at the CVP and SWP facilities at E:I ratios greater than 0.2 (Figure 6; this E:I ratio corresponds very approximately to -3000 cfs OMR); and d) delta smelt larvae only hatched during the VAMP export curtailment and San Joaquin River flow enhancement, a period during which OMR flows have averaged approximately -1500 cfs, survived to the summer.

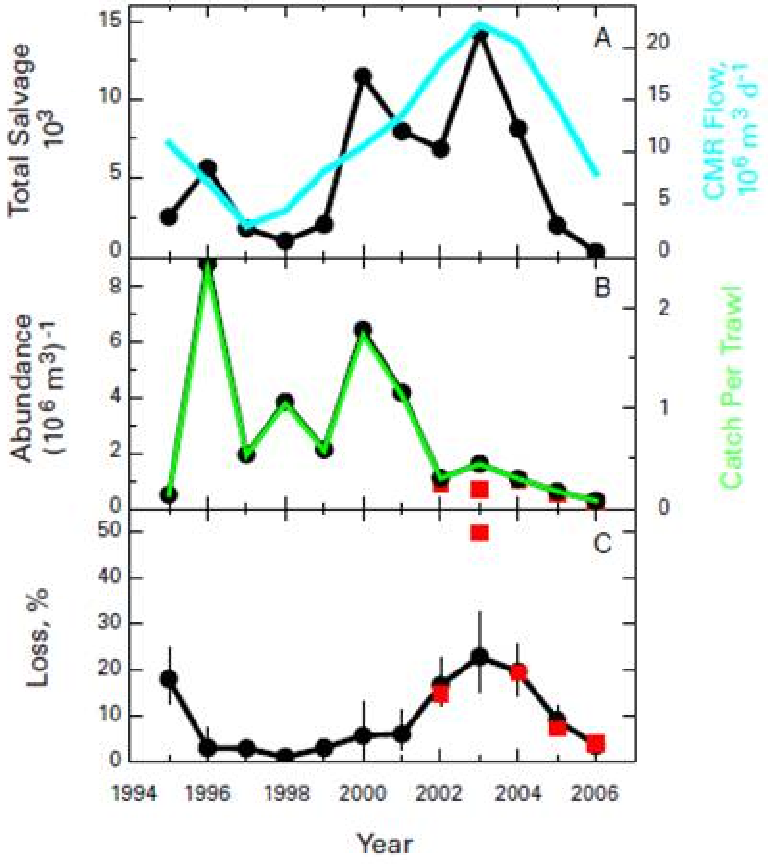

**Figure 12.** Reconstruction of export losses of adult delta smelt for 1995–2006. (A) Total salvage (line with circles) and Old and Middle River flow (line, right axis); (B) Predicted (line with circles) and measured (squares) population abundance, and mean catch per trawl for the fall trawl surveys in November and December (line, right axis); (C) Predicted (error bars, 5th and 95th percentiles) and measured (squares) proportional losses to export entrainment.

**Figure 5**
From Kimmerer 2008. See caption for explanation.

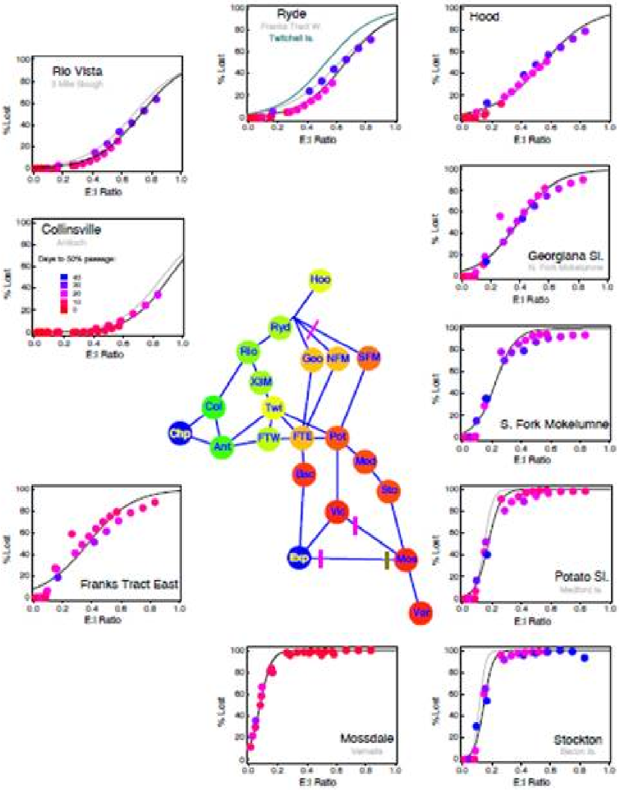

**Figure 6**
Results of particle tracking model simulations showing the percentage of particle released at different locations within the Delta entrained into the CVP or SWP export facilities at different E:I ratio conditions. For particles released in the southern Delta, most or all of the particles were entrained by the CVP or SWP pumps within a few weeks at E:I ratio >0.2. From: Nobriga and Kimmerer 2008.

**Figure 7.** Percent of particles lost to export pumps for spring tide runs with no agricultural diversions and 24 combinations of inflow and export flow. Data are shown for selected release sites, color-coded by the time needed for 75% of particles to leave the Delta. Lines are logistic functions fit to the data, and are dark for selected sites and light gray for other sites with similar responses. Central diagram is a schematic arrangement of the sites in Figure 1, with principal links between sites. Short lines represent barriers including the DCC in the northern Delta, the Head of Old River barrier in the south Delta (dark yellow), and south Delta agricultural barriers (pink).

## Recommendation: Hydrodynamic criteria to improve abundance and productivity of public trust resources (delta smelt)

Hydrodynamic conditions in the Delta should be managed to maintain OMR flows that are greater than -1500 cfs during the period from December to June in all years**.**

*Longfin smelt:* Patterns of longfin smelt entrainment are highly consistent with what is known about this species' reproductive behavior. Adult longfin smelt enter eastern Susiun Bay and the western Delta in preparation for spawning during the late fall and early winter (Moyle 2002; Rosenfield and Baxter 2007). Eggs hatch into larvae from March-May and larvae are distributed throughout the northern estuary. Larvae metamorphose into juveniles predominantly in April-June, at which point they are detectable in sampling and salvage programs (Baxter 1999; Rosenfield and Baxter 2007). Both the general location of longfin smelt spawning and the distribution of their larvae are highly dependent on freshwater flow through the Delta; higher freshwater flows in the winter shift the location of spawning to the west and higher flows during the spring increase the rate of larval transport out of the Delta (Dege and Brown 2004; Rosenfield and Baxter 2007; Sommer et al 2007; R. Baxter, CDFG, personal communication, December 3, 2009). Thus, outflows, which are strongly positively correlated with productivity in this species (see Exhibit 2) are also expected to correlate negatively with entrainment at the South Delta export facilities.

Among juveniles, entrainment is highest in April and May; entrainment of adults is greatest December-February (Figure 7). Entrainment exceeded 20,000 individuals in more than 25% of years between 1981 and 2007 (7 of 27 years; Figure 8). Entrainment of larval longfin smelt is not measured but given the timing of spawning and juvenile entrainment, it is probably greatest during March and April. The number of entrained larvae is expected to vastly outweigh the number of juveniles entrained based simply on the greater abundance of earlier life stages. Grimaldo et al. (2009) demonstrated a clear and statistically significant relationship between combined Old and Middle River flows and entrainment of both juvenile and spawning-age longfin smelt (Figure 9).

