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Pre-Screen Loss and Fish Facility Efficiency for Delta Smelt at the South Delta's State Water Project, California

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Keywords:

fish entrainment, *Hypomesus transpacificus*, mark-recapture, salvage, calcein, photonic, water diversion, reservoir, predation, temperature

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Abstract:

Water exports have been implicated in the decline of fish populations in the upper San Francisco Estuary, California. We evaluated the relation between delta smelt salvage at the John E. Skinner Delta Fish Protective Facility (SFF) and underlying entrainment losses at the State Water Project (SWP, south Delta). We used cultured delta smelt in mark–recapture experiments in February and March 2009 (adults) and June 2009 (juveniles) to estimate: (1) the percent of fish recaptured at the SFF of the total released at the entrance of the SFF (fish facility efficiency), (2) the percent of fish recaptured at the SFF of the total released in Clifton Court Forebay (CCF), a reservoir for SWP exports, and (3) the fish losses in CCF and before the SFF (pre-screen loss). Mean fish facility efficiency was lower in successive releases: February (53.2%), March (44.0%) and June (24.0%). The mean percent recapture of fish released at the CCF entrance was also lower over time: February (3.01%); March (0.41%) and June (0.03%). Correspondingly higher mean pre-screen losses occurred over time: February (94.3%); March (99.1%) and June (99.9%). We concluded that: (1) entrainment losses of delta smelt could be higher at times, compared to other species previously studied at the SWP; (2) pre-screen loss was the largest source of mortality for delta smelt; (3) increased release distance from the SFF and residence time in CCF—and decreased exports—resulted in a lower percentage of recaptured fish at the SFF; and (4) salvage of delta smelt at the SWP does not seem to be a consistent index of entrainment.



Pre-Screen Loss and Fish Facility Efficiency for Delta Smelt at the South Delta's State Water Project, California

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ABSTRACT

Water exports have been implicated in the decline of fish populations in the upper San Francisco Estuary, California. We evaluated the relation between delta smelt salvage at the John E. Skinner Delta Fish Protective Facility (SFF) and underlying entrainment losses at the State Water Project (SWP, south Delta). We used cultured delta smelt in mark-recapture experiments in February and March 2009 (adults) and June 2009 (juveniles) to estimate: (1) the percent of fish recaptured at the SFF of the total released at the entrance of the SFF (fish facility efficiency), (2) the percent of fish recaptured at the SFF of the total released in Clifton Court Forebay (CCF), a reservoir for SWP exports, and (3) the fish losses in CCF and before the SFF (pre-screen loss). Mean fish facility efficiency was lower in successive releases: February (53.2%), March (44.0%) and June (24.0%). The mean percent recapture of fish released at the CCF entrance was also lower over time: February (3.01%); March (0.41%) and June (0.03%). Correspondingly higher mean pre-screen losses occurred over time: February (94.3%); March (99.1%) and June (99.9%). We con-

cluded that: (1) entrainment losses of delta smelt could be higher at times, compared to other species previously studied at the SWP; (2) pre-screen loss was the largest source of mortality for delta smelt; (3) increased release distance from the SFF and residence time in CCF—and decreased exports—resulted in a lower percentage of recaptured fish at the SFF; and (4) salvage of delta smelt at the SWP does not seem to be a consistent index of entrainment.

KEY WORDS

Fish entrainment, *Hypomesus transpacificus*, mark-recapture, salvage, calcein, photonic, water diversion, reservoir, predation, temperature.

