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Losses of Sacramento River Chinook Salmon and Delta Smelt to Entrainment in Water Diversions in the Sacramento-San Joaquin Delta

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ABSTRACT

Pumping at the water export facilities in the southern Sacramento-San Joaquin Delta kills fish at and near the associated fish-salvage facilities. Correlative analyses of salvage counts with population indices have failed to provide quantitative estimates of the magnitude of this mortality. I estimated the proportional losses of Sacramento River Chinook salmon *(Oncorhynchus tshawytscha)* and delta smelt *(Hypomesus transpacificus)* to place these losses in a population context. The estimate for salmon was based on recoveries of tagged smolts released in the upper Sacramento River basin, and recovered at the fish-salvage facilities in the south Delta and in a trawling program in the western Delta. The proportion of fish salvaged increased with export flow, with a mean value around 10% at the highest export flows recorded. Mortality was around 10% if pre-salvage losses were about 80%, but this value is nearly unconstrained. Losses of adult delta smelt in winter and young delta smelt in spring were estimated from salvage data (adults) corrected for estimated pre-salvage survival, or from trawl data in the southern Delta (young). These losses were divided by population size and accumulated over the respective seasons. Losses of adult delta smelt were 1–50% (median 15%), although the highest value may have been biased upward. Daily losses of larvae and juveniles were 0–8%, and seasonal losses accumulated were 0–25% (median 13%). The effect of these losses on population abundance was obscured by subsequent 50-fold variability in survival from summer to fall.

KEYWORDS

Chinook salmon *Oncorhynchus tshawytscha*, delta smelt *Hypomesus transpacificus*, diversions, population ecology

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INTRODUCTION

One of the greatest challenges facing resource managers is assessing the effectiveness of their actions in influencing ecosystems or biological populations. This difficulty arises from three sources: 1) weak or

inaccurate understanding of the causal links between actions and responses; 2) inability to control for other sources of variability; and 3) inherent inaccuracy in monitoring causal and response variables. Yet, managers are held accountable for successes and failures, as we have witnessed recently with the decline of pelagic organisms in the upper San Francisco Estuary (Sommer et al. 2008). Thus, the challenge for the scientific community is how to detect and quantify effects of management actions in the absence of strong correlative relationships between these actions and the response variables. This requires an analysis of mechanisms rather than one based on correlative relationships alone.

The San Francisco Estuary is a highly altered and managed system (Nichols et al. 1986) in which conflicts over resources are particularly strong. Perhaps the greatest conflict is due to the diversion and export of substantial quantities of freshwater from the tidal freshwater reach in the Sacramento-San Joaquin Delta. Losses of fish to mortality associated with export pumping have been blamed in part for declines of numerous species including striped bass (Stevens et al. 1985), Chinook salmon (Kjelson and Brandes 1989), and delta smelt (Bennett 2005). Nevertheless, no quantitative estimates have been made of the population-level consequences of losses to the export facilities of any fish species. Kimmerer et al. (2001) concluded that large proportional losses to the export facilities were a minor contributor to variability in the striped bass population of the Estuary. Jassby et al. (2002) conducted a mass balance of chlorophyll concentration in the Delta and concluded that losses of phytoplankton to export pumping must be large, but were masked in correlative analyses by other sources of variation. Similar calculations have not been made for other taxonomic groups, and there have been no published reports of correlations between any measure of export losses and subsequent population size.

Despite the lack of evidence for population-level effects, a strong influence of the south Delta export facilities on populations of estuarine and anadromous fish has been assumed for several reasons. First, large numbers of fish are entrained in the fish facilities (Brown et al. 1996). Second, it is reasonable to expect a large effect on some fish because of the large quantities of water exported, at times more than half of the inflow to the Delta (Kimmerer 2004). Third, manipulations of flow patterns in the Delta provide the only apparent tool for managing some fish populations such as delta smelt.

In this paper I estimate the effects of export pumping in terms of proportional losses of two fish species. Chinook salmon *(Oncorhynchus tshawytscha)* and the threatened delta smelt *(Hypomesus transpacificus)* are target taxa for restoration and management in the Delta. Data for several races of Chinook salmon are available to estimate the losses of these fish to direct effects of entrainment. I focus on winter Chinook because it has been the target of considerable restoration effort, although data for other races are used to provide greater resolution. Two life stages of delta smelt are examined: adults in late winter, and larvae and juveniles in spring. Effects of export pumping are estimated mechanistically, rather than through correlative analyses with the respective population abundances.

The conceptual framework for these calculations differs for the two species. Young Chinook salmon are exposed to export effects during movement through the Delta. Data on length distributions at the export facilities and in field studies suggest that juvenile Chinook generally are exposed to entrainment only during movement, and are rarely entrained while rearing. Young Chinook rear in or migrate through the Delta at various times of year but are most abundant in the Delta from March through June (Williams 2006). Although most of the migrating fish are small fall-run Chinook, winter Chinook and other runs form a substantial pulse of fish larger than the fall run in February–March (Williams 2006). Chinook smolts may take any of several pathways that lead them through the Delta either to the export facilities or through the western margin of the Delta at Chipps Island, and then to sea (Figure 1). When control gates in the Delta Cross-Channel (Figure 1) are open, the smolts may enter the central Delta further upstream, and this could increase their probability of entrainment in the export facilities.

Delta smelt are considered to be resident fish but are actually weakly anadromous, spending most of their

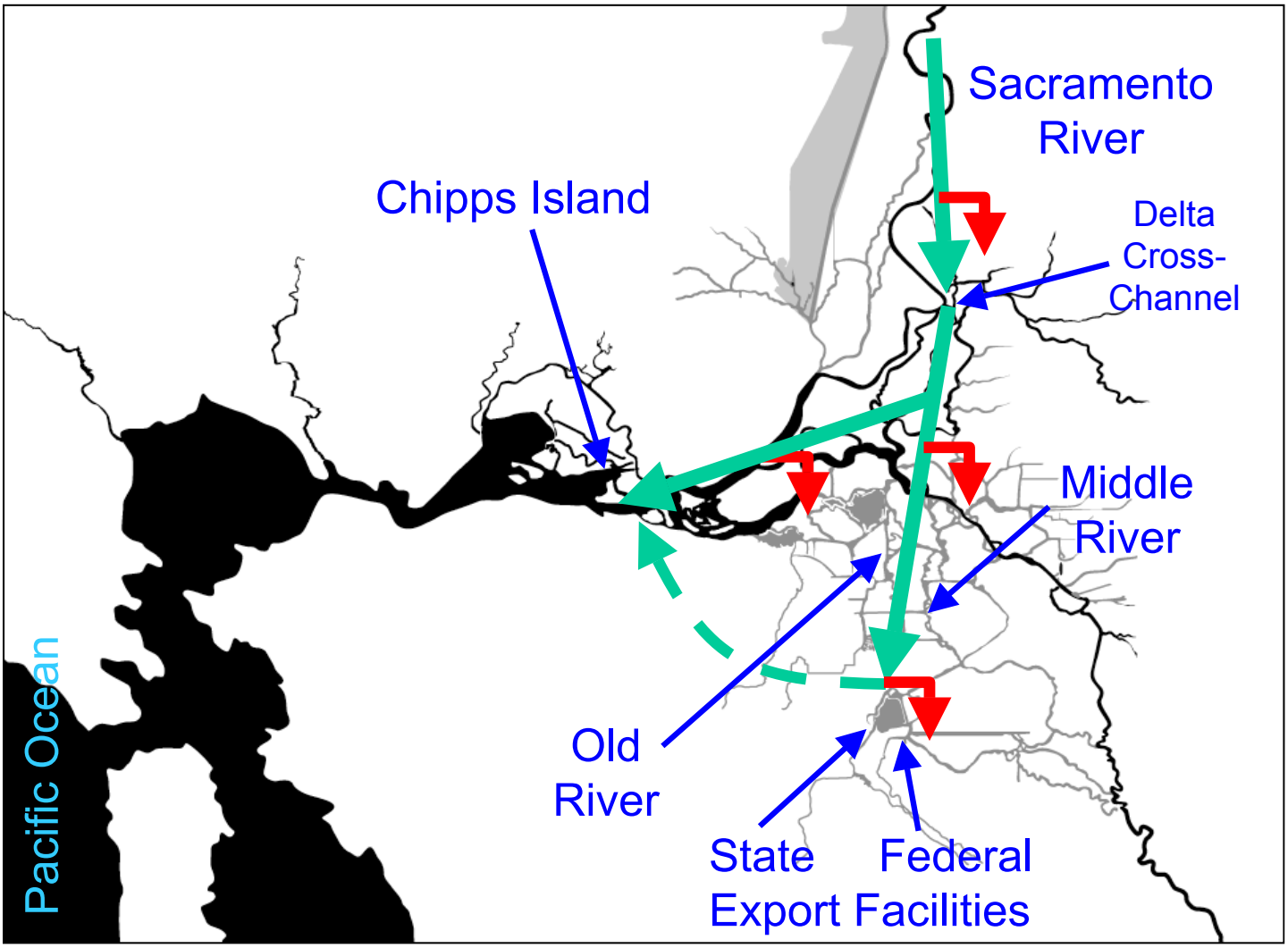

Figure 1. Map of the San Francisco Estuary showing locations mentioned in the text. Green arrows indicate general movement pathways for winter Chinook salmon; the dashed arrow represents movement of salvaged fish by truck. Red arrows indicate mortality losses; only those occurring at the export facilities are accounted for here.

lives in brackish water where they are not exposed to export entrainment (Bennett 2005). The adults spawn in freshwater in late winter, and those in the southern Delta are then vulnerable to entrainment at the export facilities. Eggs are demersal and therefore invulnerable to entrainment, but the pelagic larvae and juveniles in the southern Delta are vulnerable from the time they hatch until they move seaward into brackish water. Thus, export pumping causes a continuous mortality that acts on the population over time during two life stages.

Fish Facility Operations

Fish facilities associated with the state and federal water export facilities (Figure 1) are designed to salvage fish from the water and return them to the Estuary (Brown et al. 1996; Haefner and Bowen 2002). These facilities use two sets of louvers to concentrate the fish behaviorally, but this process is not very efficient. For example, many salmon and other fish are lost to predation in the waterways leading to the fish facilities (Gingras 1997). The efficiency with which the louvers concentrate the fish can be << 100% (Bowen et al. 2004). In addition, few delta smelt probably survive the salvage process (Bennett 2005).

The salvage facilities accumulate fish in holding tanks during sampling periods that are most often 2 hours but have ranged from 10 minutes to 9 hours during 1995–2006. During each sampling period, a sub-sample may be taken over a shorter time-period, nominally 20 minutes (state facility) or 10 minutes (federal facility) although it may be longer or shorter. Karp et al. (1997) compared the sub-sampling procedure for the federal facility with complete analysis of the salvaged fish, validating this procedure. All fish > 20 mm in a sub-sample are counted and identified, and salmon marked with clipped adipose fins are inspected for coded-wire tags and, if present, the tags are read.

It is helpful to define terms (see Table 1 for symbols). Daily *salvage* is the number of fish of given characteristics (species, stage, length) estimated to have entered a fish facility in a day. Daily *entrainment* is the estimated net number of fish that arrived at the entrance to the fish facility per day, i.e., those that arrived and did not leave the area except via the fish facilities. Entrainment exceeds salvage because of mortality in the waterways, leading to the export facilities and losses through the louvers. Daily *loss* is the estimated number entrained that were not subsequently salvaged and returned alive to the Estuary, which includes losses both before and after the salvage process; these are also termed "direct" losses because they are directly attributable to pumping operations.