**FIGURE 7: Average seasonal distribution of longfin smelt in CVP/SWP salvage. Timing differs between the two longfin smelt age classes**

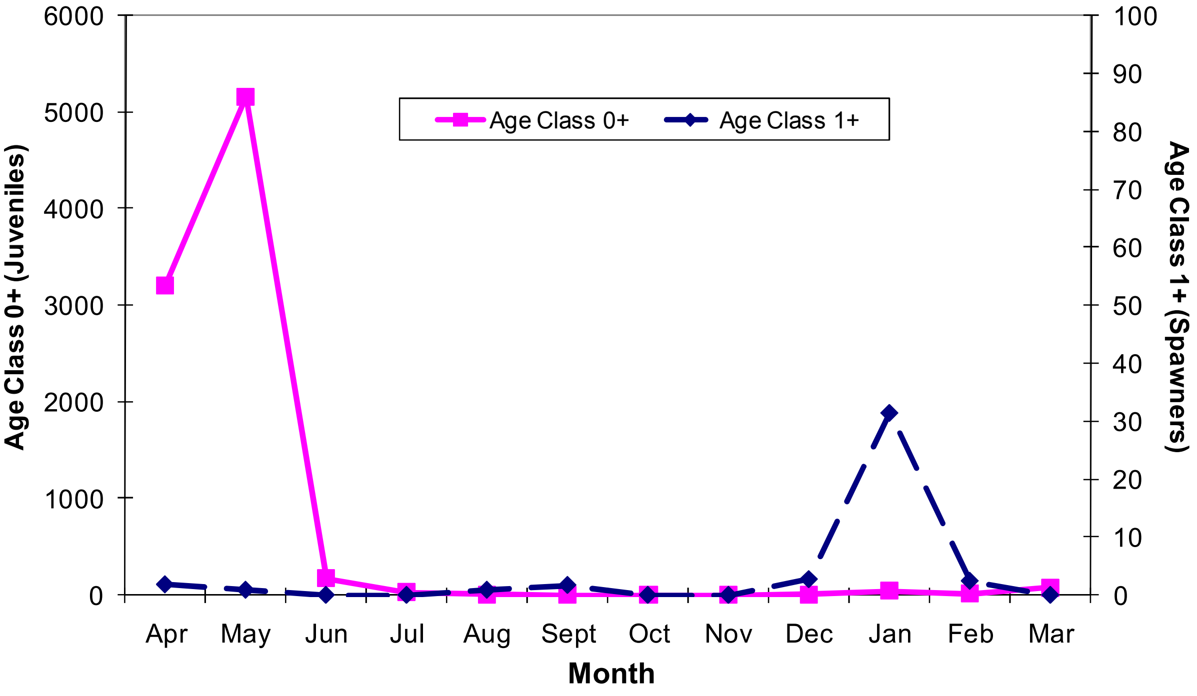

FIGURE 8:
Total longfin smelt entrainment (1981-2007) as a function of March-May Delta Outflow

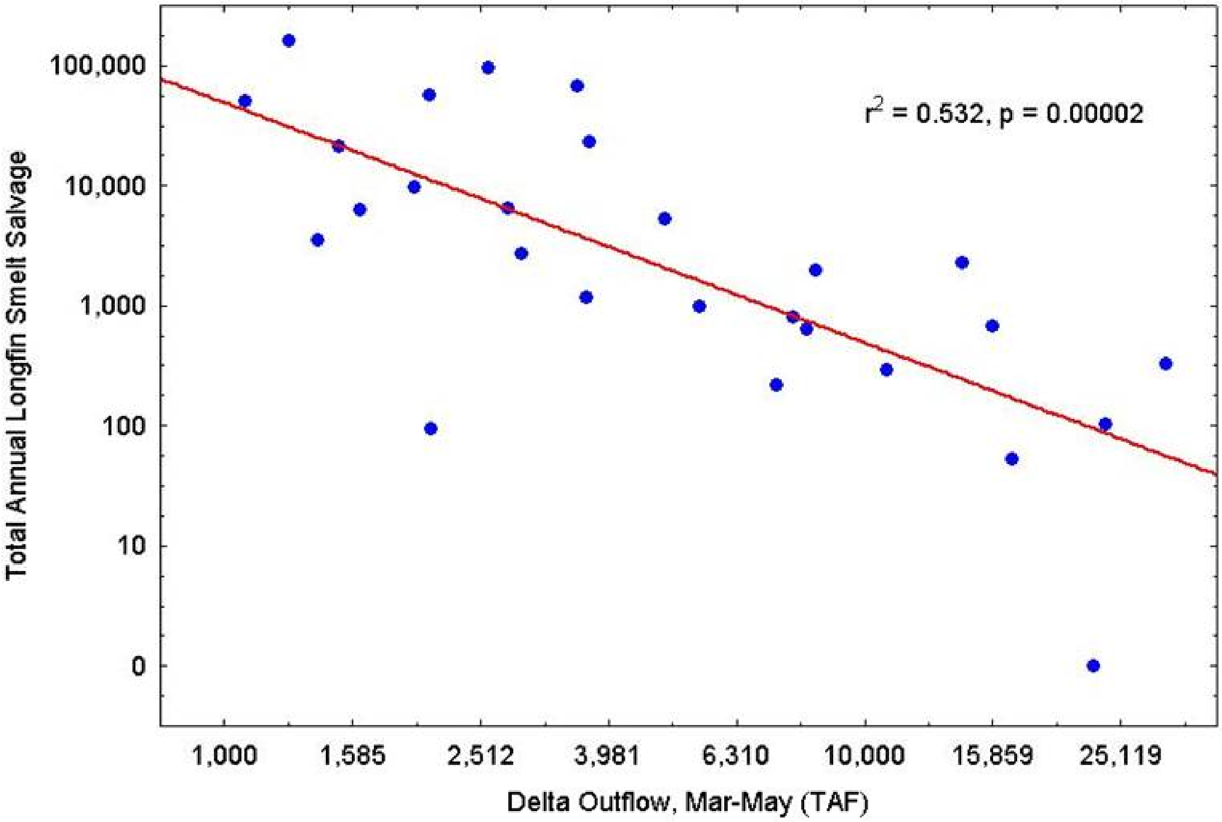

Figure 9: Relationship between OMR flows and entrainment of two different age classes of longfin smelt, (top panel, subpanel "B") and (bottom panel, "longfin smelt" panel) mature adults.

(TOP)

