Losses of winter-run Chinook salmon and delta smelt to export entrainment in the southern Sacramento-San Joaquin Delta

Wim Kimmerer

Romberg Tiburon Center

San Francisco State University

3152 Paradise Drive

Tiburon CA 94920

kimmerer@sfsu.edu

November 28, 2006

Fish of the Sacramento-San Joaquin Delta are vulnerable to entrainment in flows leading to the water export facilities in the southern Delta. Although fish facilities associated with the export facilities are designed to salvage fish from the water and return them to the estuary (Brown et al. 1996), this salvage process is not very efficient. Many salmon and other fish are lost to predation in the waterways leading to the fish facilities (Gingras 1997). Delta smelt are inefficiently concentrated by the fish facilities (M. Bowen, US Bureau of Reclamation, pers. comm.) and it is unlikely that many survive the salvage process.

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 had unmeasurable effects on the striped bass population of the estuary. Jassby et al. (2002) concluded losses of phytoplankton to export pumping were large but undetectable given other sources of variation. Similar calculations have not been made for other taxonomic groups, although there have been no reports of correlations between any measure of export losses and subsequent population size.

Despite the lack of evidence for population-level effects, the influence of the south Delta export facilities on estuarine and anadromous fish has been assumed important for several reasons. First, large numbers of fish are entrained in the fish facilities. Second, it is reasonable to expect a large effect on some fish because of the large quantities of water exported. Third, flows and barrier emplacement in the Delta are the only apparent mechanism for human influence on some fish populations such as delta smelt.

Operation of the fish facilities and many of the actions taken to protect fish (e.g., the Environmental Water Account, Brown et al. in prep.) are aimed at protecting these fish from losses due to the export facilities. Given the cost of these and alternative measures, it is worth estimating the magnitude of these losses and their likely effects on the fish populations. In this paper I estimate these effects for two fish species. Chinook salmon (*Oncorhynchus tshawytscha*), including the endangered winter run and threatened spring run, and the threatened delta smelt (*Hypomesus transpacificus*), are target taxa for restoration and management in the Delta. Data for winter-run Chinook salmon (hereinafter, winter Chinook) and delta smelt are available to make estimates of the losses of these fish to direct effects of entrainment. I calculate these effects for winter Chinook smolts moving through the Delta, and for two life stages of delta smelt: adults in late winter, and larvae and juveniles in spring.

The conceptual framework for these calculations differs for the two species. Chinook salmon are exposed to export effects during movement through the Delta. Young winter Chinook emerge from redds in the upper Sacramento River mainly in September – October (Kimmerer and Brown in prep.). Winter Chinook juveniles move gradually down the river, arriving in the Delta in winter; a later, broad pulse of pre-smolts and smolts moves downstream to arrive in the Delta in ~ January but these are not distinguishable in data from the Delta, where size criteria for identifying salmon runs are ambiguous. Most of the winter Chinook leave the Delta by the end of March. Thus, they are potentially vulnerable to export pumping throughout winter, but mainly from January to March. Winter Chinook 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).

Data on length distributions at the export facilities and in the field studies suggest that juvenile Chinook generally are exposed to entrainment only during movement, and are rarely entrained while rearing. The risk of loss to entrainment can therefore be considered a one-time risk of mortality; the corresponding survival can be estimated as:

$$S = 1 - \frac{F_t}{A} \qquad (1)$$

where F_t is the total entrainment loss of winter Chinook and A the total number migrating through the Delta.

Delta smelt are considered to be resident fish but are actually somewhat anadromous, and spend most of their lives in brackish water not exposed to export entrainment (Bennett 2005). The adults spawn in freshwater in late winter, so the adults are vulnerable to entrainment during their spawning migrations. Eggs are demersal and therefore invulnerable to entrainment, but the pelagic larvae and juvenile stages are vulnerable from the time they hatch until they move seaward into brackish water. In contrast to the situation for salmon, the loss of delta smelt to entrainment can be considered a continuous mortality source, for which the corresponding survival is:

$$S = \prod \left(1 - \frac{F_d}{A}\right) \qquad (2)$$

where S is survival, F_d the daily fish flux going to the export facilities (fish d^{-1}), and A the size of the population. The product is calculated over the entire season of vulnerability.

Methods

Data on entrainment into the south Delta fish salvage facilities were obtained from salvage records. The facilities collect fish for counting and identification during about 2-3 hours each day or 8-12% of the time. These counts, when divided by the fraction of time when samples were taken for counts, provide estimates of the rate at which fish are entering the fish facilities. Fish smaller than 20mm are not counted, and delta smelt of all sizes are ineffectively concentrated by the louvers. In addition all fish species suffer mortality in the waterways leading to the fish facilities, presumably because of predation. Therefore entrainment in the water going to the export pumps is considerably larger than the calculated salvage, or the rate of arrival in the salvage facilities.

Data were obtained from various additional sources. Flow data were obtained from the Dayflow accounting program (Jassby et al. 1995; http://iep.water.ca.gov/dayflow). Data on salmon tagging studies, trawl data, and salvage data were obtained from the Interagency Ecological Program's Bay Delta and Tributaries Project (BDAT) web site (http://bdat.ca.gov/). Sample data for delta smelt were obtained from the California Department of Fish and Game (K. Fleming and K. Souza, pers. comm.).