INTRODUCTION

Water regulation and withdrawals contribute to habitat and population fragmentation and degradation (Dynesius and Nilsson 1994; Aparicio and others 2000) and affect multiple trophic levels (Arthur and others 1996; Jassby and others 2002; Kennish 2002; Moyle and Williams 1990; Gumpinger and Scheder 2008). Although water diversions for urban and agricultural uses have long been a common feature of aquatic ecosystems, the long-term implications of reduced freshwater inflow and increased entrainment losses on aquatic organisms present challenging management trade-offs for ecosystem sustainability and water use reliability (e.g., Lund and others 2010;

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Vörösmarty and others 2010). Because of record low fish population abundance indices for several pelagic species since the early 2000s (Feyrer and others 2007; Sommer and others 2007; Messineo and others 2010), water allocation has become increasingly critical for the Delta of the upper San Francisco Estuary (hereafter the Delta), one of the most intensively water-managed estuarine systems in the world. The water diversions by the State Water Project (SWP) and Central Valley Project (CVP), including water export from the south Delta for agricultural, industrial, and urban use, have long been considered factors that contribute to the decline of fishes in the upper San Francisco Estuary (Erkkila and others 1950; Stevens and Miller 1983; Moyle and others 1992; Arthur and others 1996; Bennett and Moyle 1996; Sommer and others 2007; Grimaldo and others 2009).

The operation of the SWP and CVP results in entrainment of aquatic organism, that is, the incidental removal of a variety of species in the water diverted from the estuary. Limiting entrainment losses is a major fisheries management goal in the Delta, particularly for listed species such as the delta smelt (*Hypomesus transpacificus*), an endemic osmerid and predominantly annual species. Delta smelt was listed as threatened (federal and state) in 1993. The state of California up-listed the delta smelt to endangered in 2009. Delta smelt was also deemed to warrant federal endangered status in 2010, but was precluded from a status change because of other listing priorities (Federal Register 2010).

The SWP and CVP use fish facilities to collect a fraction of the fish that are entrained, which is termed salvage (the estimated number of fish that are recovered at a fish facility for re-introduction in the estuary). Salvage comprises one of the largest historical databases on Delta fish species. Salvage has been used to evaluate the effects of new facilities and programs and proposed water project operations and as index of fish entrainment by the SWP and CVP in the south Delta (e.g., Moyle and others 1992; Brown and others 1996; Bennett 2005; Hymanson and Brown 2006; Grimaldo and others 2009). Salvage data from the SWP's John E. Skinner Delta Fish Protective Facility (SFF) has been commonly used as

an index of direct entrainment of some fish, including delta smelt, into Clifton Court Forebay (CCF), a SWP reservoir located in the south Delta (37.8298°N, 121.5574°W, [Figure 1](#)).

A percentage of the fish entrained into CCF is lost and unable to reach the screens of the SFF. Such loss has been termed pre-screen mortality or pre-screen loss (Tillman 1993; Brown and others 1996), ([Figure 2](#)). Results of 11 studies conducted for juvenile fishes between 1976 and 2007 in CCF (Chinook salmon, striped bass, and steelhead) revealed consistently high pre-screen losses ranging from 63% to 99% (Gingras 1997; Clark and others 2009). Pre-screen loss excludes the loss from the partial collection of fish entering the fish facility, which is termed fish facility efficiency. In the case of delta smelt, lack of empirically derived pre-screen loss estimates and fish facility efficiency at the SWP are an important source of uncertainty in interpretations of salvage data, in terms of effectiveness at screening fish (Brown and others 1996) or losses to the populations (Kimmerer 2008). Thus, there is a critical need for empirical estimates on the magnitude of the entrainment that results from pre-screen loss and fish facility efficiency. Complementary information derived from hydrodynamic particle entrainment models, fish surveys, and water quality data have also been used to infer fish entrainment by the SWP and CVP (Kimmerer 2008; USFWS 2008a). Process-oriented methods are still needed to validate these indirect methods.

We conducted the first mark-recapture experiments to assess entrainment losses of delta smelt at the SWP. We investigated two key sources of entrainment losses of delta smelt at the SWP: fish facility efficiency and pre-screen losses in CCF, as defined earlier. Other factors can reduce the survival of delta smelt following salvage, including injury and mortality from collection, handling, transport, and release (e.g., Miranda and others 2010; Morinaka, in press). In addition, potential effects from water diversions occur as a result of environmental changes in the estuary (e.g., Feyrer and others 2007; Nobriga and others 2008; Moyle and others 2010). None of these factors are included in the fish loss estimates considered here.