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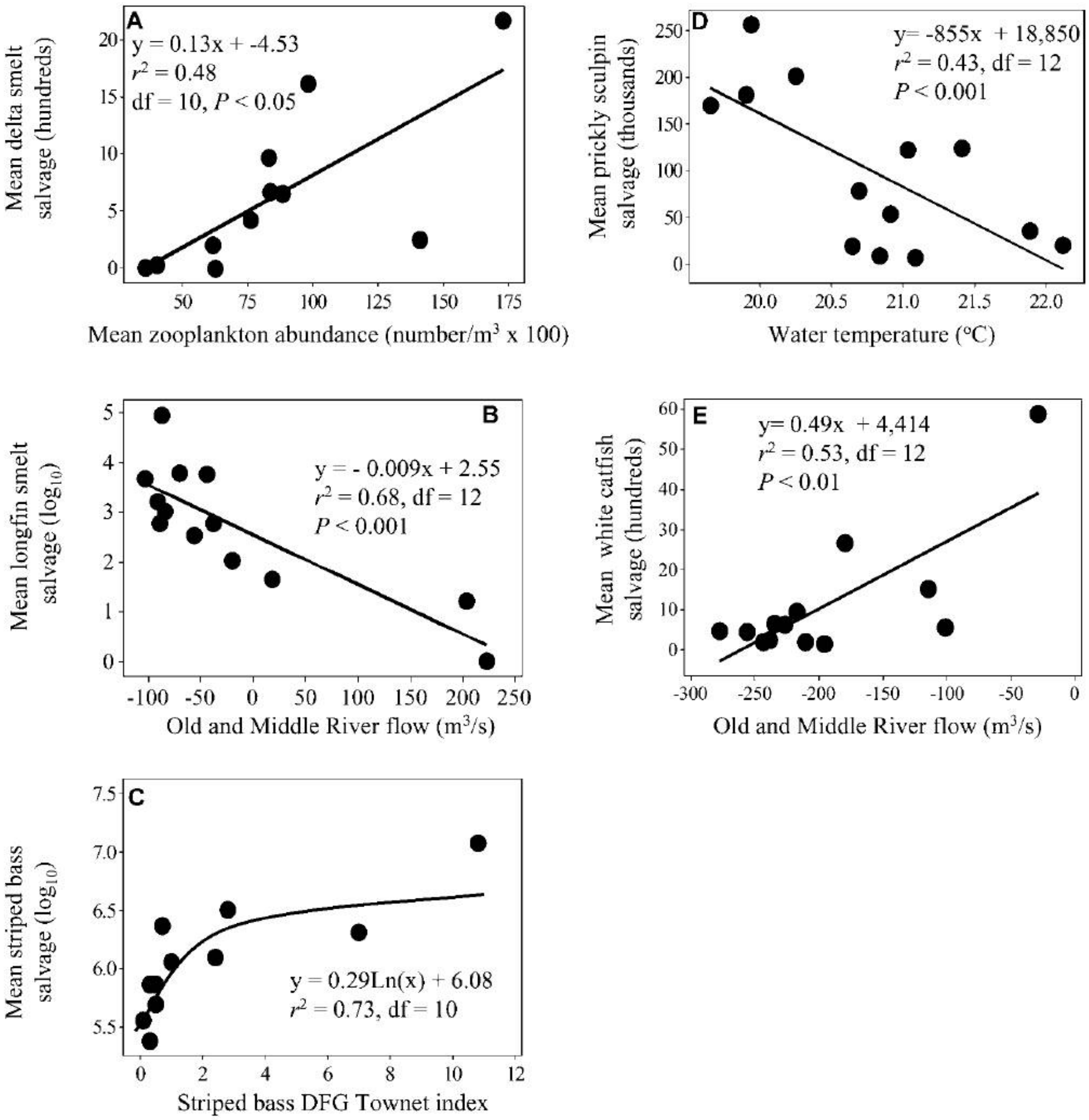


FIGURE 7.—Relationships between (**A**) age-0 delta smelt annual salvage in the State Water Project and Central Valley Project, California, and zooplankton abundance; (**B**) longfin smelt salvage and combined flow of the Old and Middle rivers; (**C**) striped bass salvage and the California Department of Fish and Game (DFG) tow-net survey index; (**D**) prickly sculpin salvage and water temperature; and (**E**) white catfish salvage and Old and Middle River flow. No other parameters explained the salvage of these species. See Table 1 for averaging periods.

We analyzed the effect of Delta outflow and export rates on total entrainment (which is largely composed of juvenile longfin smelt in April and May; Grimaldo et al. 2009) and entrainment of spawning age longfin smelt. Total (juvenile) entrainment is strongly correlated with outflow during Mar-May (Figure 8) whereas spawning adult entrainment is strongly correlated with export rates (Figure 10). Both relationships are logarithmic, meaning that as outflows decline or exports increase (respectively) entrainment-related mortality increases in an accelerating fashion. Interestingly, entrainment levels are not a positive function of longfin smelt abundance; indeed, as abundance increases, entrainment decreases (Figure 11). This is likely a result of the multiple effects of Delta outflow on longfin abundance, productivity, and distribution.

FIGURE 10:
Entrainment of Spawning-Age Longfin Smelt vs. CVP/SWP Combined Export Rates, 1993-2007

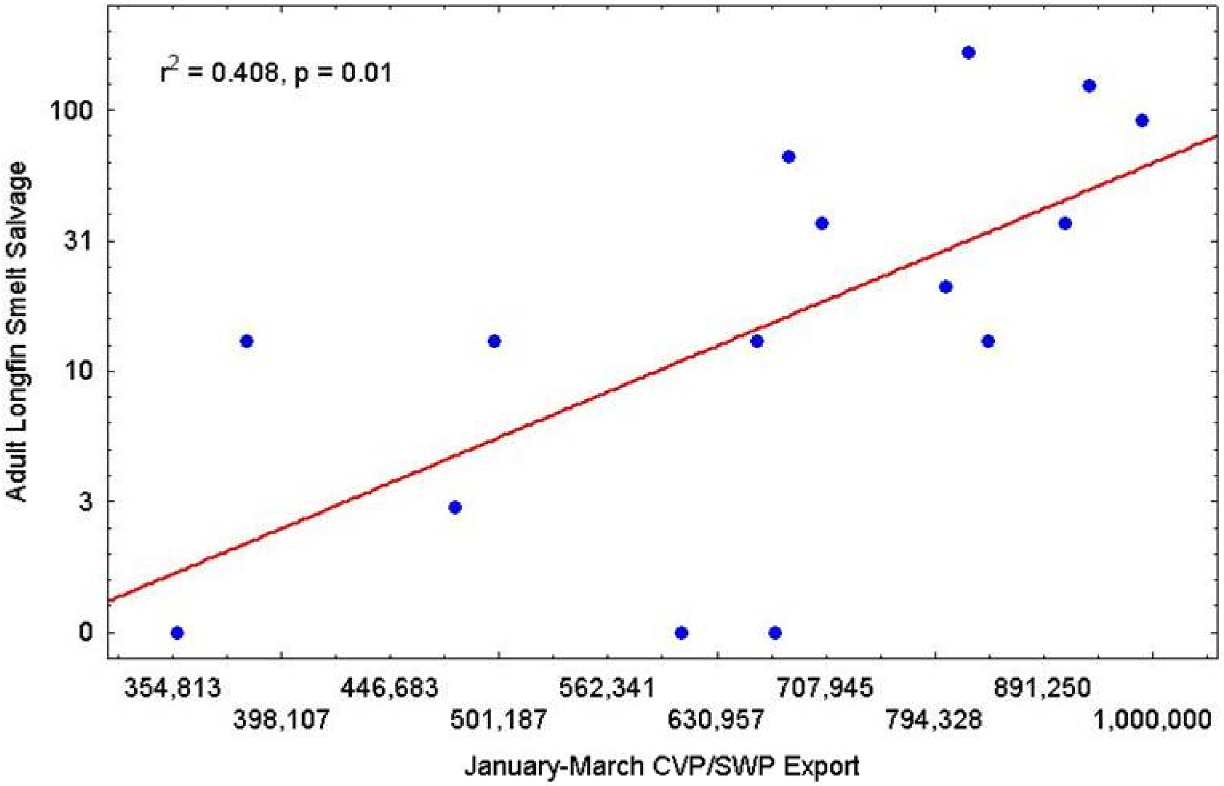
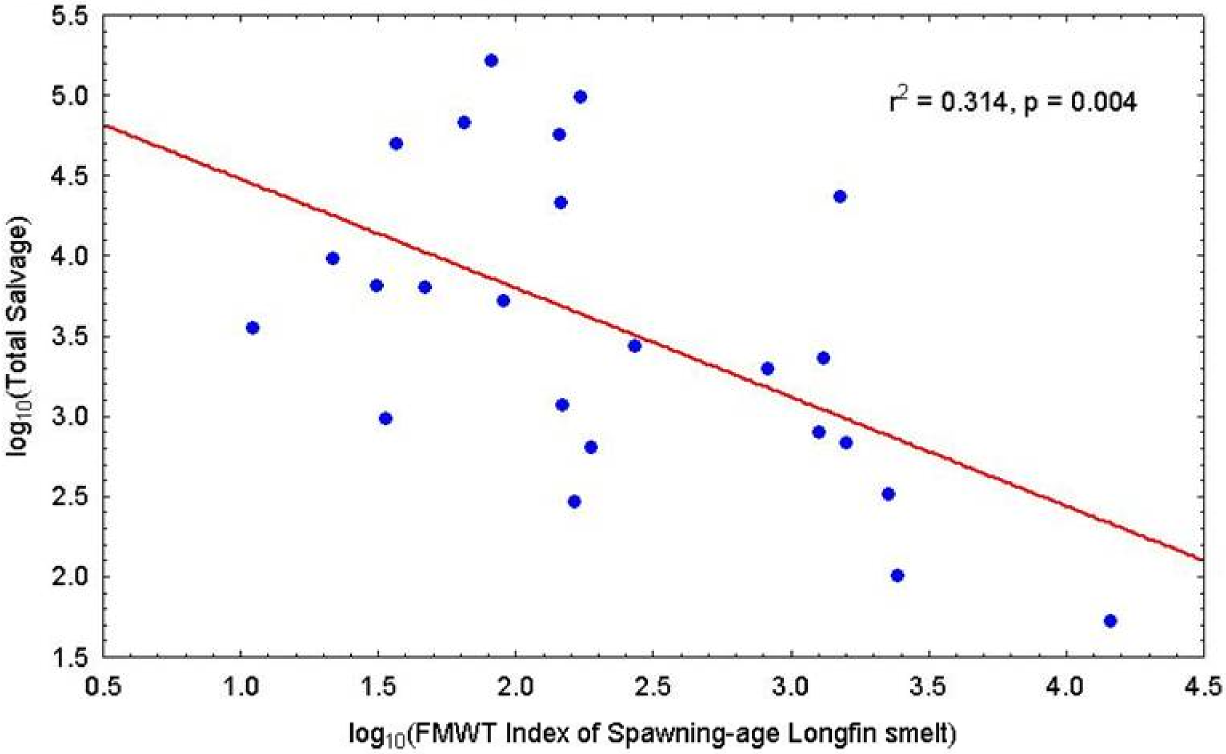