Losses of fish due to altered hydrodynamic conditions or migration cues in the Delta are called "indirect" losses. Although export pumping has substantial impacts on flow patterns in the Delta, the extent to which such alterations affect survival of fish is much less clear. Indirect losses may be important (NMFS 2004), but they remain hypothetical and unquantified, and are not calculated in this paper.

METHODS

Daily salvage (see Table 1 for all symbols used in this paper) is calculated from the counts taken during each sampling period as:

$$\hat{N}_{di} = \sum_{p=1}^{P_{di}} \frac{N_{dpi} M_{dpi}}{m_{dpi}} \quad (1)$$

where hats indicate estimated quantities. For tagged Chinook salmon (see below), salvage counts were available only for the entire day, so Equation 1 was simplified by summing over all time-periods within each day:

$$\hat{N}_{di} = \frac{\sum_{p=1}^{P_d} N_{dpi} \sum_{p=1}^{P_d} M_{dpi}}{\sum_{p=1}^{P_d} m_{dpi}} \quad (2)$$

Equations 1 and 2 were compared using salvage data for total Chinook salmon from 1995–2006. The mean ratio of estimates from Equation 2 to those from Equation 1 for all samples with total daily counts > 100 was 0.98 ± 0.017 (95% CL, N = 219), so these equations were considered equivalent for tagged

Table 1. Definition of terms used in the models for Chinook salmon (C) and delta smelt (D). Terms are unitless unless stated. Subscripts may be added to indicate export facilities (i, state = 1, federal = 2, combined = x), cohorts (j), surveys (s), sampling time-periods for calculating salvage (p), or calendar time-periods (d, mo).

Term	Species	Definition
A	D	Total abundance of fish = Ds V
$A_{L,t}$	D	Abundance of fish of length L at time t
D	CD	Duration of the sampling period (days)
D_s	D	Mean density over all samples (m^{-3})
E_i	CD	Louver efficiency of facility i
E_k	D	Efficiency of Kodiak trawl
E_L	D	Relative efficiency of the 20-mm net as a logistic function of length of fish
g	D	Growth rate (mm d^{-1})
H	D	Number of fish hatching per day
L	D	Length of fish (mm)
m	D	Daily mortality rate (d^{-1})
m_n	D	Daily natural mortality rate (i.e., not due to direct export effects) (d^{-1})
M_{dpi}	CD	Duration of fish salvage period p (min) on day d
m_{dpi}	CD	Duration of subsampling during salvage period p (min) on day d
N_{dpc}	C	Number of fish counted during Chipps Island trawl p on day d
N_{dpi}	CD	Number of fish counted at facility i during period p on day d
N_{di}	CD	Daily salvage for facility i (d^{-1})
N_i	CD	Total salvage for facility i
N_{Ri}	C	Daily number of fish successfully released from fish facility i (d^{-1})
N_{SD}	D	Total fish caught in trawl samples in the south Delta during a survey
$N_{w\delta}$	C	Five-day running mean of total fish caught centered on day δ (weighting factor)
P_d	C	Total number of samples on day d (fish facilities or Chipps Island)
P_S	C	Proportional salvage of fish leaving Delta
P_L	CD	Proportional loss of fish to export effects
Q_{SD}	D	Daily flow to the south Delta (= Old and Middle River flow) ($m^3 d^{-1}$)
S	D	Survival (fraction); subscripts indicate time-period or cohort j
S_{HT}	C	Fraction of fish surviving handling and trucking
S_{Pi}	CD	Fraction of fish entrained that reach louvers
S_{Si}	C	Fraction of fish entrained that enter salvage facility
t	D	Any day between T_0 and the final date of the simulation (d)
T_0	D	Initial hatch date (d)
T_j	D	Initial hatch date (d) for cohort j
T_1	D	Final hatch date (d)
T_f	D	Final day of survey
u	C	Migration speed, m d^{-1}
V	D	Volume of habitat over which trawl catches are averaged (m^3)
V_{dpc}	C	Volume sampled by sample p on day d in the Chipps Island Trawl (m^3)
V_{SD}	D	Total volume filtered in survey s at South Delta stations (m^3)
W	C	Width of channel at Chipps Island (~ 1,000 m)
Z	C	Depth over which salmon are assumed to migrate (4 m)
θ	D	Efficiency ratio, a free parameter in adult loss equation (18)
λ	C	Ratio of loss to salvage, calculated from pre-salvage survival
Λ_{di}, Λ_i	D	Daily or cumulative loss to export facilities
Φ_{di}, Φ_i	CD	Daily or cumulative entrainment to export facilities
Φ_{dc}, Φ_c	CD	Daily or cumulative flux of fish past Chipps Island

Chinook salmon. For either method, the total salvage for a sampling period D is:

$$\hat{N}_i = \sum_{d=1}^{D} \hat{N}_{di} . \quad (3)$$

Entrainment is calculated as:

$$\hat{\Phi}_{di} = \frac{\hat{N}_{di}}{S_{Pi} E_i} , \quad (4)$$

and daily total loss is:

$$\hat{\Lambda}_{di} = \hat{\Phi}_{di} - \hat{N}_{Ri} = \hat{N}_{di} \left(\frac{1}{S_{Pi}\ E_i} - S_{HT} \right) . \quad (5)$$

$\Lambda = \Phi$ for delta smelt since they are assumed not to survive salvage. Proportional loss is calculated differently for salmon and for adult and young delta smelt (below).

Flow data were obtained from the Dayflow accounting program (Jassby et al. 1995; see http://iep.water.ca.gov/dayflow). Net flows in Old and Middle Rivers (Figure 1) have been determined by the U.S. Geological Survey since 1987 (Ruhl and Simpson 2005; Ruhl et al. 2006; P. Smith, USGS, pers. comm.). X_2, or the distance up the axis of the Estuary to where the tidally-averaged near-bottom salinity is 2 psu, was determined from daily Delta outflow as described in Jassby et al. (1995). Data on salmon-tagging studies and trawl data were obtained from the Interagency Ecological Program's Bay Delta and Tributaries Project (BDAT) website (http://bdat.ca.gov/). Salvage data for all species, sample data and abundance indices for delta smelt, and zooplankton abundance data were obtained from the California Department of Fish and Game (K. Fleming, R. Gartz, K. Hieb, and K. Souza, pers. comm.). Zooplankton biomass was determined from abundance data (Kimmerer 2006).

Chinook Salmon

Migrating salmon suffer a one-time risk of entrainment, in that fish that survive through the Delta either arrive at the export facilities and are entrained, or migrate past Chipps Island and presumably become invulnerable to entrainment. Salmon that arrive at the export facilities and are successfully salvaged also pass Chipps Island on their way to sea, and are vulnerable to capture there.

The general approach was to use recapture rates of coded-wire-tagged (CWT) hatchery smolts released in or near the upper Sacramento River and recaptured in the Delta fish facilities or at Chipps Island. The number of fish recaptured at each location was used to calculate salvage and losses at the fish facilities and flux of fish past Chipps Island, which were accumulated over the season and then used to calculate proportional salvage and loss.

The Livingstone Stone National Fish Hatchery (LSNFH) on the upper Sacramento River has released winter Chinook smolts marked with CWT and clipped adipose fins each spring since 1998. The Coleman National Fish Hatchery (CNFH) has released tagged fall and late-fall Chinook smolts each spring since 1981. Tagged fish have been released in groups of 81 to approximately 300,000 with unique tag codes, and up to 14 separate tag codes with up to approximately one million fish have been released on a single date. Tagged fish are recaptured at various locations, and data are stored in the BDAT database. I estimated the flux of tagged fish past Chipps Island and the losses to the fish facilities for years starting with brood-year 1998.

The following assumptions were made throughout this analysis:

1. The proportional loss of CWT hatchery fish represents that of naturally-spawned Chinook salmon.
2. Mortality factors at the fish facilities are constant in time and with export flow.
3. Fish are randomly distributed in time and across the Chipps Island channel in the top 4 meters, and migrate equally by day or night at a constant speed unaffected by flow.
4. Sampling at Chipps Island and at the fish facilities is unbiased, and the net is 100% efficient.
5. All CWT fish caught have their tags read.

Assumption 1 is fundamental to this approach as well as to numerous other studies (e.g., Newman and Rice 2002), but at present is untestable. Possible biases introduced by the other assumptions are discussed below.

Each year, CWT smolts in several tag groups have been released on a single day (Table 2). LSNFH winter Chinook have been released between January 27 and February 5, except that fish were released on April 9 in 1998. CNFH Chinook have been released in November through April, with one release in July 2005 which was not used in this analysis. I treated all groups of fish released on a single day as a single release; recaptures were too few to estimate variability among groups within single days.

Parameter values in Equation 5 were previously established for regulatory purposes (NMFS 2004). A series of experiments with marked juvenile Chinook salmon was used to estimate the pre-screen proportional loss for the state facility ($1 - S_{p1}$), which had a mean of 85% and range of 63–99% (Gingras 1997). The regulatory value is 75% (NMFS 2004). The pre-screen loss term for the federal facility has been set at 15% without any justification other than that the federal facility lacks the large forebay (Clifton Court) leading to the state facility, which may enhance predation on fish arriving at the facility. Studies conducted when the louvers were installed (Skinner 1973) gave a louver efficiency E_1 of ~ 90%, although more recent data suggest lower louver efficiency: Karp et al. (1995) reported overall efficiency of 50% at the federal facility with substantial variation, and Bowen et al. (2004) reported 85% efficiency for the secondary louvers at the federal facility. Handling and trucking loss terms ($1 - S_{HT}$) together amount to 4%. Given the high uncertainty about the pre-screen loss and louver efficiency, and the low rate of loss due to handling and trucking, I simplified Equation 5 by setting $S_{HT} = 1$ for both facilities, and assuming the same pre-salvage survival term S_S for both facilities, combining both pre-screen mortality and loss through the screens:

$$\hat{\Lambda}_i = \left(\frac{1}{S_S} - 1\right)\hat{N}_i = \lambda\hat{N}_i \qquad (6)$$

Tagged fish are captured by the U.S. Fish and Wildlife Service (USFWS) Chipps Island trawl survey, which takes 10–20 trawl samples daily in spring and less often during other seasons (Brandes and McLain 2001). The number of tagged fish collected by the Chipps Island trawl during each survey was extrapolated to a "fish flux" from the mean catch per volume and the migration speed past Chipps Island. The midwater trawl net is 4.6 meters deep and 9.1 meters wide (Brandes and McLain 2001), and the volume sampled is based on readings of a flowmeter in the net mouth. Fish were caught at the fish facilities slightly more often by night than by day (data from 1996–2004, 39% of all salmon and 49% of the samples were by day), which could be due to higher predation rates during daylight, so we are justified in assuming roughly equal passage at Chipps Island by day and night.