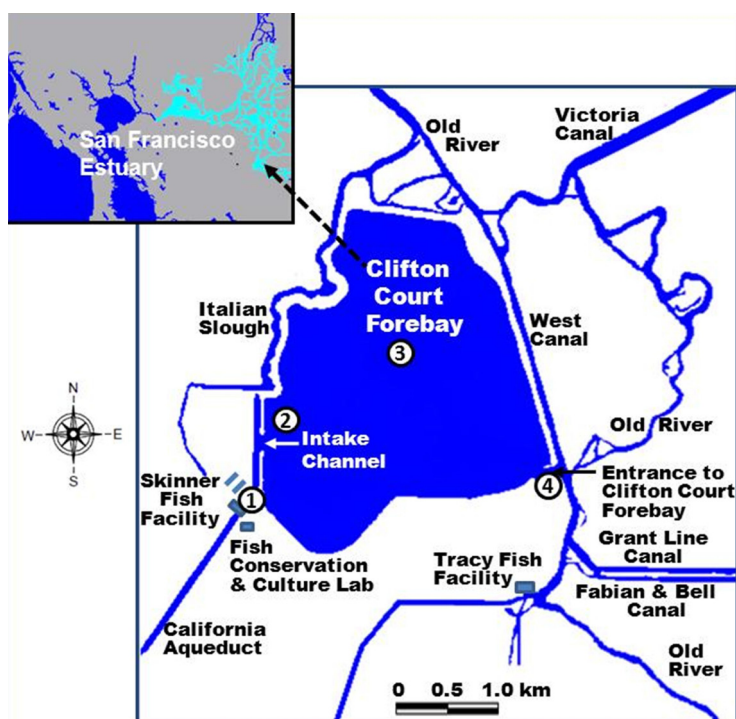
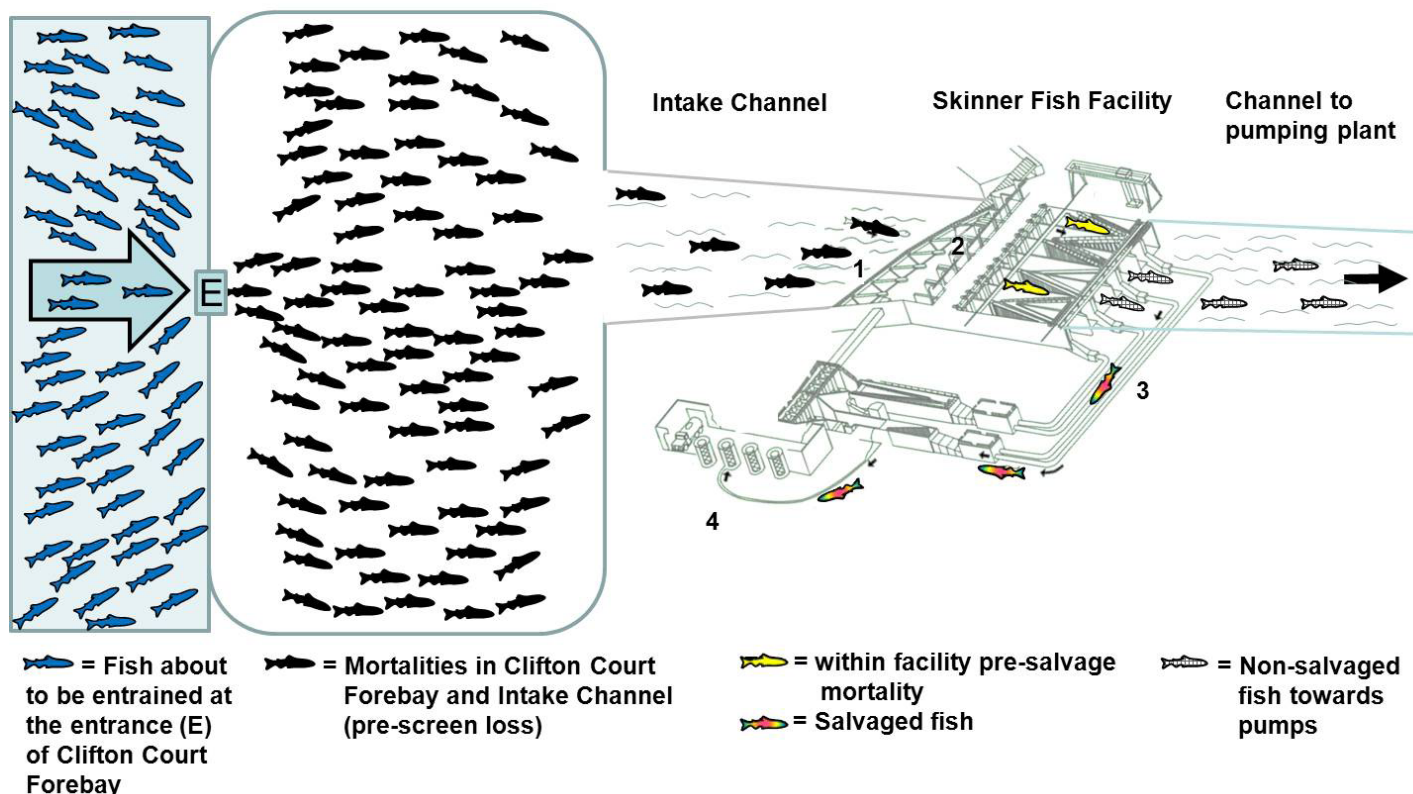