FIGURE 11:
Total annual longfin smelt salvage (CVP and SWP combined) as a function of abundance (Fall Midwater Trawl Survey) in the same year. The negative correlation indicates that increases in salvage are not a result of increased abundance.



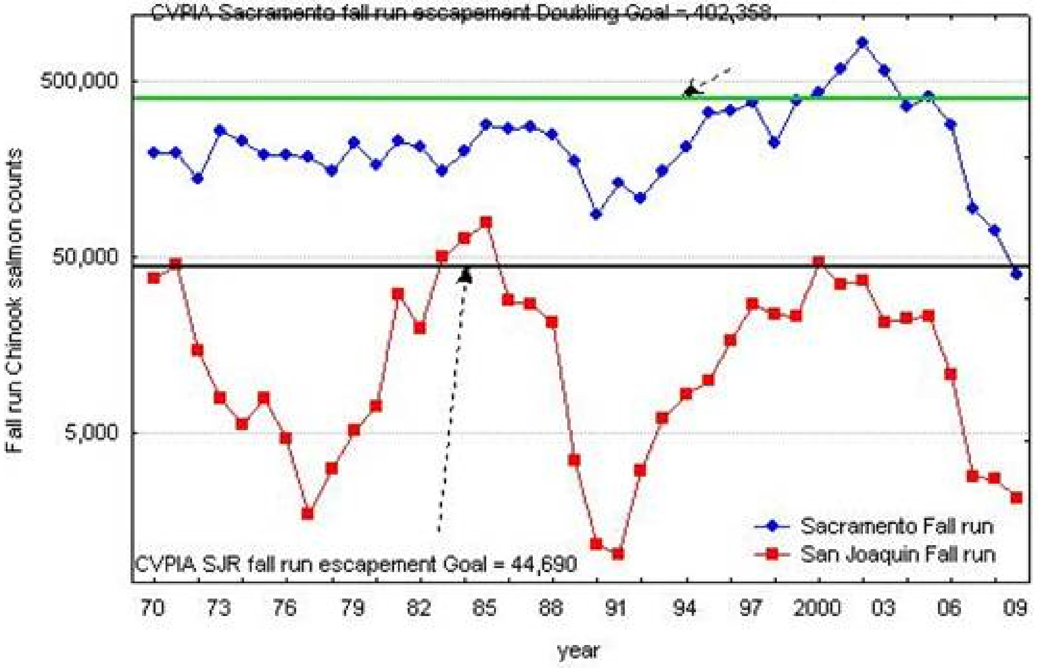
These results are consistent with expectations based on longfin smelt life history. They indicate that export-related mortality may be highest in exactly those low outflow years when the longfin smelt population is already expected to perform poorly. Export related mortality, which is seriously underestimated by the salvage numbers recorded at the CVP and SWP facilities, increases as the population decreases and has a disproportionate impact on longfin smelt when populations are low. Thus, the effect of export entrainment is to destabilize the longfin smelt population by driving it to lower-lows and eliminating the very individuals that would allow the population to grow when higher winter-spring outflows return.

**Recommendation: Delta hydrodynamic criteria to improve productivity of public trust resources (longfin smelt)**

Reduce entrainment losses of longfin smelt in dry years (i.e., March – May Delta flow is less than 3.2 MAF) and when longfin smelt abundance in low (i.e., when the Fall Midwater Trawl Index for longfin smelt is less than 500) by maintaining positive OMR flows (i.e., OMR >0 cfs) in April and May.

*San Joaquin Basin Chinook salmon:* We examined escapement and cohort return ratios (CRR, the ratio of the number of adult fish that return to spawn in a particular year to the number of adult fish that produced them several years earlier) for San Joaquin Basin Chinook salmon. We found that escapement numbers have declined significantly in recent years (Figure 12) and the CRR has been substantially less than 0.5 for each of the past 6 years, indicating that the population has been declining by more than 50% each generation. We next examined the effect of the VF:E on productivity of San Joaquin Basin Chinook salmon using the CRR metric (Figure 13) and found that population growth of San Joaquin fall-run Chinook salmon is significantly related to the VF:E. Review of data showed that in 86% of years with average March-June VF:E ratios greater than or equal to 1.0, the CRR is greater than 1.0 (positive population growth), while in 70% of years with a VF:E ratio less than 1.0, the CRR is less than 1.0, indicating a population decline. VF:E ratios greater than 1.0 produce positive growth in almost all years: two of the three years with VF:E ratios greater than 1.0 that corresponded to negative population growth were in the 2000s, coincident with the Pelagic Organism Decline and when a number of other environmental conditions were also extremely poor. In contrast, incremental decreases in the VF:E ratio result in marked declines in the likelihood of positive growth: for example, a VF:E ratio of 0.8 or less results in positive population growth in only 30% of years.