The fish flux past Chipps Island for each day on which a survey was conducted was calculated as:

$$\hat{\Phi}_{dc} = \frac{\sum_{p=1}^{P_d} N_{dpc}}{\sum_{p=1}^{P_d} V_{dpc}} WZu\ , \qquad (7)$$

which is the fish per unit volume multiplied by cross-sectional area and migration speed. Previous analyses have used the time spent sampling to provide a time-scale for migration (Brandes and McLain 2001), but that approach does not account for the migration speed of the fish, and is appropriate only for a stationary sampler. Migration speed u in Equation 7 was estimated at about 6 km/d based on the median date of recapture of tagged late-fall Chinook released at Ryde on the Sacramento River and caught at Chipps Island (Brandes and McLain 2001; Newman 2003). The fish flux was calculated for each day when a survey was conducted, and values were interpolated for days with no survey, then summed over the period between the first and last days when fish were captured:

$$\hat{\Phi}_c = \sum_{d=1}^{D} \hat{\Phi}_{cd}\ . \qquad (8)$$

Table 2. Chinook salmon. Summary of data from mark-recapture studies. Source is Coleman National Fish Hatchery (C) or Livingstone Stone National Fish Hatchery (L). LSNFH fish were all winter Chinook; Coleman fish were fall, late-fall, or spring Chinook. Dates are for the brood year if later than October, or for the next year if in January–June.

Source	Brood Year	Release Date	Recapture Dates		Length at Release (mm)	Number Released	Catch		
			Initial	Final			Chipps Is.	SWP	CVP
C	1997	11/10	11/26	03/09	118	66316	22	2	0
C	1997	12/09	12/19	03/16	134	66244	34	11	5
C	1997	01/12	01/18	03/18	137	61048	26	0	1
C	1997	01/13	01/19	03/16	141	63100	63	0	0
C	1997	01/14	01/20	03/16	137	67408	54	0	3
C	1997	01/22	01/27	03/18	138	57046	31	0	3
C	1997	03/04	03/25	05/15	56	27628	34	0	0
C	1997	03/06	03/27	05/11	59	35122	23	0	0
C	1997	03/31	04/16	05/22	64	37067	162	0	0
C	1997	04/07	04/19	05/29	65	33392	87	0	0
C	1997	04/22	04/28	06/03	72	28585	336	0	0
C	1997	04/23	05/01	06/03	66	32007	53	0	0
C	1998	11/12	11/24	02/05	116	66119	32	1	0
C	1998	12/15	12/22	03/30	120	64546	48	2	1
C	1998	01/04	01/11	05/26	126	59032	110	5	1
C	1998	03/31	04/29	05/09	59	29869	3	1	0
C	1998	04/20	04/26	05/20	78	24239	158	7	0
C	1998	04/21	05/01	05/23	69	32464	37	0	0
C	1998	04/27	05/05	05/28	75	34513	133	3	2
C	1998	04/28	05/05	05/13	78	34037	28	0	0
C	1999	11/12	11/27	01/28	110	70500	6	2	1
C	1999	12/09	12/20	02/19	110	75948	16	8	3
C	1999	12/21	01/03	02/21	110	83383	9	6	0
C	1999	01/04	01/19	04/20	120	79868	53	63	28
C	1999	01/12	01/21	03/21	120	81680	14	8	6
C	1999	04/07	04/15	04/28	75	33820	50	1	0
C	1999	04/14	04/20	05/21	77	32504	258	2	0
C	1999	04/21	04/26	05/29	78	35228	256	0	0
C	2000	11/03	12/11	01/21	113	58050	6	1	2
C	2000	12/08	12/25	02/26	119	54568	0	5	1
C	2000	01/02	01/17	04/23	128	62127	53	51	18
C	2000	01/09	01/20	03/15	129	65284	11	9	4
C	2000	04/13	04/23	05/13	73	62634	186	0	1
C	2000	04/27	05/07	05/30	76	62325	217	2	0

Source	Brood Year	Release Date	Recapture Dates		Length at Release (mm)	Number Released	Catch		
			Initial	Final			Chipps Is.	SWP	CVP
C	2001	11/14	11/28	04/27	120	88039	11	4	4
C	2001	12/12	12/21	03/01	120	73856	9	23	5
C	2001	01/04	01/10	03/08	135	65237	55	15	6
C	2001	01/08	01/14	04/23	120	77418	283	155	51
C	2001	04/18	04/25	05/27	77	79730	419	2	0
C	2001	04/25	05/03	05/29	77	71246	289	0	0
C	2002	11/08	12/06	01/06	102	67650	13	5	3
C	2002	12/02	12/18	05/01	117	59887	50	81	29
C	2002	01/02	01/08	03/31	125	66571	166	656	221
C	2002	01/15	01/22	03/21	131	74760	21	46	15
C	2003	11/28	12/11	02/27	126	65339	37	16	6
C	2003	12/31	01/08	04/06	130	72716	166	333	81
C	2003	01/02	01/08	03/24	127	69247	137	222	67
C	2003	01/30	02/11	03/17	146	64983	3	35	6
C	2003	04/16	04/24	05/14	79	75162	58	0	0
C	2004	11/05	12/10	01/03	121	87000	3	1	1
C	2004	11/29	12/14	01/31	117	69993	24	1	1
C	2004	01/04	01/11	03/03	134	32348	231	124	20
C	2004	01/13	01/27	02/27	134	69795	6	25	1
C	2005	12/02	12/12	02/10	116	80014	47	18	5
C	2005	01/03	01/08	03/22	141	82691	126	14	5
C	2005	01/19	01/27	03/06	141	65496	20	2	1
L	1998	01/28	03/15	04/19	70	10243	21	8	0
L	1999	01/27	02/22	05/01	80	1145	4	1	0
L	2000	02/01	03/05	04/04	80	4826	8	2	0
L	2001	01/30	03/07	05/07	80	62138	24	2	2
L	2002	01/30	02/14	04/14	82	8131	34	26	12
L	2003	02/05	02/20	04/09	88	11568	21	26	6
L	2004	02/03	02/22	03/31	87	8584	21	1	1
L	2005	02/02	02/17	03/27	86	15603	20	3	6

All recaptured fish from each release group were included in estimates of fraction salvaged and lost at the export facilities. Smolts were recaptured over various time intervals, with occasional stragglers recaptured weeks to months later than others in the same group (Figure 2). A relationship was calculated between proportional salvage and export flow averaged over the migration period (see below), but averaging export flow evenly over the migration season would give excessive weight to the later period when few fish were migrating. I therefore calculated a weighted mean export flow during the migration season, using the total daily catch at the fish facilities and Chipps Island as the weighting factor. The total daily catch was first interpolated to fill in days with no survey, then smoothed using a 5-day running mean:

$$N_{w\delta} = \frac{\sum_{d=\delta-2}^{\delta+2} \sum_{p=1}^{P_d} (N_{dp1} + N_{dp2}) + N_{dc}}{5}. \quad (9)$$

For each release group, I calculated total salvage and total losses (Equation 6) over the season as a proportion of the fish leaving the Delta. Proportional salvage P_S is unaffected by pre-salvage survival, whereas proportional loss P_L is very sensitive to the magnitude of S_S (see below). The proportional salvage for the migration period is the ratio of total salvage to the sum of salvage and migration past Chipps Island:

$$\hat{P}_S = \frac{\hat{N}_1 + \hat{N}_2}{\hat{N}_1 + \hat{N}_2 + \Phi_c}. \quad (10)$$

This proportion has a slight bias (<10%) because some fish are salvaged but not counted and subsequently pass Chipps Island. This calculation does not require knowledge of mortality patterns within the Delta or the details of alternative migration pathways. Proportional salvage was related to weighted export flow by a generalized linear model with a log link function and error distribution proportional to the mean (McCullagh and Nelder 1989). This model was fit for the combined data from the two hatcheries, including all data points with > 6 fish recaptured, and with source (hatchery) as a covariate. Additional covariates tried in this model were Sacramento River flow and position of Delta cross-channel gates (0 = both gates closed, 1 = both gates open), both weighted means over the migration season as described above for export flow.

Proportional loss is the total loss divided by the total number of fish departing the Delta either via loss at the export facilities or migration past Chipps Island:

$$\hat{P}_L = \frac{\hat{\Lambda}_1 + \hat{\Lambda}_2}{\hat{\Lambda}_1 + \hat{\Lambda}_2 + \Phi_c} = \frac{\lambda}{\lambda + \frac{1}{\hat{P}_S} - 1}, \quad (11)$$

in which the bias due to double-counting is negligible. The difference in denominators of the left-hand term of Equation 11 and Equation 10 arises because pre-salvage mortality is not included in Equation 10. The principal sources of uncertainty in the calculations of proportional loss arise from great uncertainty about the pre-salvage survival of fish at the fish facilities, and the migration speed of the fish. Although the estimate of migration speed could be refined, the lack of resolution of the pre-salvage survival is the principal impediment to even estimating —much less reducing—the errors in the estimates of

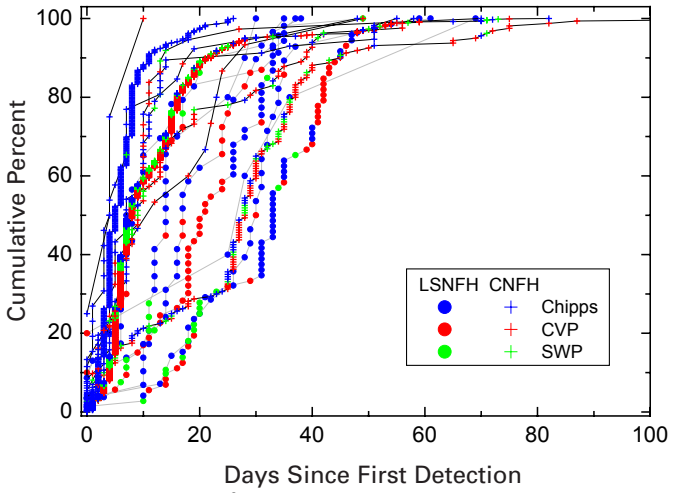

Figure 2. Chinook salmon. Examples of cumulative percent of coded-wire-tagged smolts captured at the fish facilities and at Chipps Island. All releases from LSNFH are shown, and a sample of 10 releases from CNFH. Each symbol represents an individual fish.

proportional losses. I estimated $\hat{P}_L$ as a function of export flow based on the fitted value of $\hat{P}_s$ from the above relationship with export flow, and alternative assumed values of pre-salvage survival.

Delta Smelt

In contrast to the situation for salmon, the loss of delta smelt to entrainment can be considered a continuous mortality, for which a greatly simplified expression in the absence of natural mortality is:

$$P_L = 1 - \prod_{d=1}^{D}\left(1-\frac{\Lambda_x}{A}\right) . \quad (12)$$

The product is calculated over the entire season of vulnerability.

Two groups of delta smelt are prominent in the salvage estimates from the fish facilities: adults from mid-December to mid-April, and larvae and juveniles from mid-April to mid-July (Figure 3). From approximately mid-July to mid-December, the fish are in brackish water, and few are salvaged in the fish facilities. I therefore focused on losses of adults and larvae/juveniles. Adults are also captured in the spring Kodiak trawl survey (Bennett 2005, see http://www.delta.dfg.ca.gov/data/skt/), and young fish are captured in the spring–summer 20-mm survey of late larvae and juveniles (Dege and Brown 2004, see http://www.delta.dfg.ca.gov/data/20mm/).

The general approach was to estimate entrainment as a mortality (since successful salvage is assumed to be negligible), and multiply the corresponding survival values for each day of exposure to entrainment (Equation 12). The sum of net flows in Old and Middle Rivers (Figure 1) was used to estimate the movement of fish toward the fish facilities. Net flow is southward toward the export facilities when export pumping is large compared to flow in the San Joaquin River. Salvage of adult and young delta smelt is usually low when this flow is positive, although substantial salvage of adult smelt occurred at the federal facility in some years of positive Old and Middle River flow (Figure 4).