Chinook salmon Although the focus is on endangered winter Chinook salmon, some calculations use information about other runs as well to increase the amount of usable data. Our general approach was to use recapture rates of coded-wire tagged (CWT) hatchery smolts released in or near the upper Sacramento River and recaptured at Chipps Island in the western Delta, and at the fish facilities in the south Delta. These recapture rates are used to calculate loss rates at the facilities and fish flux out of the Delta; the ratio of these is the proportional loss, which may be reduced through export curtailment using EWA. This is an estimate of direct loss only, and does not consider any losses due to altered hydrodynamic conditions or migration cues in the Delta, which we have no method to quantify.

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. Coleman National Fish Hatchery (CNFH) has released marked fall and late-fall Chinook smolts each spring since 1981, and we used some of these data to supplement the limited data for winter Chinook. Below we examine the data for differences between these sources. The marked fish have been recaptured at various locations in the Delta, allowing for estimates of the relative importance of losses at the south Delta water project intakes. Only fish released in the upper Sacramento River basin were used in this analysis. We estimated the flux of tagged fish past Chipps Island and the fluxes to the fish facilities for years starting with brood-year 1998. The statistic of interest was the estimated loss of tagged fish at the fish facilities as a percentage of the estimated total flux of fish passing through the system. This does not require knowledge of mortality patterns within the Delta or the details of alternative migration pathways.

The fundamental assumption underlying this approach is that the results determined using these hatchery fish are representative of the responses of naturally-spawned winter Chinook. We made the following additional assumptions throughout this analysis: 1) The fractional loss of CWT hatchery fish represents that of naturally-spawned winter Chinook; 2) Estimates of mortality factors at the fish facilities are accurate, and these factors are constant in time and with export flow; 3) Fish migrate past Chipps Island at the same speed as they do from Sacramento to Chipps Island; 4) Fish are randomly distributed across the Chipps Island channel in the top 4 meters, and migrate equally by day or night; 5) Sampling at Chipps Island and at the fish facilities is unbiased, and the net is 100% efficient; 6) All CWT fish have their tags read; and 7) "Indirect" effects of water exports, by which migrating salmon suffer additional losses due to changes in flow conditions in the Delta far from the pumps, are neglected since we have no way to estimate them. Possible biases introduced by these assumptions are discussed below.

Each year CWT smolts in several tag groups have been released on a single day (Table 1). LSNFH winter Chinook have been released between 27 January and 5 February except that fish were released on 9 April in 1998. CNFH late fall Chinook have been released in November through April, with one release in July 2005 which was not used in this analysis. We treated all groups of fish released on a single day as a single release. We show below that the fish from the two hatcheries were recaptured in similar patterns, justifying the use of CNFH data to bolster the rather limited data set from LSNFH.

Smolts were recaptured over various time intervals, with occasional stragglers recaptured weeks to months later than the others in the same group (Figure 2). Since flow and export conditions could change markedly through the season, these late captures had excessive influence on the calculations. To reduce the effect of the stragglers we used the estimated 90th percentile of migration date as the termination date for the migration. The same recapture period was used for both trawl and salvage recoveries of fish released on the same date. Thus, we used the cumulative passage of fish during each of these time intervals to determine the fraction lost to the export facilities.

Marked fish may enter the south Delta and move toward the export pumps, and some are then entrained into the south Delta fish facilities. The export facilities use louvers and screens to concentrate fish which are then trucked to release points in the Delta (Brown and others 1996). Samples are taken to identify and measure fish every 2 hours. Because of differences in operations, the samples average about 18% of the time of operation of the SWP and about 8% of the time of operation at the CVP. Salmon with clipped adipose fins are sacrificed and coded-wire tags are read. We calculated the total fish flux at each of the fish facilities and determined estimated losses as:

$$\Phi_i = N_0 - N_R$$
$$\hat{\Phi}_i = \hat{N}_0 - \hat{N}_R = \frac{24N}{h_i(1-F_{Pi})E_i} - \frac{24N}{h_i}(1-F_{HT}) \quad (3)$$

where symbols are defined in Table 2. Hats indicate estimated quantities Based on a series of experiments with marked juvenile Chinook salmon, the predation loss term L_P for the state facility is assumed always to be 75% , although the mean from the experiments was 85% and values ranged from 63 to 99% (Gingras 1997). Based on studies from the 1960s when the louvers were installed (Skinner 1974), the louver efficiency E is assumed to be 90%, and handling and trucking loss terms together amount to 4%. The predation loss term for the federal facility has been set at 15% without any justification other than observations that structures in water attract predators,and the fact that the State facility has a large forebay at the intake, presumed to enhance predation, whereas the federal facility pumps directly from the channel (Kimmerer and Brown 2006) .

Tagged fish are captured by the 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 time interval was extrapolated to a "fish flux" from the mean catch per volume and the migration speed past Chipps Island. The midwater trawl net is 4.6m deep and 9.1m 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 higher predation rates during daylight, so we are justified in assuming roughly equal passage at Chipps Island by day and night.