Figure 1 (left) Location of Clifton Court Forebay (CCF) and the John E. Skinner Delta Fish Protective Facility (SFF) in the south Delta of the upper San Francisco Estuary. Locations denoted by numbers are release sites: (1) entrance to the SFF; (2) west-CCF; (3) mid-CCF and 4) east-CCF (CCF entrance). Light color in the upper San Francisco Estuary denotes the general distribution of delta smelt. Source: DFG-IEP.

Figure 2 (below) Conceptual schematics (not to scale) of the hypothesized fate of 100 fish entrained into Clifton Court Forebay assuming a pre-screen loss of 90% and a fish facility efficiency of 30%. Also shown are release and recapture areas at the Skinner Fish Facility used in the present study: (1) trashboom; (2) trash rack (fish release area) in front of the primary louvers; (3) bypass pipes toward the secondary channel with louvers/screens; (4) holding tanks where fish are collected (recapture area). Only shown are the holding tanks for the old building. Source: CDWR.

South Delta

Clifton Court Forebay



The objectives of this study were to obtain mark-recapture estimates for the: (1) fish facility efficiency for juvenile and adult delta smelt at the SFF, (2) percent of marked juvenile and adult delta smelt released in CCF and recaptured at the SFF, and (3) pre-screen loss for juvenile and adult delta smelt.

Study Area

Clifton Court Forebay is a 38.24 million m³ reservoir (31,000 acre-feet) primarily used for off-peak pumping storage (i.e., it stores diverted water so that most export pumping can occur at night when electricity is less costly) (Figure 1).

The original SWP operations in the south Delta began in late 1968 and did not utilize CCF. Fish were initially entrained directly into the SFF (Heubach ca. 1973; Kano 1990). The CCF became operational in November of 1969 by connecting the end of the original intake channel to the reservoir. Inflow into CCF is regulated by five radial gates (hereafter, CCF entrance) positioned side by side at the southeast corner of the reservoir, with a combined operational limit of 339.8 m³ s⁻¹ (12,000 cfs).

Water circulation patterns in CCF are largely driven by the interaction of wind and the operation of the CCF entrance, and by the operation of the pumping plant that exports water from CCF (Kano 1990; M. MacWilliams and E. Gross, River Modeling, unpublished data). The minimum distance from the CCF entrance to the SFF is 4.0 km (Figures 1, 2).