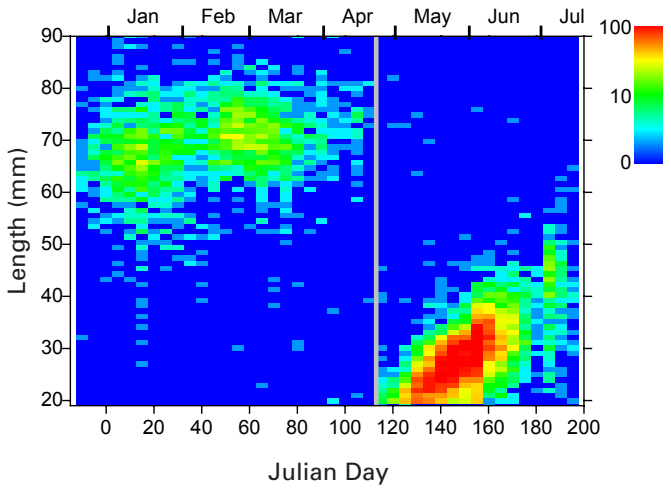

Figure 3. Delta smelt. Combined salvage at south Delta fish facilities for 1997–2005. Image plot showing numbers of fish by length and day, according to log scale at right. Larger fish are adults, and small ones are larvae and juveniles, roughly separated by the vertical line. Larvae smaller than 20 mm are generally not counted. Very few fish were caught between July and mid-December.

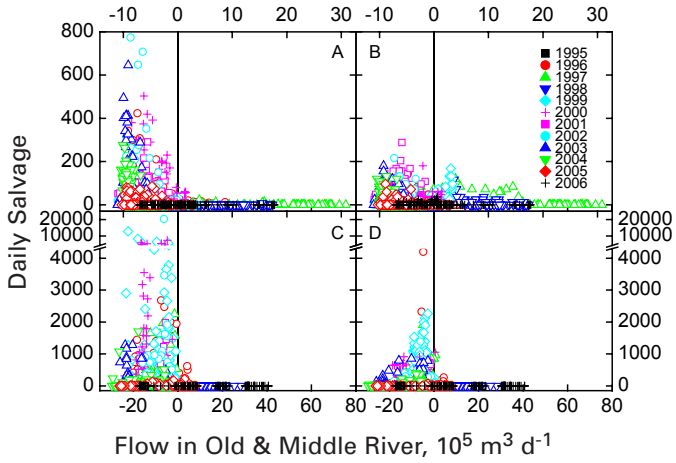

Figure 4. Daily salvage of delta smelt at the fish facilities vs. flow in Old and Middle Rivers, positive northward, 1995-2006. (A) and (B) are adults; (C) and (D) are juveniles. (A) and (C) are for the state facility; (B) and (D) are for the federal facility.

Adults

The general approach for adult delta smelt was to divide estimated daily entrainment by the monthly estimated population size from the Kodiak trawl survey to get a daily proportional loss rate, which was accumulated over each day in the month and each month in the season (December–April):

$$\hat{P}_L = 1 - \prod_{mo=12}^{4} \prod_{d=1}^{d(mo)} \left(1 - \frac{\Phi_{dx}}{A_{mo}}\right). \quad (13)$$

Natural mortality was not considered explicitly in this formulation because most of the losses occur early in the season before the population begins to decline. The principal difficulty with this method is that the fish flux is determined from the salvage sampling program, whereas the population size is determined from the Kodiak trawl data; thus, differences in efficiency between the two programs introduce an unknown parameter. I estimated this parameter as explained below by using Kodiak trawl data from stations in the southern Delta, where the fish are most vulnerable to entrainment.

Principal assumptions were:

1. The Kodiak trawl survey takes a representative sample of the adult delta smelt population.
2. Entrainment is proportional to the combined southward flow in Old and Middle Rivers.
3. All delta smelt entrained toward the export facilities are lost from the population.
4. The efficiency of sampling by the fish salvage facilities is constant.

The first assumption is unlikely to be true given the fixed stations of the Kodiak survey and the concentration of stations in some areas. An alternative approach is to calculate mean catch by sub-region, extrapolate to abundance by sub-region, and sum these values across sub-regions. Doing so results in only a small change in the calculated population size (e.g., see Kimmerer and Nobriga 2005). Assumption 2 is not strictly true since some adult delta smelt are reported from the salvage facilities even when flow is northward, probably because of dispersion (Figure 4A and B). However, this relationship was applied only during times when flow was southward, when advection would have dominated the entrainment flux. Although adult smelt do not drift passively, the patterns in Figure 4A and B support the idea that entrainment is related to the southward flow toward the export facilities. Adult and juvenile delta smelt do not tolerate much handling, and most are probably killed in the salvage process (Bennett 2005). Assumption 4 is unlikely to be true, and violation of this assumption introduces error variance into the calculations.

The Kodiak trawl program has taken surveys from January–May since 2002 but only the three to four surveys using standard stations were included (surveys designated by single digits). Based on reported lengths, all fish appeared to be adults, except for those smaller than 60 mm in May. Catch per volume was calculated assuming a volume filtered of 6,223 m^3, which is the median based on flowmeter readings and a mouth area of 12.5 m^2 (R. Baxter, California Department of Fish and Game, pers. comm.). The Kodiak trawl samples the upper ~ 2 meters of the water column, and adult delta smelt are most abundant in the upper half of the water column, ~ 4 meters. Population size throughout the habitat was calculated as the mean catch per m^3 multiplied by the volume of habitat shallower than 4 meters, about 0.9×10^9 m^3.

Data from the fish facilities included length for about 90% of the fish identified. Fewer than 1% of the fish caught and measured in May were adults—i.e., larger than 60 mm—so data from May were eliminated. About 40% of the fish measured in April were larger than 50 mm, and considered adults. This fraction was used to draw a random sample of the fish salvaged but not measured, which was added to salvage data for fish measured as > 50 mm in April. These fish, and all fish collected in December–March, were included in the analysis.

The daily proportional loss rate for both facilities is (from Equations 4 and 5, assuming no salvage is successful):

$$\hat{P}_{Ld} = \frac{E_k(\hat{\Phi}_{d1} + \hat{\Phi}_{d2})}{\hat{D}_s V} = \frac{E_k\left(\frac{\hat{N}_{d1}}{S_{P1}E_1} + \frac{\hat{N}_{d2}}{S_{P2}E_2}\right)}{\hat{D}_s V} \quad (14)$$

The efficiency E_2 for the federal facility is about 13% (M. Bowen, U.S. Bureau of Reclamation, pers. comm.). However, neither E_1 nor the pre-screen survivals S_{Pi} are known for delta smelt, nor is E_k. To simplify the analysis, I combined the two parameters into one for each facility, and assumed that the two resulting values scale as the mean catch at the two facilities. For adult delta smelt from 1995–2006, on days when both facilities had non-zero catches (a total of 235 days), the median ratio of the catch per volume at the state facility to that at the federal facility was 0.95, with 10th and 90th percentiles of 0.2 and 3.8. If fish were arriving at the two facilities in equal abundance per unit volume, the combined efficiency parameters are not consistently different between the two facilities. Therefore, Equation 14 was rearranged to give:

$$\hat{P}_{Ld} = \frac{\theta\,(\hat{N}_{d1} + \hat{N}_{d2})}{D_s V}, \text{ where}$$

$$\theta = \frac{E_k}{E_1 S_{P1}} = \frac{E_k}{E_2 S_{P2}}. \quad (15)$$

Entrainment can also be estimated as the product of abundance per volume in the south Delta times flow in the south Delta, so:

$$\frac{N_{SD}\,Q_{SD}}{V_{SD}} = \theta\left(\hat{N}_{d1} + \hat{N}_{d2}\right). \quad (16)$$

The value of θ was estimated using the Kodiak trawl catches from four south Delta stations (902, 906, 914, and 915). Data from 2006 were excluded because flow in Old and Middle Rivers was northward most of the time. The model used for this calculation was rearranged from Equation 16, and N_{SD} was assumed to have a Poisson error distribution:

$$\hat{N}_{SD} \sim \text{Poisson}\left[\frac{V_{SD}\theta}{Q_{SD}}\left(\hat{N}_1 + \hat{N}_2\right)\right], \quad (17)$$

which was fit using a generalized linear model with a Poisson error distribution to determine θ. Inserting θ into Equations 15 and then 13 gives:

$$\hat{P}_L = 1 - \prod_{mo=12}^{4} \prod_{d=1}^{d(mo)} \left(1 - \frac{\theta\,(\hat{N}_{d1} + \hat{N}_{d2})}{A_{mo}}\right). \quad (18)$$

Salvage data for each day in a month were inserted into Equation 18 and divided by the monthly estimate of population size. Monthly estimates were extrapolated for two missing cases (April 2002 and January 2003), and to the previous December for all years, using the nearest non-missing month's data.

Usable salvage data are available for as early as 1995, but the Kodiak trawl data started in 2002. The mean catch per trawl in the fall midwater trawl survey for November–December was moderately well correlated with the subsequent population size from the Kodiak trawl (r = 0.86 for log-transformed data). This relationship was therefore used to estimate mean population size in spring of 1995–2006 from the midwater trawl data. This mean population size was then inserted into Equation 18 as a constant for December–April of each year to calculate annual proportional losses for 1995–2006.

Larvae/Juveniles

The general approach for young fish was similar to that for adults except that this calculation does not rely on reported salvage data, which can underestimate the abundance of small fish, and the extrapolation from daily to seasonal loss involves several additional complications. A flow-chart (Figure 5) shows the calculations required to estimate the seasonal loss, and to test some of the assumptions listed below. Several sources of error were propagated through the calculations.

The 20-mm survey has sampled twice a month during March or April to July from 1995–2005, at up to 52 stations throughout the upper Estuary (Dege and Brown 2004). I dropped surveys having fewer than 20 stations, and dropped stations in San Pablo Bay where delta smelt are uncommon. Catch per tow was converted to catch per volume (CPUE, catch per