The fish flux was then calculated as:

$$\hat{\Phi}_c = D_s W Z u \tag{3}$$

where W, the width of the channel at Chipps Island, is 1000 m, and Z, the depth over which the fish are assumed to migrate, is 4 m. Previous analyses have used the time spent sampling to provide a time scale for migration (Brandes and McLain 2001); however, 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 4 was estimated by calculating the difference between the median times when release groups passed Sacramento and Chipps Island, about 100 km away, both as determined from trawl samples. The principal assumption of this approach is that the fish do not change speed much once they pass Sacramento and enter the Delta. We calculated a weighted mean speed in which the weighting factor was:

$$w = \frac{n_1 n_2}{n_1 + n_2} \tag{4}$$

where n_1 and n_2 are the numbers of fish collected at Sacramento and Chipps Island, respectively . Bootstrap analysis was used to determine confidence limits on this weighted mean speed.

For each release group we calculated losses from equation 3 as a fraction of the fish leaving the Delta either at the fish facilities or at Chipps Island. For untagged salmon the salvaged fish pass Chipps Island on their way to sea, and are therefore vulnerable to capture there, so the fractional loss is:

$$F = \frac{\hat{\Phi}_s + \hat{\Phi}_f}{\hat{\Phi}_c + \hat{\Phi}_s + \hat{\Phi}_f} \qquad \textbf{(5)}$$

where the subscripts s and f refer to the two fish facilities (state and federal). Tagged salmon that are salvaged and then counted are sacrificed so their tags can be read. Thus, a proportion of the salvaged, tagged salmon cannot be retrieved at Chipps Island, so the fractional loss is estimated from the counts of tagged fish at the fish facilities as:

$$\hat{F} = \frac{\hat{\Phi}_s + \hat{\Phi}_f}{\hat{\Phi}_c + \hat{\Phi}_s + \hat{\Phi}_f + \left(N_s + N_f\right)\left(1 - F_{HT}\right)} \tag{6}$$

where subscripts s and f have been added to terms for fish facilities from equation 1.

The sum of N_0 and the Chipps Island fish flux from equation 2 was taken as the total flux of fish to measuring points in the Delta; the loss divided by this flux was then the proportional loss of fish. This proportional loss was then related to export flow by a generalized linear model with weights equal to the root of the total number of fish caught for each release group, and with a poisson error distribution (McCullagh and Nelder 1989).

Several aspects of the above calculation support error propagation, and several do not. The principal sources of measurable uncertainty come from uncertainty in migration speed through the Delta (and therefore the fish flux at Chipps Island). Migration speed has a coefficient of variation of ~20%, so a similar magnitude of error would propagate to the calculated total fish flux. Variability in recapture rates results in uncertainty about fish fluxes at all sites, but is accounted for in the variability among release dates. Smaller sources of variability include error due to extrapolation of salvage counts to each 24-hour period, and variation in sampling effort at Chipps Island.

Several sources of uncertainty cannot be addressed using the available data. There may be substantial sources of bias or error at several points in the calculation, such as in: the estimate of migration speed past Chipps Island based on migration over a 100-km distance; the assumption that mortality of fish going through the Delta to the fish facilities is similar to that of fish going to Chipps Island; the various assumptions about salvage and loss, the key one being pre-screen mortality; the assumptions about vertical and temporal (including diel) distributions of fish; and the assumption about efficiency of the sampling net at Chipps Island. Since these sources of uncertainty are unquantified, I do not feel justified in propagating other sources of uncertainty through the analysis.

Delta Smelt I examined the catch of delta smelt by size and date at the two fish facilities to determine the seasons over which export losses are substantial. Two groups of delta smelt are prominent in the data from the fish facilities: adults from mid-December to mid-April, and juveniles from mid-April to mid-July (Figure 6). During August to mid-December the fish are too far seaward to be entrained in the facilities in substantial numbers. I therefore focused on losses of juveniles captured in the 20mm survey of late larvae and juveniles (Dege and Brown 2004), and adults captured in the spring Kodiak trawl survey (Bennett 2005).

Adults The general approach for adult delta smelt was to estimate the daily flux or entrainment rate of fish toward the export facilities, and divide this by the monthly estimated population size from the Kodiak trawl survey to get a daily loss rate. The daily loss rate can be considered a daily mortality; thus survival for one month was calculated my multiplying survivals for each day in the month as follows (using symbols in Table 2):

$$S_{mo} = \prod_{mo} \left(1 - \frac{F_d}{A_s} \right) \tag{7}$$

Survival over an entire season was calculated by multiplying monthly survivals. 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 three stations in the southern Delta, where the fish are most vulnerable to entrainment.

Principal assumptions were:
1. Efficiency of the Kodiak trawl is not too far from 1 (it need not be 1 exactly).

2. The Kodiak trawl takes a representative sample of the adult delta smelt population.
3. Fish in the south Delta are vulnerable to entrainment in the export facilities,
4. The flux of fish to the export facilities is proportional to the combined southward flow in Old and Middle Rivers, and zero when that flow is northward.
5. All delta smelt entrained toward the export facilities are lost from the population.
6. The efficiency of sampling by the fish salvage facilities is constant.
7. Abundance during December (when no Kodiak trawl survey is conducted) is the same as in the following January.