FIGURE 12:
Fall run Chinook escapement for Sacramento and San Joaquin systems, 1970 -2009



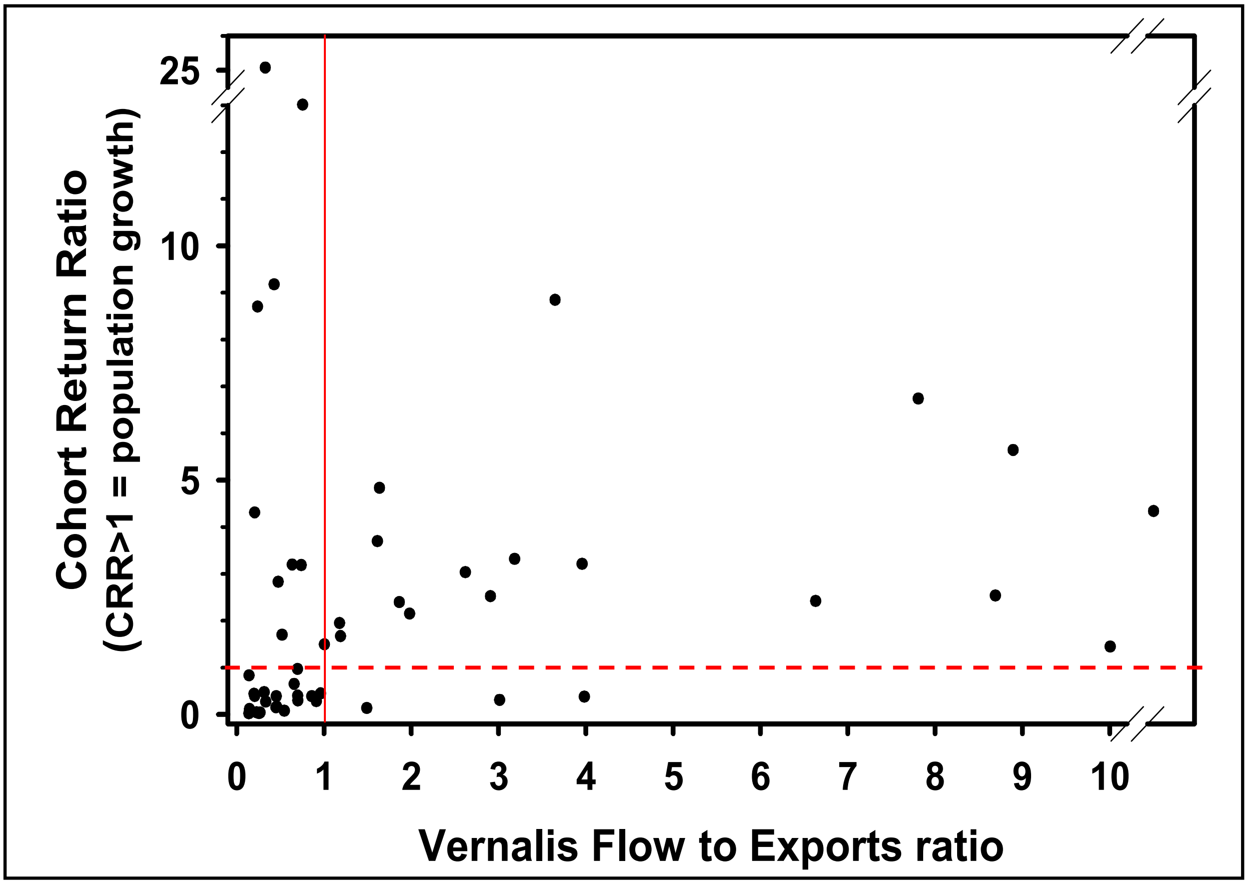


**Figure 13**
Relationship between the cohort return ratio (CRR) and the Vernalis flow to export (VF:E) ratio for San Joaquin Basin Chinook salmon. Horizontal red dashed line shows a CRR=1.0. At CRRs less than 1.0 population declines while at CRR greater than 1.0 population abundance increases. The vertical red solid line shows the VF:E ratio equal to 1.0. At VF:E ratios less than 1.0 the CRR is almost always less than 1.0.

Except during the 31-day VAMP period from mid-April to mid-May, current Vernalis flow requirements and concurrent export limits allow Delta hydrodynamic conditions that produce VF:E ratios substantially below 0.5 in all water year types. These conditions correspond to a prediction for population declines for San Joaquin Chinook salmon in 72% of years. Therefore, current flow and export levels allowed by the SWRCB (SWRCB 2006 and the Vernalis Adaptive Management Plan) would predictably result in more frequent occurrences of negative population growth for San Joaquin Chinook salmon. We concluded that current springtime Delta hydrodynamic conditions are inadequate to increase San Joaquin fall-run Chinook salmon populations to meet management objectives or to support stable populations in the long term.

**Recommendation: Delta hydrodynamic criteria to increase productivity of public trust species (San Joaquin Basin Chinook salmon)**

Limit Delta export rates to no more than the concurrent San Joaquin River flow at Vernalis to maintain Delta hydrodynamic conditions with a VF:E ratio of greater than or equal to 1.0 for each month during the March – June period in all years. Integrating this Delta hydrodynamic recommendation expressed in terms of VF:E with our recommendations for San Joaquin River inflows (i.e., Vernalis flows; see Exhibit 3), these recommendations roughly correspond to OMR flows for the March-June that are greater than -1500 cfs (in drier years) to -5000 cfs (in wetter years).

**Relationship between Delta hydrodynamics and diversity of public trust resources**

*Summary points:*

- *Entrainment levels are disproportionately impacting the most reproductively successful individuals in the delta smelt population.*
- *The abundance criterion to maintain OMR flows greater than -1500 cfs from December to June should also sufficiently protect these individuals.*

In addition to direct effects of mortality on the population abundance and productivity (and population stability) attributes of viability, there is strong, emerging evidence that Delta hydrodynamics and export-related mortality may affect life history diversity of some species because, under current Delta export operations, entrainment may disproportionately affect certain population cohorts or life history types ("strategies") more than others. For example, research by Drs. W. Bennett and J. Hobbs suggests that export-related loss of early spawning adult delta smelt and their larvae, which hatch before the Vernalis Adaptive Management Program (VAMP) export curtailment and San Joaquin River flow enhancement (typically April 15-May 15), has resulted in repeated, large-scale recruitment failure of a large component of the delta smelt population and contributed to the recently observed catastrophic population decline (Figure 14; Baxter et al. 2008). These researchers compared survey results that showed clear evidence of reproductive readiness spawning by adult delta smelt and the presence of delta smelt larvae in the Delta as early as March and early April with otolith data from juvenile delta smelt collected later in the summer. They found that the early spawning adults tended to be larger, older, and more fecund, with the resultant potential to contribute disproportionately to the population. They next showed that virtually none of the larvae hatched before mid-April survived to contribute to the delta smelt population; only larvae hatched later in April and May survived to be collected in the summer survey. Examination of data on Delta hydrodynamic conditions during these periods showed consistently high exports with high magnitude negative OMR flows in the months preceding and after the VAMP (Figure 15), leading these researchers to suggest that winter and early spring exports were selectively entraining the early spawning and/or early hatching cohort of the delta smelt population. Thus, for delta smelt, the effect of entrainment mortality may be