The Tracy Fish Facility (TFF) and the SFF share some design elements and were originally designed to salvage juvenile Chinook salmon (*Oncorhynchus tshawytscha*) and striped bass (*Morone saxatilis*), (Brown and others 1996). Delta smelt were not the focus of the design criteria. The smaller juvenile delta smelt (<30 mm FL) are particularly under-sampled in the salvage process at these fish facilities (Kimmerer 2008; Morinaka, in press).

METHODS

I. Culture and Marking

All delta smelt used for this study were produced at the U.C. Davis Fish Conservation and Culture Lab (FCCL). The FCCL is located adjacent to the SFF and is a short distance from release locations used throughout this study (Figure 1). Delta smelt were spawned during 2008 to provide ca. 4,000 juveniles for the June 2008 experiments (size range: 20 to 44 mm FL), and 11,200 adults for the February to March 2009 experiments (size range: 47 to 90 mm FL). Additional delta smelt were spawned in 2009 to provide ca. 16,200 juveniles for the June 2009 experiments (size range: 20 to 41 mm FL). Production of delta smelt was based on rearing methods developed at the FCCL (Baskerville-Bridges and others 2004). Fish marking was conducted at the FCCL and involved two types of marks: (1) calcein (Sutphin and Morinaka 2010; G. Castillo, USFWS, unpublished data)—SE-MARK™ Calcein was the primary mark used for all juvenile and adult delta smelt—and (2) photonic marks, used in all adult delta smelt to differentiate days and/or location of fish releases (Sutphin 2008; G. Castillo, USFWS, unpublished data).¹

A calcein detector (SE-MARK™, Western Chemical) was used to distinguish calcein-marked fish from unmarked fish. Calcein marking protocols consisted of: (1) a 3-minute bath (full immersion) in a 1% salt solution and 40 mg L⁻¹ ms-222 (pre-treatment) and (2) a 5-minute bath in calcein (treatment): 5.0 g L⁻¹ (adults) and 2.5 g L⁻¹ (juveniles), (USFWS 2008b). Previous marking trials revealed 100% mark retention for at least 3 months (G. Castillo, USFWS, unpublished data).

Fish were photonically marked using pressurized CO₂ guns (model BMX2000 POW'R-Ject, New West Technologies) and BMX2000 BioPhotonic Marking Solutions (cobalt green, cobalt blue, and titanium white). Only adult delta smelt were marked photoni-

¹ Trans-generational marking (Hobbs and others 2012) was further required for all adult delta smelt to resolve concerns of the California Department of Water Resources (CDWR) that the offspring of released adult delta smelt into CCF would count against their Endangered Species Act-mandated take limits.

cally because preliminary tests showed increased mortality for juveniles. Most photonic marks were readily visible by direct observation of fish in a petri dish. We also used the SE-MARK™ detector or a stereomicroscope when photonic marking required further verification. We observed 100% retention of photonic marks in all recaptured calcein-marked adults released in February and March 2009.

All recaptured delta smelt were independently examined for calcein and photonic marks by at least two people. All unmarked delta smelt were considered wild fish.²

In response to seasonal temperature increases, juvenile fish were acclimated to ambient temperatures 1 week before their release at the SFF and CCF in June 2008 and 2009.

II. Fish Releases

We released juvenile and adult fish during actual export conditions to assess fish facility efficiency and pre-screen loss (Table 1, Figure 1). Releases to estimate fish facility efficiency at the SFF were conducted at the trash rack, a debris screen located in front of the primary louvers (hereafter, the SFF entrance, location 2 in Figure 2).

Five-gallon black buckets secured with a rope in the handle and another rope attached to the bottom of the bucket were used to lower the bucket from the elevated walkway and to empty the bucket just above the water surface.

We assessed partial pre-screen loss by releasing juvenile delta smelt in west CCF (near the intake area) and mid-CCF locations, which are closer to the SFF relative to the east CCF location (near the entrance area) (Figure 1). Marked juveniles were transported by boat, in two, 20-gallon carboys (west CCF) and in five, 20-gallon carboys (mid-CCF) and released mid-day in June 2008 (Table 1).