The Kodiak trawl program has taken surveys from January to May since 2002 but only the surveys using standard stations were included (surveys indicated by single digits). A total of 3-5 surveys were conducted per year during 2002 – 2005. Based on reported lengths all fish appeared to be adults except for those smaller than 45mm in May, which were eliminated. Catch per volume was calculated assuming a volume filtered of 6223 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.). Population size throughout the habitat was calculated as the mean catch per m^3 multiplied by the volume of habitat, about 1.5×10^9 m^3 (Kimmerer 2004). In the data from the fish facilities only fish larger than 40mm, or larger than 60mm in May, were included, because fish smaller than those lengths were clearly juveniles.

The daily entrainment of fish at the export facilities F_d is the daily catch divided by the fraction of the day sampled (i.e., the expanded catch C_i), corrected for pre-screen losses and losses through the louvers. This is assumed equal to the daily flow in the south Delta toward the export pumps times the mean abundance of delta smelt per unit volume in the south Delta:

$$F_d = \sum_{1,2} \frac{C_i}{E_i(1-F_{Pi})} = Q_{SD} D_{SD} \qquad (8)$$

The daily flow is the sum of southward flow in Old and Middle Rivers, which has been determined by the U.S. Geological Survey since 1987 (Ruhl and Simpson 2005, Ruhl et al. 2006). This flow is southward, toward the export facilities, most of the time; northward flows were set to zero before the above calculation was made since the flux of fish is expected to be only southward. Density per cubic meter of adult delta smelt in the south Delta was estimated by Kodiak trawl samples at three stations (numbered 902, 914, and 915). The expected catch in all three south Delta stations is then:

$$E(N_{SD}) = \frac{V_{FSD} E_k}{Q_{SD}} \sum_{1,2} \frac{C_i}{E_i(1-F_{Pi})} \qquad (9)$$

Based on a series of experiments with marked juvenile Chinook salmon, the predation loss term F_{P1} for the state facility is assumed always to be 75% , although the mean from the experiments was 85% and values ranged from 63 to 99% (Gingras 1997). The equivalent value for the federal facility has been assumed to be 15%. About 13% of the smelt that arrive at the federal facilities are counted in the salvage operation (M. Bowen, US Bureau of Reclamation, pers.

comm.). Using 13% for louver efficiencies and 75% and 15% for predation losses, the estimates of the above products $E_i(1-F_{Pi})$ are 3.2% and 11% respectively.

However, since there is only one analysis and we have two free parameters, we assume that the two efficiencies scale as the mean catch at the two facilities. For adult delta smelt from 1995 to 2005, on days when both facilities had non-zero catches (total of 235 days) the median ratio of the SWP catch to that at CVP was 0.67. Substituting and rearranging gives

$$E(N_{SD}) = \frac{V_{FSD}\theta}{Q_{SD}}\left(\frac{C_1}{0.67} + C_2\right) \tag{10}$$

where θ is a free parameter to be estimated, containing both the deviation of the Kodiak trawl efficiency from 1 and the deviation of the CVP salvage efficiency from 1.

The value of θ was estimated using the Kodiak trawl catches from the three south Delta stations. The model applied was:

$$\hat{N}_{SD} \sim Poisson[E(N_{SD})] \tag{11}$$

which was fit using a generalized linear model. Inserting the revised efficiency values with θ into equation 2 gives

$$F_d = \theta\left(\frac{C_1}{0.67} + C_2\right) \tag{12}$$

Values of F_d for each day in a month were inserted into equation 8 and divided by the monthly estimate of population size. Missing data from 32 days (mostly April-May 2004 when salvage rates were low) were replaced with the geometric mean F_d values for the respective year and month. Then the daily F_d values were multiplied out to get monthly survival (equation 8), and the monthly survivals were multiplied to get a seasonal survival, which was subtracted from 1 to get a cumulative loss for the season.

Juveniles The general approach here 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 to a seasonal loss involves several additional complications. The 20mm survey has sampled twice a month during March or April to July from 1995 through 2005, at up to 52 stations throughout the upper estuary (Dege and Brown 2004). We dropped surveys having fewer than 20 stations, and dropped stations in San Pablo Bay, where delta smelt are uncommon. We estimated the fractional loss from the delta smelt population to water exports in the south Delta for each 20-mm survey. We converted catch per tow to catch per unit volume assuming 100% net efficiency and 855 m^3 volume per tow. The fractional daily loss of fish to the export facilities based on a single survey was estimated as:

$$F_s = \left(\frac{N_{SDs}}{V_{SDs} A_s} \right) Q_{SD} \qquad (13)$$

with terms defined in Table 2 . Three stations (914, 915, and 918) in Old and Middle Rivers nearest the fish facilities were used to calculate N_{SDs}.