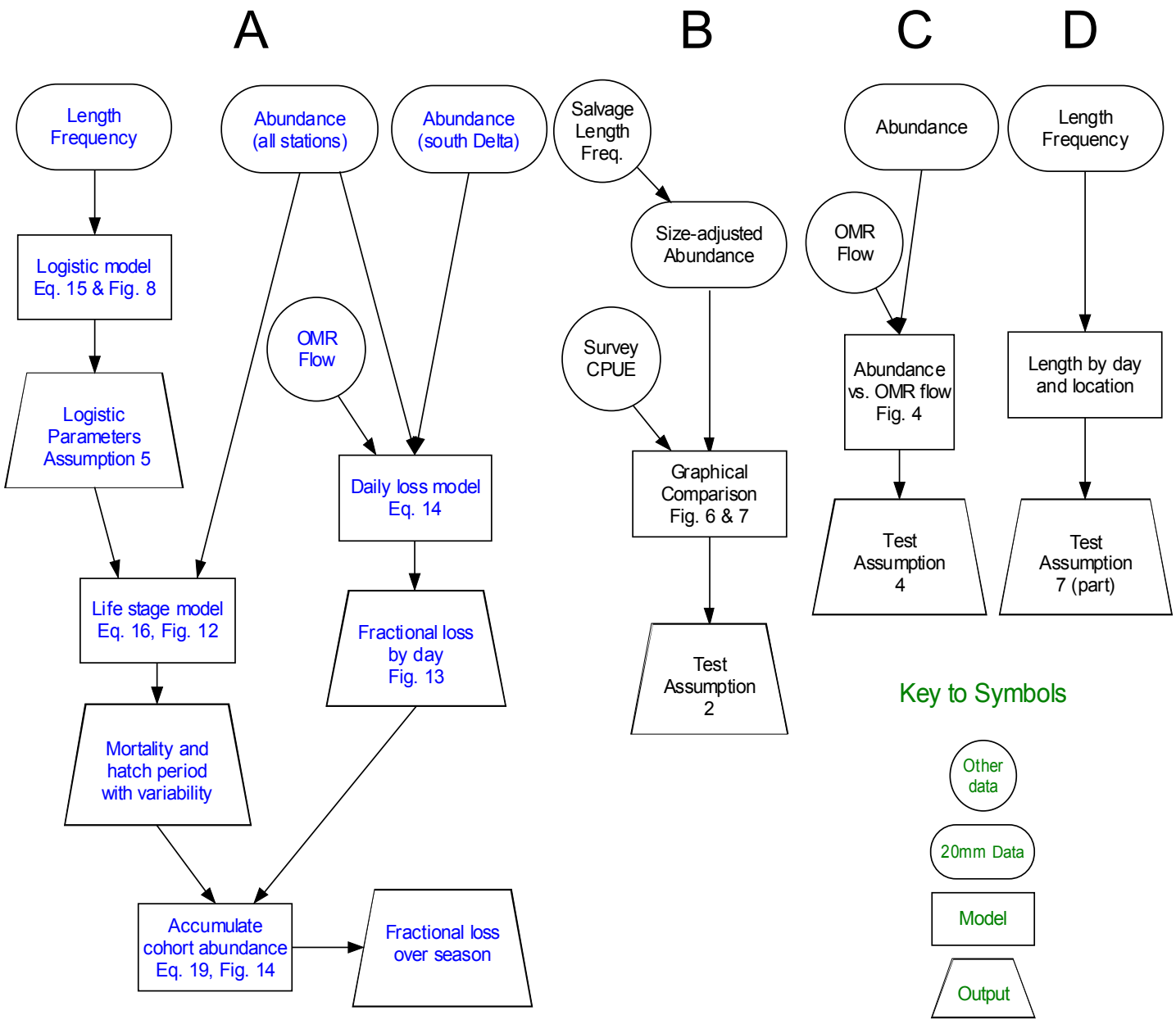

Figure 5. Flow diagram for calculations to estimate losses of juvenile delta smelt. (A) Main calculation of seasonal loss as a percentage of the population. B, C, and D are ancillary calculations to test assumptions: (B) Assumption 2; (C) Assumption 4; (D) Assumption 7. A key to symbols is shown at the bottom. OMR = Old and Middle River flows. CPUE = catch per volume.

unit effort) assuming 855 m^3 volume per tow and net efficiency that increased to 100% with increasing size of the fish (see below). The proportional daily loss of fish to the export facilities based on a single survey was estimated as:

$$\hat{P}_{Ld} = \left(\frac{N_{SDs}}{A_s} \right) \frac{Q_{SD}}{V_{SD}} . \quad (19)$$

Six stations (902, 906, 910, 914, 915, and 918) in the southern Delta nearest the fish facilities were used to calculate N_{SD} for each survey.

To calculate the total loss for the entire time-period of the 20-mm survey involves several complicating factors. Delta smelt hatch over a period of several weeks to months. The proportional loss to entrainment early in the season applies only to the fish that have hatched, so the product of daily survival values (Equation 12) underestimates overall survival. Furthermore, natural mortality (i.e., that not attributable to export pumping) suffered by the fish that hatch early requires a further discount of the proportional loss suffered by these fish. This occurs because all of the fish leave the Delta about the same date, after which vulnerability to export effects is considered negligible (the last date of the survey; see Assumption 8 below). Fish that hatch early suffer a longer period of mortality before this date, and thus contribute less to the population; therefore, losses of fish from these cohorts have less effect on subsequent population size.

Assumptions: Principal assumptions for calculating daily loss for each survey were:

1. Delta smelt that arrive in the vicinity of the export facilities are lost from the population.
2. The six stations listed above provide estimates of CPUE that represent the part of the population in the water going to the export facilities.
3. Mean CPUE in all stations represents the entire population.
4. The relevant flow toward the export facilities is the southward flow in Old and Middle Rivers.

Additional assumptions needed to extrapolate daily to seasonal losses (explained below) were:

5. Capture efficiency of the 20-mm net can be described by a logistic function, increasing from 0 to 100% as fish length increases.
6. Fish hatch at a constant daily rate over some time-period.
7. Daily mortality is constant from the beginning of the hatch period until the last survey.
8. Fish remain in the Delta until some date (or temperature) rather than moving to higher salinity at a certain age.
9. Fish hatch at a 5-mm length and grow at ~ 0.3 mm d^{-1}.

Assumption 1 seems reasonable since most of the smaller delta smelt go through the louvers at the fish facilities and are lost from the system (see below), and the few that are salvaged probably do not survive (Bennett 2005). Assumption 3 is probably true for surveys of pelagic fish (Kimmerer and Nobriga 2005). A constant hatch rate (Assumption 6) greatly simplifies the calculations, and is unlikely to have a big effect on the outcome. Daily mortality

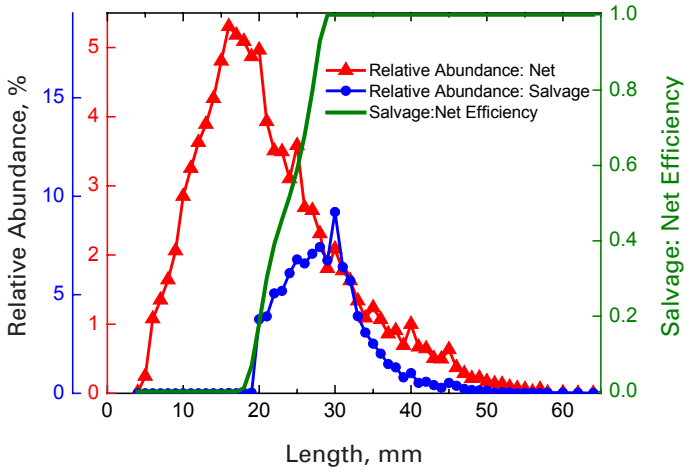

Figure 6. Larval/juvenile delta smelt. Length distributions for all fish caught in the 20-mm survey or in salvage, shown on different scales (left) so relative abundances overlap at ~ 30 mm. Also shown is the ratio of capture efficiency of the salvage sampling to the net sampling (right axis, solid line).

(Assumption 7) is almost certainly not constant, but there are no data on which to base reliable estimates. The growth rate value is supported by Figure 6 in Bennett (2005), and is also the approximate mean value obtained by fitting straight lines to data on length at date.

Assumption 2 is supported by the similar temporal pattern of catches in the south Delta sampling stations and the salvage facilities (Figure 5B). To match these catches, it was necessary to account for poor sampling of small fish in the salvage facilities (Figure 6). A relative capture efficiency of the salvage facilities was calculated as the ratio of catch at each size in salvage to that in the net samples, normalized to a total of 1. Since the decline in relative abundance in the salvage data at lengths greater than the modal length was likely due to movement of the fish rather than capture efficiency, the efficiency above the mode was set to 1 (Figure 6). Then the abundance in net samples in the southern Delta was reduced by the calculated relative capture efficiency. The resulting catches per volume (examples in Figure 7) matched reasonably well in timing and magnitude, and were weakly but significantly correlated across all days when data co-occurred ($r = 0.4$, $p < 0.01$).

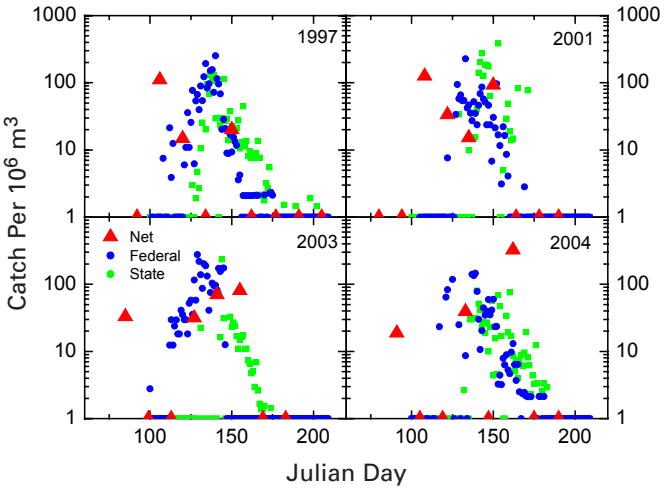

Figure 7. Examples comparing abundance of young delta smelt in the 20-mm survey and in the two fish facilities. Data from the 20-mm survey have been corrected by the relative capture efficiency of the fish facilities (green line in Figure 6) to allow direct comparison.

Assumption 4 (Figure 5C) is supported by the pattern of catch of juveniles in the salvage facilities vs. Old and Middle River flow (Figure 4C, D). Larval/juvenile delta smelt were rarely caught when flow was northward (positive).

Assumption 8 (Figure 5D) is supported by the salvage data in Figure 3: if smelt were moving to brackish water (and then becoming invulnerable to export entrainment) at a certain age, life stage, or length, the mean size in the export facilities would initially rise and then level off. Instead, the mean size increases throughout the spring, and the fish rather abruptly disappear (Figure 3, lower right). This pattern is also supported by the similarity in apparent growth rate from the 20-mm catches from the south Delta compared to that from catches from the entire system (not shown).

Net efficiency: The function describing capture probability as a function of fish length is:

$$E_L = \left(1 - \frac{1}{1 + ae^{bL}}\right) e^{kL}, \quad (20)$$

where a, b, and k are parameters to be determined. The logistic term in parentheses is small at small size and increases sigmoidally to 1 at large size. The other term contains mortality (and declining capture efficiency) per increment of length to express the decreasing catch as fish grow. This term was used only to fit this equation, and only the logistic parameters a and b were used in subsequent analyses. Parameters were determined by using a least-squares optimization procedure (function *optim* in S-Plus, Venables and Ripley 2003) to fit Equation 20 to the overall length-frequency distribution. Data from each year were used to determine these parameters, which provided means and confidence intervals for each parameter.

The logistic fits to the length-frequency data show that the 20-mm net is 50% efficient at about 16 mm, with a 12-mm window around that value in which efficiency increases from 10% to 90% (mean parameters; Figure 8). The fit of the model to the overall length frequencies is good ($r^2 = 0.99$). The proportion of the population at 5-mm length (hatch

length) varied approximately three-fold with parameters at their upper and lower 95% confidence limits (Figure 8B). These values for the logistic parameters were used to propagate error in subsequent analyses.

Mortality rates and hatch dates: These were estimated by fitting data from all stations for each year to the following equations:

$$\left.\begin{aligned} A_{L,t} &= H\, e^{-m\,(t - T_j)}, \quad T_0 \le T_j \le T_1 \\ A_{L,t} &= 0, \qquad\qquad T_j < T_0 \text{ or } T_j > T_1 \end{aligned}\right\},$$
$$L = (t - T_j)\, g \tag{21}$$

which describes the number of fish of cohort j on each day t given that H fish hatched on day T_j during an interval (T_0, T_1), with constant growth rate g and mortality rate m. The daily hatch rate H cancels out of calculations of proportional losses, so this is an arbitrary parameter that was set to 1. The calculated abundance values $A_{L,t}$ were adjusted for inefficient sampling of small fish using the logistic function from Equation 20, then the length data were aggregated into four length classes of equal size to reduce the number of zeros in the data. The data from each year were then fitted to these equations by an iterative search procedure that minimized the sum of squared deviations between the data and the model to estimate the hatch period (T_0, T_1) and the mortality m.