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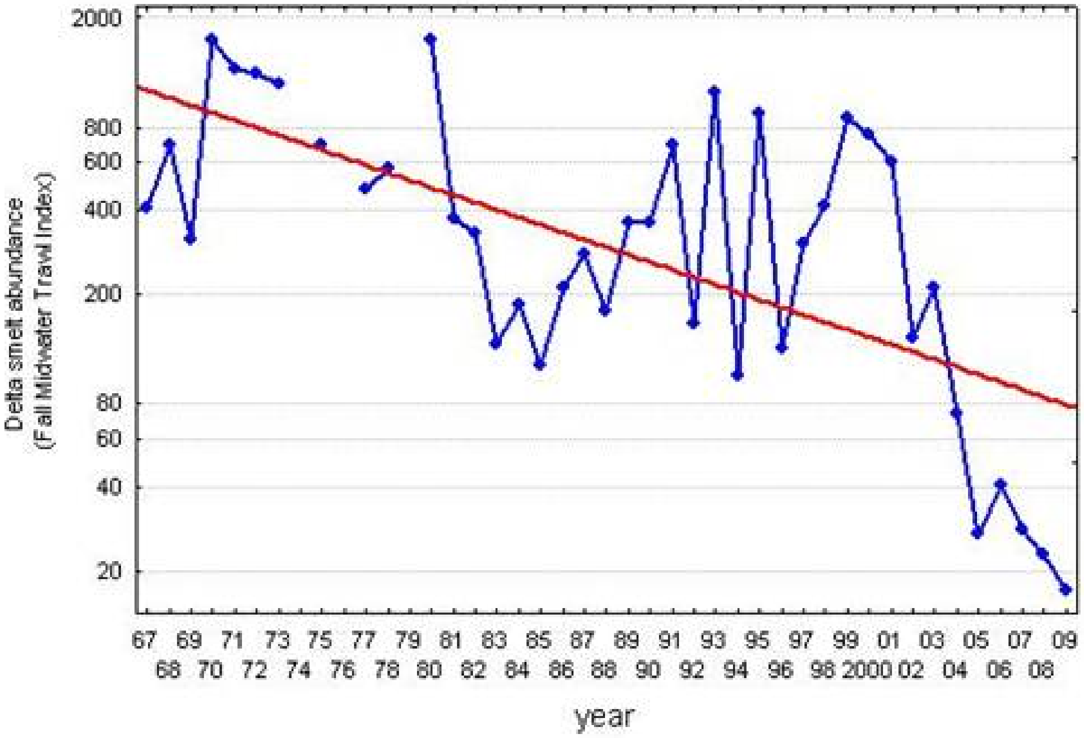
greater than that revealed by the simple ratio of entrainment to total population size (e.g., Kimmerer 2008) if the fish that are entrained are potentially more valuable reproductively than fish that hatch later and are not entrained. As interpreted by scientists synthesizing the Pelagic Organism Decline (POD) research, "…the most important result of the loss of early spawning females would manifest itself in the year following the loss, and would therefore not necessarily be detected by analyses relating fall abundance indices to same-year predictors" (Baxter et al. 2008).

FIGURE 14:
Decline of the Delta smelt (*Hypomesus transpacificus*), 1967-2009



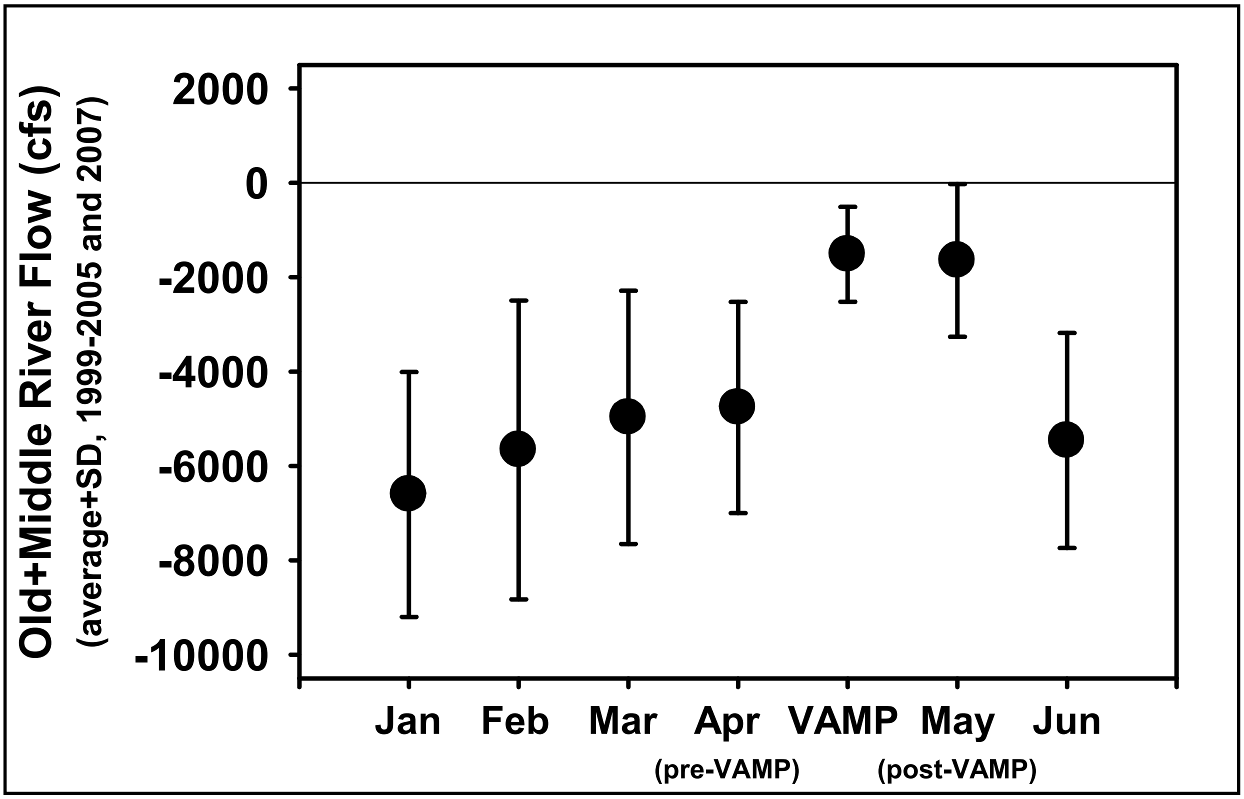


**Figure 15**
Average (+1SD) flows on Old and Middle Rivers (combined) during the months preceding and following the Vernalis Adaptive Management Program (VAMP) for the past eight years (1999-2005 and 2007; 2006 has been excluded from this analysis because it was very wet year in which Old and Middle River flows were generally positive). Data sources: CDWR dayflow and CCWD, USGS

## Methods for developing Delta hydrodynamic criteria to protect diversity of public trust resources

We reviewed OMR flow data to determine the range and average OMR flow conditions that occurred during the VAMP periods (1999-2007, this analysis excludes 2006, which was a wet year in which OMR flows were positive). Results were that average monthly OMR flows ranged from -6600 cfs to -4800 cfs in the months prior to VAMP, averaged -1500 cfs during the VAMP, remained relatively steady for the second half of May (average OMR of -1600 cfs) and became more negative again in June (average OMR of -5500 cfs). We also reviewed particle tracking model results reported by Kimmerer and Nobriga (2008) and statistical relationships between numbers of adult delta smelt salvaged and OMR flows (Figure DH-A). We concluded that, in order to protect the diversity of delta smelt and allow all age cohorts of spawning adults and larvae to survive to contribute to the population, exports and corresponding OMR flows need to be managed to levels that are comparable to those that occur during the VAMP.

## Recommendation: Delta hydrodynamic criteria to protect diversity of public trust resources (delta smelt)

The criteria described above for increasing abundance of public trust resources by maintaining OMR flows that are greater than -1500 cfs during the period from December to June should be sufficient to protect the life history diversity of delta smelt and other public trust resources.

## Relationship between Delta hydrodynamics and spatial extent of public trust resources

*Summary points:*

- *The effects of export pumping render large areas in the southern and central Delta unsuitable as habitat for public trust resources.*
- *The abundance criterion to maintain OMR flows greater than -1500 cfs from December to June should also sufficiently improve the spatial distribution of public trust resources.*

Hydrodynamic conditions in the southern Delta that result from the combined effects of Delta water export operations and low Delta inflows limit the spatial distribution of several species, essentially because the “zone of impact” of export-related entrainment mortality regularly renders large areas of the Delta functionally lethal to fishes. Sampling data from CDFG’s Fall Midwater Trawl survey indicates that longfin smelt spawning is much more common in the lower Sacramento River than in the San Joaquin River (Wang, 1986; CDFG, unpublished data). It is likely that repeated exposure to entrainment and reverse flows near the CVP and SWP pumps in the southern Delta, makes the lower San Joaquin River far less productive for longfin smelt spawning and rearing habitat than it would be without operation of the export facilities. Similarly, in recent years, delta smelt spawning and larval rearing have been largely restricted to areas outside the zone of impact of South Delta export operations. Finally, San Joaquin River Chinook salmon and steelhead must emigrate past the South Delta export facilities and are probably heavily impacted by export-related hydrodynamics – such impacts would tend to limit the geographic extent of Chinook salmon and steelhead in the Central Valley.