Principal assumptions for calculating daily loss are: 1) Delta smelt that arrive in the vicinity the export facilities are lost from the population; 2) The three south Delta stations provide CPUE estimates that are representative of the water going to the export facilities; 3) Mean CPUE is representative of the entire population. Assumption 1 seems likely since most of the smaller delta smelt go through the louvers at the fish facilities and are lost from the system. Assumption 2 is examined graphically below by comparing the pattern of captures of juvenile smelt in the net samples with those at the two fish facilities after correction for size selectivity of the respective gears. Assumption 3 is probably true for surveys of pelagic fish (Kimmerer and Nobriga 2005).

To calculate the total loss for the entire time period of the 20mm survey involves several complicating factors. Delta smelt hatch over a period of several weeks to months. The fractional loss to entrainment early in the season applies only to the fish that have hatched; therefore these losses must be discounted by the fraction that have not yet hatched. Furthermore, it can be shown that natural mortality (i.e., that not attributable to export pumping) suffered by the fish that hatch early requires a further discount of the fractional loss suffered by these fish. This occurs because the calculation is made up to a date after which vulnerability to export effects is considered negligible. Fish that hatch early suffer a longer period of mortality before this time, and therefore contribute less to the population. Since delta smelt appear to leave the delta when temperature rises above some threshold, the later-spawned delta smelt probably leave at a younger age than the earlier-spawned ones. Therefore the impact to the population of a given fractional loss of these early-hatched fish is smaller than that due to the same fractional loss of later-hatched fish.

Finally, since it is necessary to extrapolate back to the beginning of the hatch period, the low capture efficiency of the 20mm net for small larvae must be taken into account. Additional assumptions of the method used to extrapolate daily to seasonal losses (explained below) were: 1) Capture efficiency of the 20mm net can be described by a logistic function, increasing from 0 to 1 as fish length increases; 2) Fish hatch at a constant daily rate over some time period; 3) Daily mortality is constant from the beginning of the hatch period until the last survey; and 4)

Fish hatch at 5mm length and grow at 0.3 mm d^{-1} (Figure 6 in Bennett 2005; this is also the approximate mean value obtained by fitting straight lines to size at date data). The actual temporal distribution of hatching is not constant, but for purposes of this calculation the difference is minor. Daily mortality cannot be distinguished from a decrease in net efficiency as the fish grow and begin to avoid the net, but it makes no difference for these calculations.

I determined a correction for inefficient capture of smaller fish as a logistic function of size of the fish:

$$E_L = \left(1 - \frac{1}{1 + ae^{bL}}\right) e^{kL} \qquad (14)$$

The logistic part of this equation in parentheses is small at small size and increases sigmoidally to 1 at large size. The other term combines growth and mortality (or declining efficiency) to express the decreasing catch as fish grow. The parameters of this function were determined by using a least-squares optimization procedure (function *optim* in S-Plus, Venables and Ripley 2002) to fit this equation to the overall length frequency distribution using all data. The parameters of the resulting curves gave a median capture efficiency of 10% at 9mm length, 50% at 15 mm, and 90% at 21mm. This is consistent with the target length of 20mm for delta smelt in the survey.

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

$$\begin{Bmatrix} N_{L,t} = H\ e^{-m(t-T)}, T_1 \le T \le T_2 \\ N_{L,t} = 0, \qquad T < T_1 \ or\ T > T_2 \end{Bmatrix}, \qquad (15)$$
$$L = (t - T)g$$

which describes the number of fish on each day t given that H fish hatched at time T during an interval (T_1, T_2), with constant growth rate g and mortality rate m. Note that the daily hatch rate H cancels out of calculations of fractional losses, so this is an arbitrary parameter that was set to 1. The calculated values of $N_{L,t}$ were adjusted for inefficient sampling of small fish using the logistic function from equation 15 before fitting the data using a least-squares optimization procedure to determine T_1, T_2, and m.

The fractional loss for each survey was determined from equation 14. To determine daily losses F_d from the fractional loss by survey, I interpolated the term in parentheses in equation 14 for days between surveys, and extrapolated the fraction for the first survey back to the calculated first hatch date. These fractions were then multiplied by the daily value of Q_{SD}, the southward flow in Old and Middle Rivers. The resulting daily fractional loss is a mortality rate and comprises part of the mortality m determined using equation 16, since that is determined by the rate of decline of abundance. Natural mortality (i.e., mortality not due to export losses) was calculated as the difference between mortality determined using equation 16 and the effective mortality due to export effects:

$$m_n = m + \overline{\log(1 - F_d)} \qquad (16)$$

where the average was taken over the entire season from T_1 to the last survey. The resulting mortality values were highly variable among years and probably represent only a crude approximation, because of great uncertainty in both terms of equation 18. I used the mean of the mortality values for all years in the subsequent calculations, but made parallel calculations with no mortality for comparison.

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

$$S_i = \prod_{T_i}^{T_f} e^{(m_n + F_d)} \qquad (17)$$

The fractional loss of fish on final day T_f is then determined from the abundance of all cohorts on that day divided by the abundance in the absence of export losses:

$$\hat{F} = 1 - \frac{H \sum_j \prod_{T_j}^{T_f} e^{-(m_n + F_d)}}{H \sum_j \prod_{T_j}^{T_f} e^{-m_n}} \qquad (18)$$

The calculation was run for each year of the 20mm survey separately to determine a fractional loss. Equation 20 can also be used to calculate fractional losses for any hypothetical export flow by calculating the resulting Old and Middle River flow by difference, assuming the distribution of delta smelt does not change with the changes in Old and Middle River flow.