Daily and seasonal losses. The proportional loss for each survey was determined from Equation 19. To determine daily losses P_{Ld} from the proportional loss by survey, I interpolated the fraction in parentheses in Equation 19 for days between surveys, and extrapolated the fraction for the first survey back to the calculated first hatch date T_0. These fractions were then multiplied by the daily value of Q_{SD}, the southward flow in Old and Middle Rivers. The resulting daily proportional loss is a mortality rate and comprises part of the mortality m determined using Equation 21. Natural mortality (i.e., mortality not due to export losses) was calculated as the difference between mortality determined using Equation 21 and the effective mortality due to export effects:

$$\hat{m}_n = \hat{m} - \overline{\ln\,(1 - \hat{P}_{Ld})} \tag{22}$$

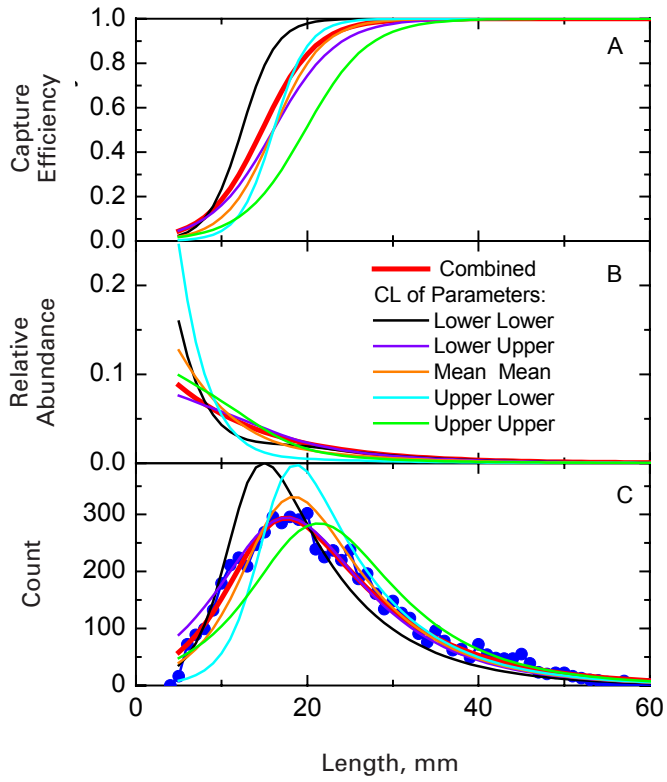

Figure 8. Fit of the net-efficiency model (Equation 20) to the count data from the 20-mm survey. Data for each year have been reduced to the same total number of fish (593) to even out all years. Each panel contains lines based on combinations of the two model parameters: both at their mean values, or either at their upper and lower 95% confidence limits. (A) Capture efficiency as logistic functions of length; (B) Relative abundance by length from the overall model; (C) Count data from the reduced data set (symbols) and model fits, which are proportional to the products of the curves in panels A and B.

where the average was taken over the season from T_1 to the last survey. I used these estimated mortality values for each year in the subsequent calculations, but made parallel calculations with no mortality for comparison.

Survival of each day's cohort j from its hatch date to the last survey day was calculated as:

$$\hat{S}_j = \prod_{T_j}^{T_f} e^{-\hat{m}_n}\,(1 - \hat{P}_{Ld}) \tag{23}$$

The proportional loss of fish up to final day T_f was

then determined from the abundance of all cohorts on that day divided by the abundance in the absence of export losses:

$$\hat{P}_L = 1 - \frac{\sum_j \prod_{T_j}^{T_f} e^{-\hat{m}_n}(1 - \hat{P}_{Ld})}{\sum_j \prod_{T_j}^{T_f} e^{-\hat{m}_n}} \quad (24)$$

The calculation was run for each year of the 20-mm survey separately to determine a proportional loss. Each year's calculation was run 100 times using three sources of variability. Variability in abundance ratio (in parentheses in Equation 19) was determined by bootstrap sampling of the abundance ratios determined from field data for each year; this variability was propagated by sampling from a normal distribution with mean and standard error from the bootstrap analysis, truncated to 1.6 standard deviations (middle ~ 90% of the values) to prevent extreme values. The logistic parameters for each run (Equation 20) were determined by sampling from a normal distribution with the mean and standard deviation of the parameter, determined as described above. The growth rate used in the model was determined by sampling from a uniform distribution over the interval (0.2, 0.4), since there is insufficient information to determine variability in growth rate.

Equations 19 and 24 were also used to calculate proportional losses for hypothetical export flows. I calculated Old and Middle River flow by assuming a 1:1 reduction of Old and Middle River flow for each increase in export flow. I also assumed that the spatial distribution of delta smelt does not change with the changes in Old and Middle River flow, provided that flow remains negative.

Output from a particle tracking model (DSM-2 PTM, Kimmerer and Nobriga 2008) was used in a comparison with the results from this analysis. The PTM was run for 30 days with particles released at 31 locations in the Delta. The proportion of particles lost to the pumping facilities was determined for each release location. These results were aggregated using a weighting factor equal to the proportion of delta smelt < 10 mm at sampling stations close to each release site during dry years. The use of small fish in dry years was meant to ensure weighting toward likely spawning locations, i.e., initial locations for larvae. The PTM results were analyzed in a regression including export flow, inflow, and an interaction term, and the predictions of this statistical model were used to compare PTM output to results of the above analysis of proportional losses.

The fall index of delta smelt abundance is used as the principal measure of status of the population. Previous reports (Miller et al. 2005) documented a relationship between spatial co-occurrence of delta smelt in summer with calanoid copepods—their principal food—and the fall midwater trawl index of delta smelt abundance. Using a slightly different approach, I determined a relationship between zooplankton biomass and summer–fall survival. The independent variable was the biomass of calanoid copepods during July–October in a salinity range of 0.15–2.1 psu, the range over which 50% of the smelt occur in the summer townet survey. The dependent variable in a least-squares regression was the log ratio of the fall midwater trawl index to the summer townet index, which is an index of survival.

RESULTS AND DISCUSSION

Chinook Salmon

The capture of individual marked fish at Chipps Island and the fish facilities typically lasted for approximately 1 month, with the capture rate usually high for about half of the time and then gradually declining (Figure 2). On some occasions, timing was bimodal, with a few fish arriving early and the remainder in a later pulse. There was no consistent difference between timing at Chipps Island and that at either of the fish facilities.

The estimated proportion of migrating fish salvaged at the export facilities increased with increasing export flow (Figure 9). Four data points based on a small number of fish caught (four to six) were excluded from the analysis. Including these points gave a similar model fit, but diagnostic plots revealed an upward bias in the distribution of residuals. Entering the source or run of fish in the statistical model did not improve the fit according to the

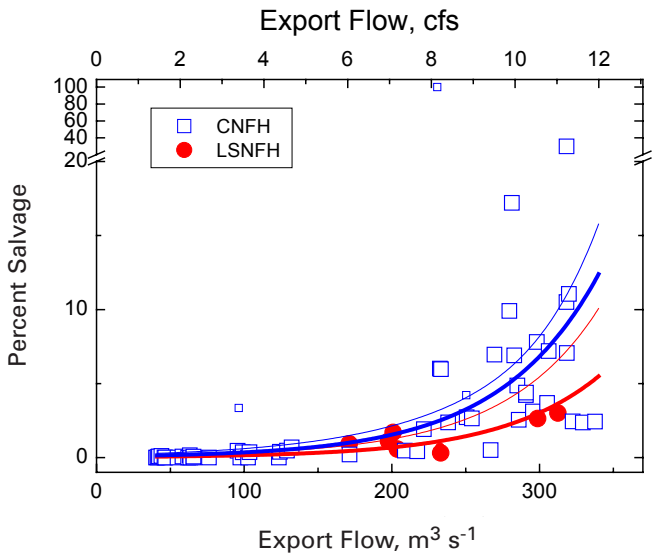

Figure 9. Chinook salmon. Relationship of estimated proportional salvage of tagged smolts at the fish facilities, P_S, to export flow. Small symbols represent data based on six or fewer fish caught, which were not used in determining the line. Lines are from a generalized linear model with log link function 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.

Akaike Information Criterion (320.9 without, 321.3 with source of fish in the model), but the term for source of fish was marginally significant ($p < 0.1$), and the source term reflects the fact that the LSNFH values tended to be lower than those from CNFH at the higher export flows (Figure 9). Clearly, more data at high export flows would be useful in distinguishing between the results from the two hatcheries.

There was no apparent relationship between proportional salvage or total salvage and either Sacramento River flow or mean position of the gates controlling the Delta Cross-Channel. The relationship of proportional salvage to export flow (Figure 9) had a coefficient of variation for the prediction of about 20% at high export flows.

Proportional loss increased at an accelerating rate with decreasing pre-salvage survival (Figure 10). For pre-salvage survival of 50%, proportional loss is equal to proportional salvage. Proportional loss increases sharply as pre-salvage survival approaches 0, as is clear from Equation 6. Confidence limits on proportional loss are large (Figure 10), but the uncertainty about pre-salvage survival means that constraints on the true value of proportional loss are weak. Pre-salvage survival depends partly on pre-screen predation (Gingras 1997), but also on louver efficiency. NMFS (2004) raised questions about the efficiency of the louver systems under routine operations, when louvers must be lifted out of the water for cleaning and repairs.

Post-salvage mortality was assumed to be small, and is generally considered to be low because of high survival in tests of handling and trucking procedures (NMFS 1997). However, there is no information on survival of these fish after release, and anecdotal evidence suggests high predation rates on the released fish. If survival is low, salvage (Figure 9) would have to be reduced by the fraction of released fish that do not survive. This would have a substantial influence on losses only if pre-salvage survival were high (Figure 10).

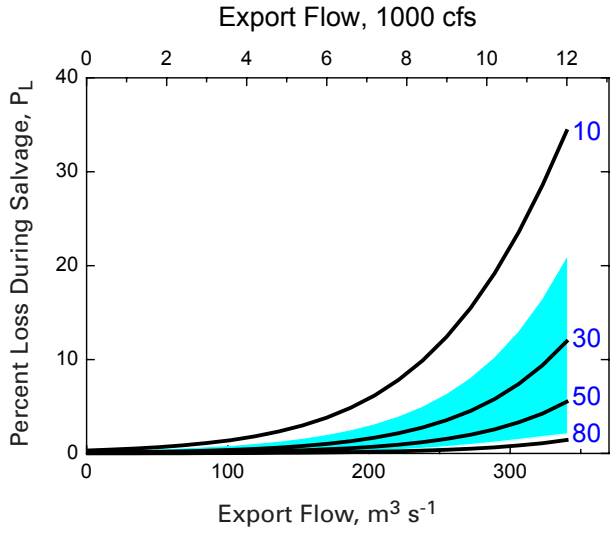

Figure 10. Calculated proportional loss of Chinook salmon, P_L, as a function of export flow and the pre-salvage survival term S_S, assumed to be the same for both fish facilities (Equations 6 and 11). Numbers on right give S_S as percent. Band gives 90% confidence limits around the 30% value based on the error term from Figure 9.