Kimmerer and Nobriga (2008) conducted detailed particle tracking model (PTM) investigations to examine the fate of neutrally buoyant particles, considered a reasonable simulation of larval and small juvenile fishes and, based on corroborating radio telemetry data that suggests that young salmon move downstream with the flow, for juvenile salmon as well, released at different locations in the Delta and under a range of export and inflow conditions. They found that the E:I ratio was the most useful predictor of entrainment and that for particles released in the central and southern Delta (in the absence of agricultural diversion effects) the majority were entrained into either the CVP and SWP export facilities at E:I ratios greater than approximately 0.2 within two to four weeks (Figure 16; from Kimmerer and Nobriga, 2008). The E:I ratio significantly affected cumulative entrainment of particles from all release locations in the Delta (e.g., at an E:I ratio of 0.2, nearly 20% of the particles released in Georgiana Slough, north of the San Joaquin River, were entrained into the CVP and SWP export facilities) but the magnitude and rapidity of entrainment increased with proximity to the export facilities.

**Figure 16**
Results of particle tracking model simulations showing the percentage of particle released at different locations within the Delta entrained into the CVP or SWP export facilities at different E:I ratio conditions. For particles released in the southern Delta, most or all of the particles were entrained by the CVP or SWP pumps within a few weeks at E:I ratio >0.2. From: Nobriga and Kimmerer 2008.

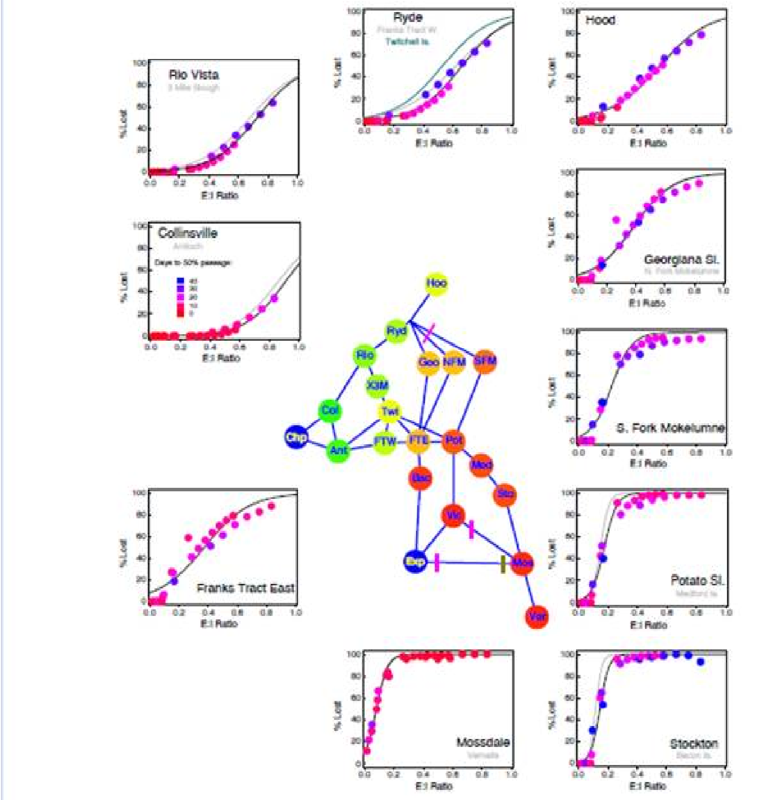
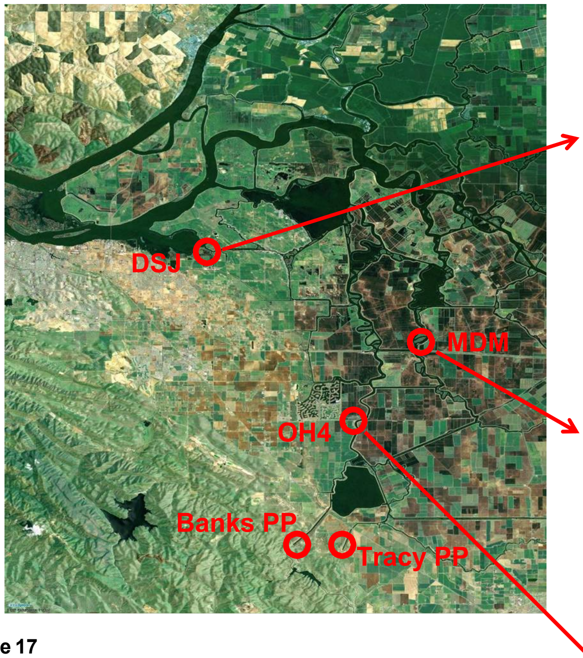


**Figure 7.** Percent of particles lost to export pumps for spring tide runs with no agricultural diversions and 24 combinations of inflow and export flow. Data are shown for selected release sites, color-coded by the time needed for 75% of particles to leave the Delta. Lines are logistic functions fit to the data, and are dark for selected sites and light gray for other sites with similar responses. Central diagram is a schematic arrangement of the sites in Figure 1, with principal links between sites. Short lines represent barriers including the DCC in the northern Delta, the Head of Old River barrier in the south Delta (dark yellow), and south Delta agricultural barriers (pink).

Analyses of flow and tidal conditions in Old and Middle River channels leading to the export facilities by the Contra Costa Water District (CCWD) provide further information on hydrodynamic conditions in the central and southern Delta. CCWD showed that export pumping at SWP and CVP facilities affects tidal flows in the South Delta by reducing the ebb tides and increasing the flood tides (Figure 17). Using data from 2006 during a period when combined CVP and SWP exports were approximately 11,500 cfs, results showed that tidal flows at Dutch Slough at Jersey Island in the western Delta were generally unaffected by export pumping: flows were roughly centered around 0 cfs, with the ebb flows generally being of the same magnitude but opposite direction as the flood flows (Figure 17, top right panel). In the northern part of Middle River, the flow still reflected the influence of the tides but ebb tides were reduced and negative flows towards the south were stronger than to the north (Figure 17, top middle panel). Further south at Old River at Highway 4, a few miles north of the export pumps, the ebb tide was effectively eliminated with channel flow towards the south and the pumps at almost all times (Figure 17, top bottom panel). For small fish moving through or transported to these channels in the southern Delta, these hydrodynamic conditions effectively preclude any possibility of successful downstream (or upstream) movement past the export facilities and virtually guarantee lethal entrainment at the pumps. Further analysis by CCWD showed that loss of the ebb tides becomes apparent at export rates of 5,000 to 6,000 cfs, levels consistent with substantial increases in salvage losses of estuarine and migratory fishes reported by Baxter et al. (2008), Kimmerer (2008) and Grimaldo et al. (2009).