Results

Winter Chinook The capture of individual marked fish at Chipps Island and the fish facilities typically lasted for ~1 month, with the capture rate usually high for about half of the time and then gradually declining (Figure 4). 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 or at either of the fish facilities. Mean swimming speed of fish passing

Chipps Island was estimated to be 16 km d^{-1} (95% confidence limits 10 - 23) for fish migrating in winter, and 24 km d^{-1} (95% confidence limits 14 – 32) for fish migrating in spring.

The proportion of migrating fish lost at the export facilities increased with increasing export flow (Figure 5). The median was 1.2% (10^{th} and 90^{th} percentiles were 0 and 9% respectively), and two anomalously high values (>20%) were from small samples (5 and 42 total fish).

All of these calculations refer to direct losses only. If there actually are indirect losses as discussed above, these would be in addition to the direct losses. Indirect losses have not been estimated, nor has a method been developed to estimate them.

The many assumptions necessary to calculate proportional losses can be criticized, but in many cases we lack data to assess the extent of violations of these assumptions. The most important assumptions are those that link the calculations of fish flux at Chipps Island to that at the fish facilities. Since the Chipps Island flux is determined using nets, and that at the export facilities using salvage, any difference 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).

Another potential source of error is that survival probability of fish passing through the Delta on the way to the fish facilities may differ from that for fish that go past Chipps Island. Salmon smolts released at Georgiana Slough in the interior Delta generally have lower survival than those released in the Sacramento River (Brandes and McLain 2001, Newman xxx). Because of the multiple pathways for movement of fish, these results are not directly applicable to survival from the Sacramento River to the fish facilities and Chipps Island. Furthermore, alternative pathways taken by the smolts are probably independent of export flow and therefore not attributable to export pumping. Flows into the Delta Cross-Channel and Georgiana Slough have been modeled as functions of Sacramento River flow only (Dayflow documentation).

To refine the above estimates would require two key pieces of information. The first is an estimate of the efficiency of the Chipps Island midwater trawl. The second is some alternative estimate of the effect of export flow on survival of winter Chinook through the Delta. 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 2005).

Delta Smelt Adults

Monthly population estimates showed a decline beginning ~ March, as the adults spawn and die (Figure 5A). Daily estimates of entrainment losses begin in mid-December, peak in January, and then decline sharply (Figure 5B) as the population declines and the southward flow in Old and Middle Rivers decreases (Figure 5C).

The calculated value of θ was 18.2 ± 7.7 (95% confidence limit, 14 df). This could indicate that the Kodiak trawl was more efficient than 1, or that the ratio of catch to entrainment at the fish facilities was less than the value discussed above, but these possibilities cannot be distinguished. A conservative estimate is that the Kodiak trawl was 100% efficient, and that more fish were entrained than expected. This is conservative in the sense of giving a higher estimate of fractional loss than if the Kodiak trawl were assumed >100% efficient.

With the estimated value of θ the cumulative loss over the season ranged from 2% to 7.5% (Table 3). If the upper confidence limit of θ is used, the values range from 2.7% to 10.4%. These confidence limits are somewhat underestimated because sampling error in the Kodiak trawl survey could lead to higher or lower estimates of population size. The confidence limits presented, however, include error that may at least partially be due to systematic error in estimating the efficiency of the salvage process which applies to all estimates.

The variability among years in cumulative loss did not appear to be related to flow conditions (by inspection).

<u>Delta Smelt Juveniles</u>

Several of the assumptions made for these calculations can be tested. First, net flow in Old and Middle River appears to be a controlling factor for flux of delta smelt to the export facilities (Figure 6). Salvage was greater than zero on only a few occasions when this flow > 0, and most of those occurred during brief transients in flow. A positive net flow in Old and Middle River occurs when all export flow is supported by flow from the San Joaquin River, where delta smelt are uncommon.

A fixed termination date was assumed to apply to all cohorts in a given year. Data from all years show the increase in length over time for fish collected in two salinity ranges (Figure 7). After late May the median length of the fish at low salinity diverges from that at higher salinity, suggesting that later cohorts may enter brackish water somewhat after the earlier cohorts. Thus, this assumption was violated to some degree. If all cohorts entered brackish water at the same age or size, then the correction for natural mortality would be inappropriate. Below I explore the consequences of setting natural mortality to zero.

Delta smelt are collected at the fish facilities, but at a larger size and a later time than in the south Delta sampling stations. This is at least partly due to the differences in length biases of the fish facilities compared with the net (Figure 8). Fish smaller than 20mm, which made up the bulk of the net samples, are not counted in the salvage facilities.

By scaling the 20mm survey down according to the ratio of salvage:net efficiency shown in Figure 8, it is possible to compare these sampling devices directly. Examples (Figure 9) show the pulses in catch at the two fish facilities, which are roughly reflected in the size-corrected abundance data from the south Delta. This comparison is crude, and fails to account for gross efficiency of any of the sampling devices, but suffices to show that the net samples in the south Delta are probably sampling the same population as the fish facilities.