Other sources of uncertainty include the swimming speed of the fish, sampling efficiency, and differences between results from fish raised in the two hatcheries. None of these is likely to be comparable to the uncertainty in pre-salvage survival. Swimming speed may vary among releases, e.g., with net flow at Chipps Island or temperature. It may also be biased, which would influence the absolute values of the salvage and loss proportions.

Since the Chipps Island flux is determined using nets, and that at the export facilities using salvage, any difference in efficiency between the two sampling methods that is not taken into account will introduce error. I assumed that net efficiency is 100%; a lower efficiency would result in an underestimate of the fish flux past Chipps Island. A comparison between a midwater trawl and a larger Kodiak trawl in the Sacramento River revealed no difference in fish per volume, suggesting that the efficiency of the midwater trawl is high (Brandes et al. 2000).

All of these calculations refer to direct losses only. Indirect losses may be large (NMFS 1997) but have not been estimated, nor has a method been developed to estimate them. This was supposed to have been the focus of investigations using mark-recapture approaches, but to date these studies have not provided insights into this question (Brown and Kimmerer 2006). Mark-recapture studies have shown that survival of fish released into the interior Delta is lower than that of fish released in the lower Sacramento River, and the ratio of these survivals is a weak function of export flow (Newman 2003). However, these results say nothing about the potential role of indirect mortality, i.e., the likelihood that fish die during migration from the Delta as a result of altered hydrodynamic conditions. This is clearly an area for further investigation.

Even without estimates of indirect loss, the losses in Figure 10 are higher than expected based on management targets for the Delta. Take limits at the state and federal fish facilities for winter Chinook salmon are based on a calculated 2% of the estimated passage through the Delta. This assumes that roughly half of the fish identified by size as winter Chinook are actually winter Chinook. The sources of the hatchery-tagged fish are unambiguous, and considerably more than 1% of them are lost at high export flows for any value of pre-salvage survival < ~ 20% (Figure 10).

Delta Smelt Adults

Monthly population estimates declined beginning approximately in March, when the adults begin to spawn and die (Figure 11A). Estimated losses to entrainment began in mid-December, peaked in January, and then declined sharply (Figure 11B) as the population declined and the southward flow in Old and Middle Rivers decreased (Figure 11C).

The calculated value of θ was 29 $\pm$ 20 (95% confidence limit, 13 df). If the Kodiak trawl were 100% efficient, approximately 30 times more fish were entrained than salvaged. This ratio would be even higher if the Kodiak trawl were <100% efficient. A louver efficiency of 13% (see above) combined with 75% pre-screen losses for both facilities gives an overall pre-salvage loss of 97%, consistent with the above ratio but likely coincidental given the uncertainties in both estimates.

With the estimated value of θ, the cumulative loss over the season ranged from 3% to 50% (Table 3). If the upper confidence limit of θ is used, the values range from 6% to 69%. These confidence limits are somewhat underestimated because sampling error in the Kodiak trawl survey could lead to higher or lower estimates of population size.

Examining data back to 1995, southward flow in Old and Middle Rivers was highest in 2002–2004 and low during the wet years of the mid-1990s (Figure 12A).

Table 3. Estimated cumulative losses of adult delta smelt to entrainment in the south Delta water export facilities.

Year	Cumulative % Loss	95% Confidence Limits
2002	15	5 – 24
2003	50	19 – 69
2004	19	6 – 31
2005	7	2 – 12
2006	4	1 – 6

This pattern was followed by annual salvage estimates for December–March. Spring abundance was estimated accurately from the midwater trawl data, except for an over-estimate in 2003 (Figure 12B). During that year, no Kodiak trawl survey was taken in January, and the abundance in March was higher than that in February (Figure 11A), so that value is highly uncertain. The extrapolated Kodiak trawl estimates were higher for years before 2002 than during or after 2002 (Figure 12B). Calculated losses followed those determined above, with 2003 again the exception. The highest monthly salvage occurred during January 2003 (Figure 11B), again possibly reflecting an underestimate of population size in the Kodiak trawl data. Overall, mean proportional losses varied from near 0 to 23% (Figure 12C), with a trend reflecting that of Old and Middle River flow (P_L = -3.7 + (1.1 ± 0.4) Q_{SD}, r^2 = 0.75, 10 df). The relationship of percent loss to X_2 was weak and not significant, presumably because Old and Middle River flow is a more proximate cause of variability in percent loss than X_2.

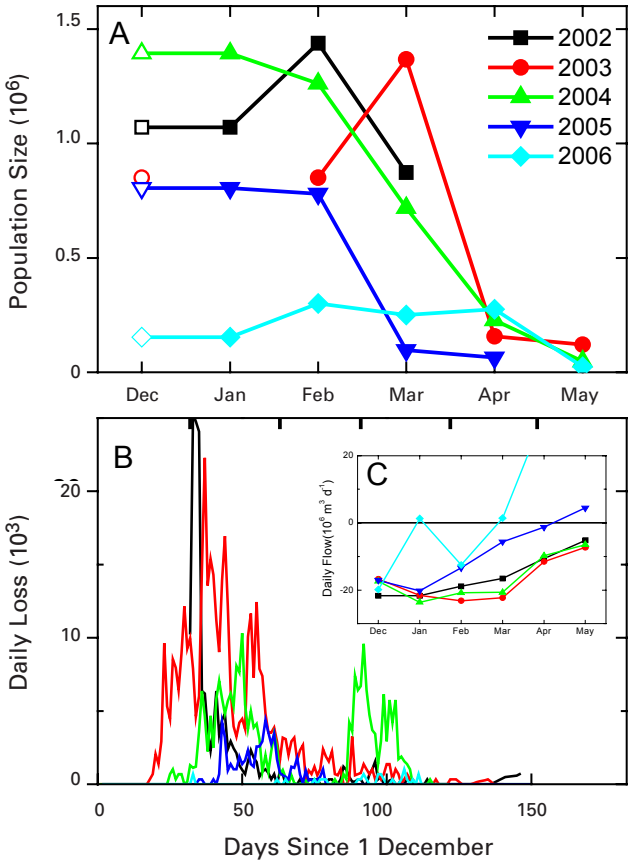

Figure 11. Adult delta smelt. (A) Estimated population size based on the Kodiak trawl survey; open symbols indicate that data for December were extrapolated back from the first survey of the following year; (B) Daily entrainment toward the fish facilities, which is salvage corrected for the ratio of capture efficiency of the Kodiak trawl to that of the fish facilities, so that these values are directly comparable to those in panel A; (C) Monthly mean of the daily combined flow in Old and Middle Rivers (positive northward, away from the export facilities).

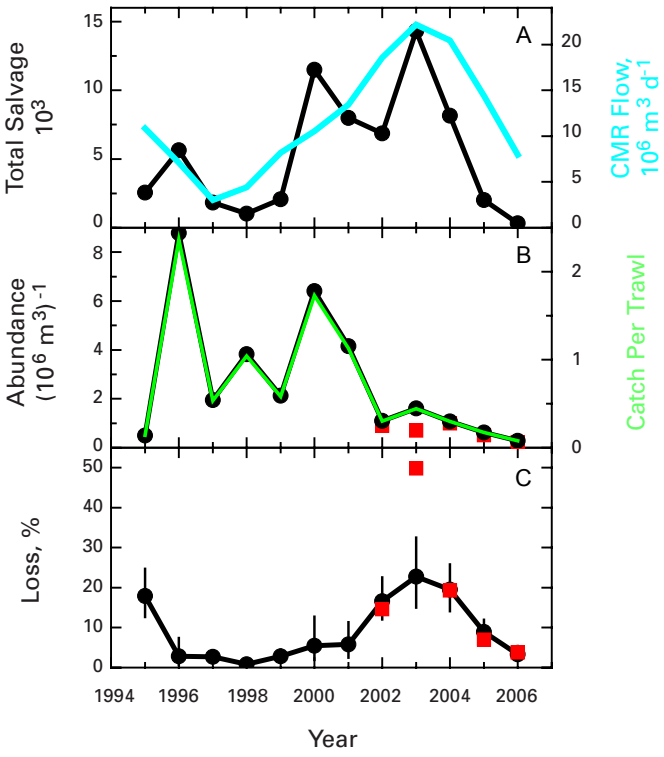

Figure 12. Reconstruction of export losses of adult delta smelt for 1995–2006. (A) Total salvage (line with circles) and Old and Middle River flow (line, right axis); (B) Predicted (line with circles) and measured (squares) population abundance, and mean catch per trawl for the fall trawl surveys in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

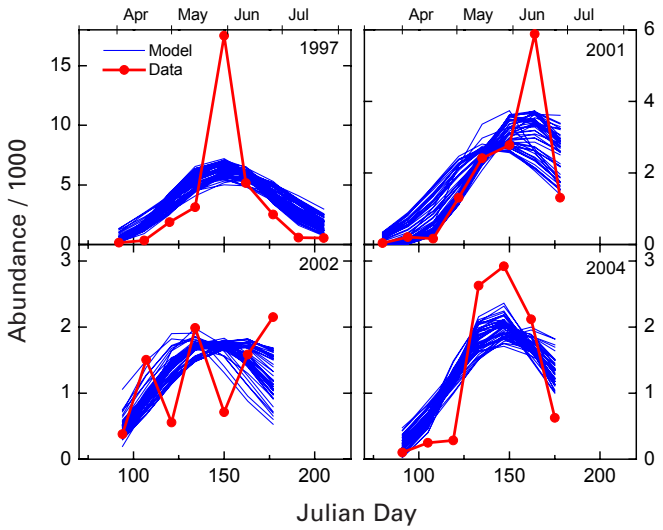

Figure 13. Larval/juvenile delta smelt. Examples of abundance by survey (line with circles) and example trajectories from repeated model runs with parameters sampled from their respective statistical distributions (thin lines).

Delta Smelt Larvae/Juveniles

The fits of the model of hatch dates and mortality (Equation 21) for each year were variable; of course the model failed to capture peaks in abundance (Figure 13), but the trends through the season were satisfactory for accumulating losses through the season. Modeled hatch dates and mortality rates varied among years (Table 4). These mortality rates seem low, but this is probably an artifact of the use of a single mortality rate for the entire period from hatch to migration.

The proportional loss data for each 20-mm survey showed a broad peak centered approximately in early April (Figure 14). Losses were low after mid-May and zero after mid-June. The seasonal or annual proportional loss was also highly variable among years, and roughly followed the maximum daily loss for each year (Figure 15). During the dry years 2001–2003, the losses were ~ 25%. Setting the natural mortality to zero raised the highest percentage loss to 37% (Figure 15). Increasing export flow to the maximum resulted in proportional losses up to 62%. The variation in annual loss was related to flow conditions (P_L = -0.4 + (1.7 ± 0.6) Q_{SD}, r^2 = 0.79, 9 df), but this

Table 4. Juvenile delta smelt. Estimated hatch dates and mortality by year from the 20-mm survey.