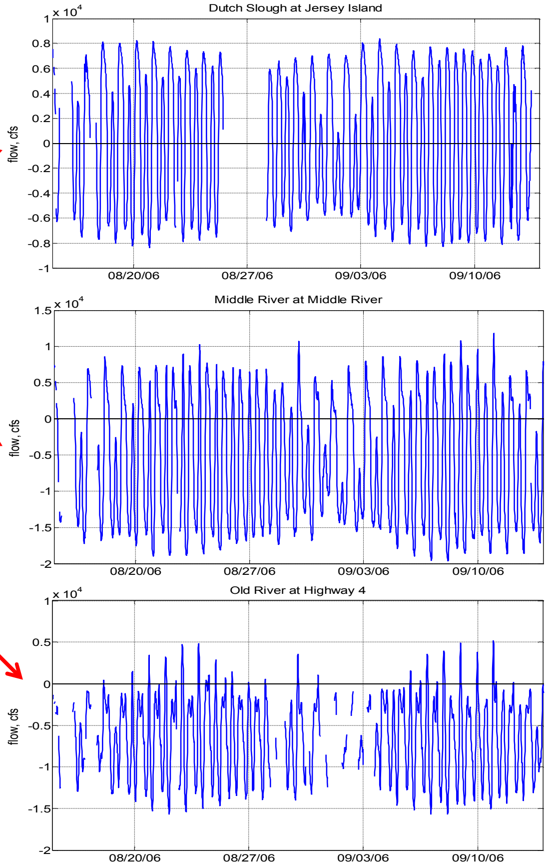


**Figure 17**
Daily tidal flows in Delta channels at different locations relative to the SWP (Banks PP) and CVP (Tracy PP) export facilities. At locations sequentially closer to the export facilities, the magnitude of the ebb tides (shown as positive or downstream flow, is progressively reduced. At the Old River at Highway 4 station, the ebb tide has been virtually eliminated by the effects of the export pumps and all water flows directly to the pumps. Source: Contra Costa Water Disitrict.

## Methods for developing Delta hydrodynamics increase to improve spatial distribution of public trust resources

We reviewed results of PTM analyses (Kimmerer and Nobriga 2008) and tidal flow analyses provided by CCWD to determine what Delta hydrodynamic conditions in the southern and central Delta provide habitat conditions suitable for rearing and migration of public trust resources, particularly for the small size and young life history stages of priority species that are already at risk due to effects of other flow conditions on other viability criteria and at high risk of extinction.

Based on this review, we determined that at moderately high export rates (i.e., 5,000-6,000 cfs, at which the localized ebb tides was reduced) and moderately high E:I ratios (>0.2; this E:I ratio corresponds very approximately to -3000 cfs OMR), habitat conditions in the southern and central Delta became lethal to small fishes, a condition that effectively reduced the spatial extent of the species and thus, its overall population viability. Therefore, we concluded that during the December through June period, when one or more vulnerable species or life stage is present in the Delta, lower levels of E:I ratios, export rates, and OMR flows were necessary to protect these public trust resources.

**Recommendation: Delta hydrodynamic criteria to improve spatial distribution of public trust resources**

The criteria described above for increasing abundance of public trust resources by maintaining OMR flows that are greater than -1500 cfs during the period from December to June should be sufficient to avoid creating lethal hydrodynamic conditions in the southern Delta.

**Synthesis of recommendations for Delta hydrodynamic criteria that protect viability of public trust resources**

In Table 1 below we have combined and integrated our recommendations for Delta hydrodynamic conditions that are needed to support the viability of public trust resources. Where different species and/or different viability attributes indicated different levels of hydrodynamic conditions were needed to protect the viability of the public trust resources, we based our recommendation on the more protective condition. All recommendations are expressed as OMR flows but, for some months in which the needs of multiple species and/or results of multiple studies contributed to the criteria, we also provide supplemental criteria which offer comparable levels of protection in other units of measure for reference. Because San Joaquin River inflows strongly influence OMR flows, we have integrated our recommendations for San Joaquin River inflows (Exhibit 3) into these recommendations for Delta hydrodynamic conditions. Abbreviations are: Old and Middle River flows (OMR, cfs), Vernalis flow to export ratio (VF:E), Export to Inflow ratio (E:I), Sacramento Basin salmonids (SBS), San Joaquin Basin salmonids (SJS), delta smelt (DS), longfin smelt (LFS),and Fall Midwater Trawl (FMWT).

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**Table 1.** Recommended Delta hydrodynamic conditions, expressed as OMR flows and, for some months, as Vernalis flow or exports ratios (VF:E) and/or export to inflow ratios (E:I), needed to protect public trust resources. These recommendations for Delta hydrodynamic conditions incorporate and integrate our recommendations for San Joaquin River inflows (Exhibit 3). Abbreviations are: Old and Middle River flows (OMR, cfs), Vernalis flow to export ratio (VF:E), Export to Inflow ratio (E:I), Sacramento Basin salmonids (SBS), San Joaquin Basin salmonids (SJS), delta smelt (DS), longfin smelt (LFS),and Fall Midwater Trawl (FMWT).

| **Frequency** | **Oct** | **Nov** | **Dec** | **Jan** | **Feb** | **March** | **April** | **May** | **June** |
|---|---|---|---|---|---|---|---|---|---|
| **Wet** | | | | | | | | | |
| OMR (cfs) | **-2000** | **-2000** | **-1500** | **-1500** | **-1500** | **>0** | **>0** | **>0** | **-1500** |
| Other metric | | | | | | VF:E>4 | VF:E>4 | VF:E>4 | |
| Species | SBS | SBS | DS<br>SBS | DS,<br>SBS | DS,<br>SBS | SJS<br>DS<br>SBS | SJS<br>DS<br>SBS | SJS<br>DS<br>SBS | SJS<br>DS<br>SBS |
| **Above normal** | | | | | | | | | |
| OMR (cfs) | **-2000** | **-2000** | **-1500** | **-1500** | **-1500** | **>0** | **>0** | **>0** | **-1500** |
| Other metric | | | E:I<0.1 | E:I<0.1 | E:I<0.1 | VF:E>4<br>E:I<0.1 | VF:E>4<br>E:I<0.1 | VF:E>4<br>E:I<0.1 | E:I<0.1 |
| Species | SBS | SBS | DS<br>SBS | DS<br>SBS | DS,<br>SBS | SJS<br>DS<br>SBS | SJS<br>DS<br>SBS | SJS<br>DS<br>SBS | SJS<br>DS<br>SBS |
| **Below normal** | | | | | | | | | |
| OMR (cfs) | **-2000** | **-2000** | **-1500** | **-1500** | **-1500** | **>0** | **>0** | **>0** | **-1500** |
| Other metric | | | E:I<0.1 | E:I<0.1 | E:I<0.1 | VF:E>3<br>E:I<0.1 | VF:E>3<br>E:I<0.1 | VF:E>3<br>E:I<0.1 | E:I<0.1 |
| Species | SBS | SBS | DS<br>SBS | DS<br>SBS | DS,<br>SBS | SJS<br>DS<br>SBS | SJS<br>DS<br>SBS | SJS<br>DS<br>SBS | SJS<br>DS<br>SBS |
| **Dry** | | | | | | | | | |
| OMR (cfs) | **-2000** | **-2000** | **-1500** | **-1500** | **-1500** | **>0** | **>0** | **>0** | **-1500** |
| Other metric | | | E:I<0.1 | E:I<0.1 | E:I<0.1 | VF:E>2<br>E:I<0.1 | VF:E>2<br>E:I<0.1 | VF:E>2<br>E:I<0.1 | E:I<0.1 |
| Species | SBS | SBS | DS<br>SBS | DS<br>SBS | DS,<br>SBS | SJS<br>DS<br>SBS | SJS<br>DS<br>SBS | SJS<br>DS<br>SBS | SJS<br>DS<br>SBS |
| **Critical** | | | | | | | | | |
| OMR (cfs) | **-2000** | **-2000** | **-1500** | **-1500** | **-1500** | **-1500** | **>0*** | **>0*** | **-1500** |
| Other metric | | | E:I<0.1 | E:I<0.1 | E:I<0.1 | VF:E>1<br>E:I<0.1 | VF:E>1<br>E:I<0.1 | VF:E>1<br>E:I<0.1 | E:I<0.1 |
| Species | SBS | SBS | DS<br>SBS | DS,<br>SBS | DS,<br>SBS | SJS<br>DS<br>SBS | LFS*<br>SJS<br>DS<br>SBS | LFS*<br>SJS<br>DS<br>SBS | SJS<br>DS<br>SBS |

*When LFS FMWT<500. If LFS FMWT>500, then OMR<-1500 cfs.

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