The fits of the model (Equation 16) for each year were variable; of course the model failed to capture peaks in abundance (Figure 10), but the trends through the season were satisfactory. Modeled hatch dates were fairly consistent from year to year, but mortalities were highly variable (Table 4).

The proportional loss during each 20mm survey shows a broad peak centered ~early April (Figure 11). Losses were low after mid-May and zero after mid-June. Most of the losses appear as sharp peaks, which occurred around the middle of each cohort.

The seasonal or annual proportional loss $\hat{F}$ was also highly variable among years and roughly followed the maximum daily loss for each year (Figure 12). During the dry years 2001-2003 the losses were ~25%. Setting the natural mortality to zero raised the highest percentage loss to 37% (Figure 12). The variation in annual loss was related to flow conditions but this relationship is somewhat tautological: since Old and Middle Rivers flow southward only under dry conditions, the calculated loss of delta smelt can only be high under those conditions.

References

TBA

Figure Captions

1. Map of the San Francisco Estuary showing locations mentioned in the text. Red arrows indicate migration pathways for winter Chinook salmon.
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.
3. Chinook salmon. Relationship of estimated percent loss of tagged smolts at the fish facilities to export flow. Area of the symbols is proportional to the total number of fish counted (maximum 1032). The regression line is a generalized linear model with poisson error variance, and with a weighting equal to the total fish counted.
4. 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. Note that larvae smaller than 20mm are generally not counted. Very few fish were caught between July and mid-December.
5. Adult delta smelt. A, Estimated population size based on the Kodiak trawl survey. B, Daily losses to the fish facilities, corrected for the difference in capture efficiency of the Kodiak trawl and 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).
6. Juvenile delta smelt in the fish facilities. Daily salvage for each of 9 years vs. net flow in lower Old and Middle Rivers (positive northward).
7. Larval and juvenile delta smelt. Length distribution and median lengths for smelt collected in the 20mm survey for 1995 – 2005 for salinity above or below 0.4 Symbols areproportional to the numbers of smelt collected.
8. Larval and juvenile delta smelt. Length distributions for all fish caught in the 20mm survey or in salvage, shown on different scales (left) so relative abundances overlap at ~30mm. Also shown is the ratio of capture efficiency of the salvage sampling to the net sampling.
9. Delta smelt. Examples comparing abundance of young fish in the 20mm survey and in the two fish facilities. Data from the 20mm survey have been corrected by the relative capture efficiency of the fish facilities (green line in Figure 8) to allow direct comparison.
10. Larval and juvenile delta smelt. Data and model prediction for total population abundance for each 20mm survey divided by the sum of population abundances in all surveys.
11. Seasonal pattern of daily fractional loss from the delta smelt population with symbols and colors for each year.
12. Estimated annual losses to export pumping of delta smelt from the 20mm survey. Black line gives the estimated loss allowing for mortality, whereas the red line uses an estimate of mortality reduced by the export losses. The blue line (right axis) gives the maximum percent loss determined in a single survey for each year.
13. Larval and 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. Estimates of actual delta smelt losses are plotted against predictions from the same model, with numbers indicating years.

Table 1. Chinook salmon. Summary of data from mark-recapture studies. Only data from releases in winter were used in this study.

Source	Brood Year	Release Date	Recapture Dates Initial	Recapture Dates FInal	Number Released	Catch Chipps Is.	Catch SWP	Catch CVP
C	1997	11/10	11/26	2/19	133975	21	7	4
C	1997	12/9	12/19	3/16	125250	34	13	8
C	1997	1/12	1/18	3/7	61048	25	0	1
C	1997	1/13	1/19	3/13	188628	62	0	0
C	1997	1/14	1/20	3/14	188761	53	0	3
C	1997	1/22	1/27	3/18	117191	31	0	3
C	1997	3/4	3/25	5/12	131141	33	0	0
C	1997	3/6	3/27	5/10	71869	22	0	0
C	1997	3/31	4/16	5/21	268821	160	0	0
C	1997	4/7	4/19	5/28	132885	86	0	0
C	1997	4/22	4/28	5/30	243842	333	0	0
C	1997	4/23	5/1	6/1	66929	52	0	0
C	1998	11/12	11/24	1/30	137993	31	1	0
C	1998	12/15	12/22	3/23	127224	48	1	1
C	1998	1/4	1/11	4/18	505948	108	5	1
L	1998	1/28	3/15	4/18	106142	18	8	0
C	1998	3/31	4/29	5/9	29869	3	0	0
C	1998	4/20	4/26	5/18	264077	158	5	0
C	1998	4/21	5/1	5/21	94945	36	0	0
C	1998	4/27	5/5	5/28	398293	131	3	2
C	1998	4/28	5/5	5/13	68208	27	0	0
C	1999	11/12	11/27	1/28	70500	5	2	1
C	1999	12/9	12/20	2/18	75948	15	8	3
C	1999	12/21	1/3	2/18	83383	9	5	0
C	1999	1/4	1/19	4/1	496853	51	63	28
C	1999	1/12	1/21	3/19	81680	13	8	6
L	1999	1/27	2/22	4/30	5459	3	1	0
C	1999	4/7	4/15	4/27	67912	49	1	0
C	1999	4/14	4/20	5/12	406189	255	2	0
C	1999	4/21	4/26	5/23	450020	254	0	0
C	2000	11/3	12/11	1/19	58050	5	1	2
C	2000	12/8	12/25	2/26	54568	0	4	1
C	2000	1/2	1/17	3/24	365425	53	49	18
C	2000	1/9	1/20	3/15	65284	11	8	4
L	2000	2/1	3/5	4/4	37113	7	2	0
C	2000	4/13	4/23	5/11	858838	184	0	1
C	2000	4/27	5/7	5/27	888937	214	2	0
C	2001	11/14	11/28	4/8	88039	10	4	4
C	2001	12/12	12/21	2/14	73856	8	23	5
C	2001	1/4	1/10	3/7	65237	55	14	6
C	2001	1/8	1/14	3/30	538226	279	155	50
L	2001	1/30	3/7	5/3	158285	21	2	2
C	2001	4/18	4/25	5/14	978004	414	2	0