Year	Natural Mortality mn, d-1	Hatch Dates Earliest	Latest
1995	0.034	03/14	06/07
1996	0.039	03/16	05/13
1997	0.040	03/20	05/12
1998	0.027	03/11	05/02
1999	0.052	03/21	06/09
2000	0.029	03/25	05/15
2001	0.027	03/19	05/09
2002	0.038	03/07	05/12
2003	0.024	03/10	06/09
2004	0.030	03/13	04/28
2005	0.028	03/12	05/03

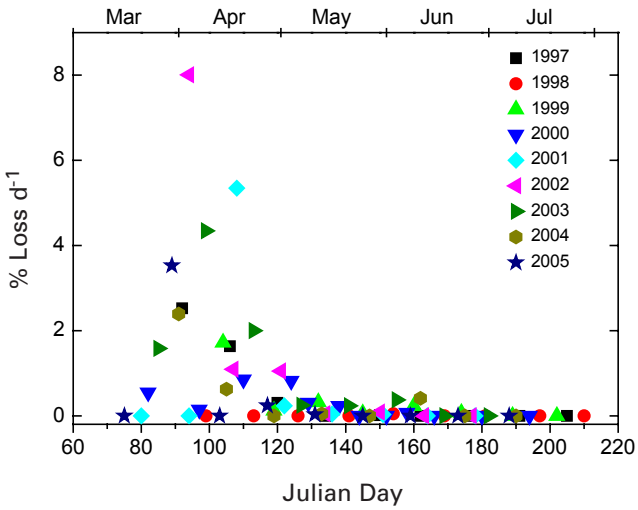

Figure 14. Seasonal pattern of daily proportional loss from the larval/juvenile delta smelt population with symbols and colors for each year.

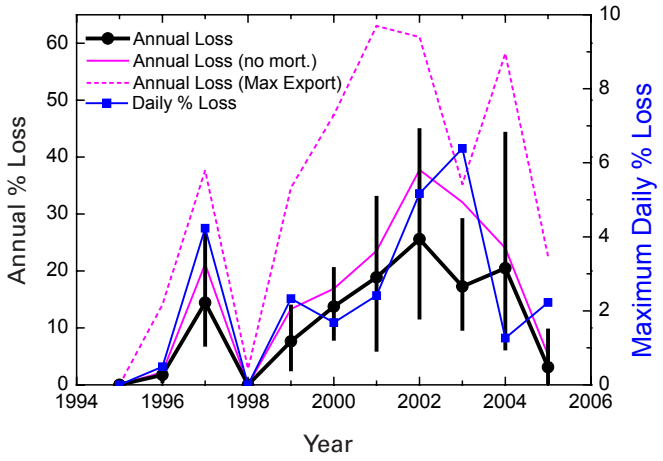

Figure 15. Estimated annual losses to export pumping of delta smelt from the 20-mm survey. The black line gives the estimated loss with 95% confidence limits allowing for mortality; red lines give annual losses without mortality (solid), and at the maximum export flow rate (dashed). The blue line with squares (right axis) gives the maximum daily percent loss determined in a single survey for each year.

relationship is tautological, since Old and Middle River flow was used explicitly in the calculations. This contrasts somewhat with the situation for adult delta smelt, for which the calculated losses were not based on flow, although flow was used in the calculation of θ (Equation 17).

The statistical analysis of output from the particle tracking model showed a reasonable ability to predict the loss of particles to export pumping from inflow and export flow (Figure 16). Placing the data from Figure 15 in the same framework gives predicted and calculated values that fall rather close to the same line, except for several values below the line at intermediate flow conditions and predicted loss rates (Figure 16). The calculated percent loss for 2005 was especially low, possibly because population abundance was so low.

The relationship of proportional loss to Old and Middle River flow (by assumption) and inflow and export flow (Figure 16) guarantees a relationship with X_2. Could this relationship underlie the weak negative relationship between X_2 and summer townet index for delta smelt after 1981 (Kimmerer 2002 Figure 8E)? A regression of summer townet index on X_2 for 1995–2005 had a slope of -0.11 ± 0.18 (95% CL, 22 df, p ~ 0.2). A regression of survival (1 – proportional loss) from the above analysis on X_2 had a slope of -0.009 ± 0.004 (9 df). The large confidence interval around the slope for the townet index includes the slope for the survival data. Applying the relationship in Figure 16 to all of the historical data for inflow and export flow replicates the X_2 effect that existed after 1981, but, in contrast to the historical data (Kimmerer 2002), there is no apparent change in the slope of the calculated X_2 effect. Thus, while the relationship of townet index to X_2 after 1981 is consistent with a mechanism based on high export losses during periods of landward X_2, this mechanism cannot explain the positive slope with X_2

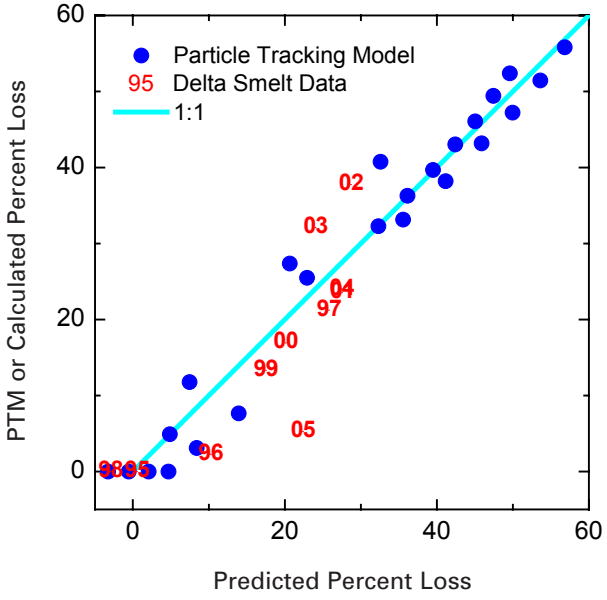

Figure 16. Larval/juvenile delta smelt. Predicted percent loss to the population by regression using log of Delta inflow and log of export flow as predictors (with interaction), and particle-tracking model results as the dependent variable (circles), with the line indicating a 1:1 relationship. The regression is: log (y) = 4.29 – (0.36 ± 0.17) log(inflow) – (0.90 ± 0.11) log(export flow) + (0.10 ± 0.03) log(inflow) × log(export flow), parameters with 95% confidence limits. Estimates of delta smelt losses from Figure 15 with no natural mortality (to match the particle tracking model results) are plotted against predictions from the above statistical model using mean flow conditions during the hatch period; numbers indicate years.

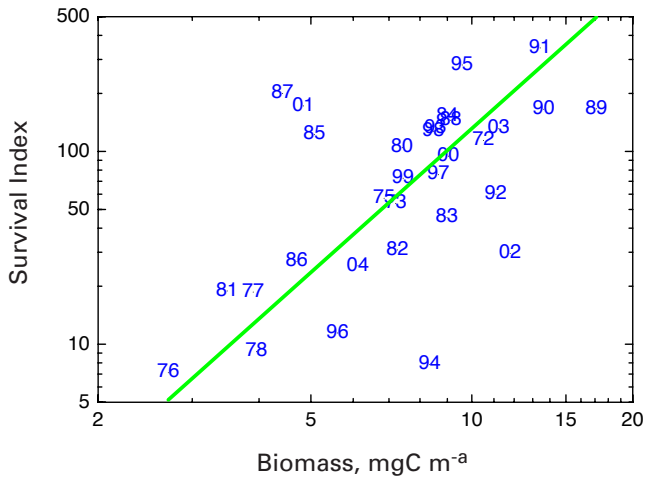

Figure 17. Relationship of survival index (fall trawl index / summer townet index) of delta smelt vs. mean zooplankton biomass during July–September for all stations in a salinity range of 0.15 to 2.09, the central 50% of the summer delta smelt distribution. The line is the geometric mean regression for log(10)-transformed data, y = 2.48x – 0.36. The correlation coefficient for the log-transformed data is 0.58 with a 95% confidence interval of (0.26, 0.78).

observed before 1981 (Kimmerer 2002). The causal mechanism for that relationship, and the reasons for the change, remain unknown (Bennett 2005).

The summer–fall index of survival varied over a range of 50-fold, and was significantly related to summer zooplankton biomass in the low-salinity zone (Figure 17). This may indicate food-limited survival. Observations of evidence for food shortage using histopathological methods (Bennett 2005) provides some support for this interpretation.

Population Consequences

Are these proportional loss rates excessive? This question cannot be answered using science alone. From a scientific perspective, all we can do is compare these losses with other sources of mortality or other data about the populations.

For Chinook salmon, a loss rate on the order of 10% or less, depending on pre-screen mortality (Figure 10), is less than fishing mortality: harvest index for all Chinook salmon off California in recent years has been around 40% (Williams 2006), which is close to fishing mortality rate for reasonable values of natural mortality. The harvest index for winter Chinook has probably been closer to 20% in recent years (Grover et al. 2004). From a population maintenance standpoint, the calculated loss rate at the export facilities would be a significant component of direct anthropogenic mortality. Furthermore, to the extent that the ocean fishery is supported by the large fall-run hatcheries, fishery losses could be offset by higher hatchery production. However, this 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.

Clearly, the big unknown is the pre-screen mortality. Although experiments have been conducted to attempt to determine this value, these have been hampered by incomplete design and by high variability. Furthermore, systemic problems with the operations and maintenance of the fish facilities (NMFS 2004) may prevent not only determining these factors but reducing them to an acceptable level. Thus, it is imperative that experimental designs be developed to better quantify pre-salvage survival if the current export configuration is to remain.

Delta smelt may suffer substantial losses to export pumping both as pre-spawning adults and as larvae and early juveniles. In contrast to the situation for salmon, pre-salvage mortality has been constrained in the calculations for adult delta smelt, and its effects eliminated from the calculations for larval/juvenile delta smelt. Combining the results for both life stages, losses may be on the order of 0–40% of the population throughout winter and spring. The estimates have large confidence limits, which could be reduced by additional sampling, particularly to estimate θ in Equation 18. If there is interest in improving these estimates further, some attempts should be made to examine the assumptions not fully tested above, particularly those used in extrapolating larval abundance to hatch dates.

Although the upper bound of this range represents a substantial loss, the effect of this loss is complicated by subsequent variability in survival (Figure 17). If this variability is uncorrelated with entrainment losses, then these losses will contribute little to the variability in fall abundance index. The simplest way to evaluate this is by regression of fall midwater trawl index on winter–spring export flow, but this relationship is contaminated by the downward step change in abundance in approximately 1981–1982, together with the long-term upward trend in export flow (mainly up to the mid-1970s, see Kimmerer 2004). Including this step in a regression model eliminates the effect of export flow on the fall midwater trawl index (coefficient = -1.5 ± 2.4, 95% CL, 36 df). It seems unlikely that the downward step change was due to the earlier increase in export flow; furthermore, despite substantial variability in export flow in years since 1982, no effect of export flow on subsequent midwater trawl abundance is evident.

This is not to dismiss the rather large proportional losses of delta smelt that occur in some years; rather, it suggests that these losses have effects that are episodic and that therefore their effects should be calculated rather than inferred from correlative analyses. In the absence of density dependence, using means in Figure 15 with natural mortality, fall abundance should have been reduced by ~ 10% during 1995–2005. This would have an equivalent effect of reducing the summer–fall survival index by 10%. This would have made little difference to fall abundance in the context of the approximately 50-fold variation in summer–fall survival (Figure 17), and would be difficult to detect through correlation.

Although summer–fall survival appears to dominate variability in abundance of delta smelt in fall (Figure 17), this does not imply that control of export effects would be fruitless, as these effects can be considerable during dry years. Management of delta smelt should incorporate any opportunities that arise to improve habitat or food supply and to reduce any negative impacts of predation or toxic contamination. However, current evidence does not provide a clear path toward improving the status of delta smelt using these factors. Manipulating export flow (and, to some extent, inflow) is the only means to influence the abundance of delta smelt that is both feasible and supported by the current body of evidence, even though export effects are relatively small. The results presented here can be used to suggest when, and under what conditions, control of export effects would be most helpful.

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