In 2009, adult and juvenile fish were released from the boat ramp adjacent to the CCF entrance to assess the percent recapture at the SFF, and to estimate pre-screen loss (Figure 1, Table 1). Fish were released in CCF in the early afternoon hours in February, March, and June, concurrent with normal water export operations.

III. Release Controls

Control groups of marked fish were held in tanks at ambient water temperature to compare to post-release survival of marked fish. Water was pumped to the control tanks from the export channel immediately downstream of the primary louvers of the SFF. Control fish were fed daily and held in 235-gallon circular tanks (122-cm diameter by 76-cm height) at the FCCL. Tanks were covered with shade cloth to protect fish from avian predators. Controls were terminated after no fish were recaptured at the SFF for at least a week.

IV. Data Analyses

Fish Recapture

All recaptured delta smelt were collected at the SFF, irrespective of release site (Figures 1, 2). We used two estimates to quantify the number of delta smelt recaptured (N_{rec}). The first recapture estimate is:

$$N_{rec'} = C \cdot \left[\frac{P}{D} \right] + S \quad (1)$$

where C is the number of marked delta smelt in regular CDWR counts, P is the collection period, D is the duration of the counts—usually 25% of the collection period during our experiments—and S is the number of marked delta smelt in weekly CDWR predator removal operations in the secondary channel (Figure 2). No attempt was made to count the delta smelt in the stomach contents of predators in the secondary channel (Figure 2).

² No trans-generationally marked juvenile delta smelt were detected in salvage operations at the SFF during the 2009 juvenile salvage season (J. Hobbs, University of California, Davis, unpublished data).

Table 1 Purpose of delta smelt mark-recapture experiments conducted at the SWP in 2008–2009. Releases at the entrance of the SFF (Area 1) are denoted as SFF0 to SFF3. Releases in CCF included: Area 2 (west CCF, near intake channel), Area 3 (mid-CCF), and Area 4 (east CCF, CCF entrance). See also Figure 1.

| Experiment | Release area | Distance to SFF (km) | Date | Life stage | Tests (n) | Fish/Test (n) | Purpose of experiment |
|------------------------|--------------|----------------------|-----------------|------------|-----------|----------------|-------------------------------------------------------------------------------------------------------------------------------------------|
| SFF0 ^a | 1 | 0.0 | 6/04/08 | juvenile | 1 | 200 | Fish facility efficiency. Partial pre-screen loss (along with the June 2008 juvenile releases in west CCF and mid-CCF). |
| SFF1 ^a | 1 | 0.0 | 2/23/09 | adult | 4 | 100 | Fish facility efficiency. Pre-screen loss (along with the February 2009 adult release: east CCF1). |
| SFF2 ^b | 1 | 0.0 | 3/23/09 | adult | 2 | 100 | Fish facility efficiency. Pre-screen loss (along with the March 2009 adult release: east CCF2). |
| SFF3 ^a | 1 | 0.0 | 6/19/09 | juvenile | 1 | 800 | Fish facility efficiency. Pre-screen loss (along with the June 2009 juvenile release: east CCF3). |
| West CCF ^a | 2 | 1.2 | 6/12/08 | juvenile | 1 | 500 | Percent recapture at the SFF. Partial pre-screen loss by fish released near the exit point of CCF (west CCF), towards the intake channel. |
| Mid-CCF ^a | 3 | 2.8 | 6/26/08 | juvenile | 1 | 2,647 | Percent recapture at the SFF. Partial pre-screen loss by fish released in the central area of CCF. |
| East CCF1 ^a | 4 | 4.0 | 2/24/09–2/27/09 | adult | 4 | 1,382 to 1,501 | Percent recapture at the SFF. Pre-screen loss by fish released at the 2/27/09 1501 entrance of CCF under high export flows. |
| East CCF2 ^b | 4 | 4.0 | 3/26/09–3/27/09 | adult | 2 | 1,402 to 1,447 | Percent recapture at the SFF. Pre-screen loss by fish released at the 3/27/09 1447 entrance of CCF under intermediate export flows. |
| East CCF3 ^a | 4 | 4.0 | 6/22/09 | juvenile | 1 | 14,413 | Percent recapture at the SFF. Pre-screen loss by fish released at the entrance of CCF under low export flows. |

a Estimated recapture using $N_{rec'}$ (see data analyses).

b Estimated recapture using $N_{rec''}$ (see data analyses).