C	2001	4/25	5/3	5/28	980986	288	0	0
C	2002	11/8	12/6	1/6	67650	13	4	3
C	2002	12/2	12/18	3/12	119306	49	80	29
C	2002	1/2	1/8	3/7	467010	161	653	218
C	2002	1/15	1/22	3/19	74760	20	46	15
L	2002	1/30	2/14	4/10	184080	28	24	12
C	2003	11/28	12/11	2/27	136522	37	16	6
C	2003	12/31	1/8	3/11	345853	164	329	81
C	2003	1/2	1/8	3/16	193906	136	218	67
C	2003	1/30	2/11	3/12	64983	2	35	6
L	2003	2/5	2/20	4/2	171584	18	26	5
C	2003	4/16	4/24	5/13	142798	57	0	0
C	2004	11/5	12/10	1/2	87000	3	0	1
C	2004	11/29	12/14	1/28	69993	23	1	1
C	2004	1/4	1/11	2/28	413207	229	123	19
C	2004	1/13	1/27	2/25	69795	6	24	1
L	2004	2/3	2/22	3/30	124409	18	1	1

Table 2. Definition of terms used in the models for Chinook salmon (C) and delta smelt (D). Terms are unitless unless stated.

Term	Species	Definition
A_s	D	Total abundance of fish caught in a given trawl survey s or month mo
C_i	D	Expanded catch per day for facility i (1=SWP, 2=CVP)
D_s	DC	Abundance (density) in fish per m^3 in survey s
E_i	DC	Louver efficiency of facility i
E_k	D	Efficiency of Kodiak trawl
E_L	D	Efficiency of the 20mm net as a logistic function of length of fish
F	D	Fraction of fish lost to export facilities through the season
F_d	DC	Fraction of fish lost to export facilities on a single day (d^{-1})
F_{Pi}	DC	Fraction of fish lost (e.g., through predation) in front of louvers for facility i
F_s	D	Fraction of fish lost to export facilities on the day of survey s
F_{HT}	C	Fraction of fish lost to handling and trucking mortality
h_i	C	Number of hours sampled in fish facility i
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})
N	C	Number of fish counted at a fish facility during a day
N_0	C	Number of fish arriving at a fish facility per day (d^{-1})
N_R	C	Number of fish successfully released from a fish facility per day (d^{-1})
$N_{L,t}$	D	Number of fish of length L at time t
N_{SDs}	D	Total fish caught in trawl survey s in the south Delta
P_t	D	Proportional contribution to eventual population of fish hatched by day t
Q_{SD}	D	Daily flow to the south Delta (= Old and Middle River flow)
S	D	Survival (fraction)over some time period indicated by subscript, e.g. mo (month),
t	D	Any day between T_0 and the final date of the simulation (d)
T_0	D	Initial hatch date (d)
T_1	D	Final hatch date (d)
T_f	D	Final day of survey
T_j	D	Hatch date of daily cohort j
Z	C	Depth over which salmon are assumed to migrate (m)
V_{SDs}	D	Total volume filtered in survey s at 3 South Delta stations (m^3)
θ	D	Free parameter to be estimated by regression
Φ_c	C	Flux of fish past Chipps Island
u	C	Migration speed (m d^{-1})
W	C	Width of Chipps Island channel (m)

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

Year	Cumulative % loss	Confidence limits
2002	3.2	1.8– 4.5
2003	7.5	1.3 – 10.4
2004	5.0	2.8 – 6.9
2005	2.0	1.1 - 2.7

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

	Natural mortality	Hatch dates	
Year	m_n, d^{-1}	Earliest (T_1)	Latest (T_2)
1995	0.007	03/13	05/22
1996	0.034	03/14	05/20
1997	0.032	03/11	05/13
1998	0.016	03/15	05/21
1999	0.037	03/11	05/31
2000	0.031	03/15	05/22
2001	0.003	03/12	05/12
2002	0.028	03/17	05/25
2003	0.014	03/16	05/29
2004	0.023	03/15	05/24
2005	0.026	03/16	05/23