The second recapture estimate is:

$$N_{rel''} = C + S + H \quad (2)$$

where C and S are as defined above, and H is the total count of the remaining marked delta smelt in all the holding tanks (Figure 2, Table 1). We determined H just before loading fish on the transport truck for release in the Delta.

We used $N_{rec'}$ for the March 2009 experiments because of constraints on the authorized take permit for winter run Chinook salmon. For all remaining experiments, we used $N_{rec''}$ (Table 1).

Fish Releases at the Skinner Fish Facility

The percent fish facility efficiency (FFE) was computed as:

$$FFE = \left[\frac{N_{rec1}}{N_{rel1}} \right] \cdot 100 \quad (3)$$

where N_{rec1} is the number of recaptured fish from the original number released at the entrance of the SFF (N_{rel1}), (Figures 1, 2, Table 1).

Fish Releases at CCF

For each of the three release locations in CCF (Figure 1), the percent recapture (PR) was computed as:

$$PR = \left[\frac{N_{rec\ i}}{N_{rel\ i}} \right] \cdot 100 \quad (4)$$

where $N_{rec\ i}$ is the number of recaptured fish originally released at location i in CCF and $N_{rel\ i}$ is the number of fish released at the corresponding location i (Figure 1, Table 1).

The percent pre-screen loss (PSL) of fish released at the CCF entrance was computed as:

$$PSL = \left[1 - \left\{ \left(\frac{N_{rec\ 4}}{N_{rel\ 4}} \right) \cdot \left(\frac{1}{0.01 \cdot FFE} \right) \right\} \right] \cdot 100 \quad (5)$$

where $N_{rec\ 4}$ is the number of recaptured fish from the originally released number in CCF at location 4 ($N_{rel\ 4}$), (Figure 1, Table 1), and FFE is as defined earlier.

Bypass velocity ratio (BR) for primary or secondary louvers at the SFF is defined as:

$$BR = \frac{Vb}{Vc} \quad (6)$$

where Vb is the water velocity entering the primary or secondary bypass openings, and Vc is the average channel velocity upstream of the louvers (Bates and others 1960). Bypass velocity ratios above 1.0 provide a “capture velocity” for fish near the bypass entrance (Bowen and others 2004). (See Appendix A for the detailed formulas used to compute BR and water velocities.)

The daily residence time for entrained water in CCF over each recapture period (T) was computed as:

$$T = \frac{V}{Q} \quad (7)$$

where V is the estimated volume of CCF at 12:00 a.m. and Q is the daily average outflow (export). Because of the changes in outflow and residence time, exchange in CCF often varied greatly over the course of a mark-recapture experiment. Therefore, average T was computed over different periods to evaluate hydrodynamic patterns during mark-recapture experiments. Daily exports were obtained from the dayflow database (CDWR 2010). Daily water volume of CCF was provided by T. Hinojosa (CDWR). Hourly volumes used to estimate volume of CCF at 12:00 a.m. were provided by M. MacWilliams (River Modeling).

Regression analysis was used to evaluate potential linear relations between: (1) the percent of recaptured fish and the minimum distance from the release sites, and (2) the percent of recapture and residence time (or exports). To evaluate the short-term influence of residence time and export flow on the percent recapture, 3-d and 10-d averages were considered for these parameters, because such periods corresponded with the peak in recapture, and the time when all, but one fish, had been recaptured. Only the 3-d averages of residence time (and export flow) are subsequently reported, because they produced better fit than the 10-d averages. Differences in size composition between released and recaptured fish were analyzed with the Mann-Whitney U test.

RESULTS

I. Fish Facility Efficiency, Percent Recapture, and Pre-Screen Loss

Juvenile Experiments (June 2008–2009)

Only 24% to 30% of the juvenile fish released at the entrance of the SFF in June 2008–2009 were recaptured, indicating low FFE (mean = 27.0%, SE = 3.0, Table 2). The recapture of all juvenile delta smelt released in CCF—west side (intake area), mid-CCF, and east side (entrance area)—took place within 7 days in 2008 and 4 days in 2009. Increasing distance between the release location and the SFF did not result in consistently longer recapture time (Figure 1, Table 3). Juvenile experiments in June

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Table 2 Delta smelt released and recaptured at the Skinner Fish Facility, south Delta, in February–March 2009 (adults) and June 2008–2009 (juveniles) and concurrent mark–recapture results and hydrodynamic conditions

| Experiment | Mark | Release date | Mean daily export (m s ⁻¹) | Channel velocity ^b (m s ⁻¹) | Primary bypass ratio | Secondary bypass ratio | | Fish released (n) | Fish recaptured ^c (n) | Facility efficiency |
|------------|--------------------|--------------|----------------------------------------|----------------------------------------------------|----------------------|------------------------|-----------|-------------------|----------------------------------|---------------------|
| | | | | | | Old bldg. | New bldg. | | | |
| SFF1 | G–A/D ^a | 2/23/09 | 82.0 | 1.00 | 1.22 | 1.24 | 0.61 | 100 | 39 | 39 |
| SFF1 | W–A/D ^a | 2/23/09 | 82.0 | 1.00 | 1.22 | 1.24 | 0.61 | 100 | 36 | 36 |
| SFF1 | B–C/D ^a | 2/23/09 | 82.0 | 1.00 | 1.22 | 1.24 | 0.61 | 100 | 89 | 89 |
| SFF1 | B–A/D ^a | 2/23/09 | 82.0 | 1.00 | 1.22 | 1.24 | 0.61 | 100 | 49 | 49 |
| SFF2 | G–A ^a | 3/23/09 | 70.7 | 0.94 | 1.19 | 1.21 | N/A | 100 | 43 | 43 |
| SFF2 | B–D ^a | 3/23/09 | 70.7 | 0.91 | 1.22 | 1.21 | N/A | 100 | 45 | 45 |
| SFF0 | Calcein | 6/04/08 | 64.0 | 0.52 | 1.19 | 1.21 | N/A | 200 | 60 | 30 |
| SFF2 | Calcein | 6/19/09 | 16.1 | 0.40 | 1.22 | N/A | 1.18 | 800 | 193 | 24 |

- a First letter denotes photonic mark colors: B, G, W (blue, green, white). Second and third letters denote marked fins per fish: A, C, D (anal, caudal, dorsal). All juvenile and adults were calcein marked.
- b Average channel velocities upstream of louvers at the time of fish releases.
- c Total time from release to the last recaptured fish <24 hr.

Table 3 Delta smelt released in Clifton Court Forebay and recaptured at the Skinner Fish Facility, south Delta, in February and March 2009 (adults) and June 2008–2009 (juveniles) and concurrent mark–recapture results and hydrodynamic conditions

| Experiment | Mark | Date of release | Recapture period ^b (d) | Mean daily export ^c (m s ⁻¹) | Residence time ^c (d) | Fish released (n) | Fish recaptured (n) | Percent recaptured | Pre-screen loss |
|------------|------------------|-----------------|-----------------------------------|-----------------------------------------------------|---------------------------------|-------------------|---------------------|--------------------|-----------------|
| East CCF1 | G–D ^a | 2/24/09 | 24 | 83.4 | 2.36 | 1398 | 75 | 5.36 | 89.9 |
| East CCF1 | W–D ^a | 2/25/09 | 10 | 81.6 | 2.42 | 1426 | 33 | 2.31 | 95.6 |
| East CCF1 | B–C ^a | 2/26/09 | 4 | 79.9 | 2.47 | 1382 | 31 | 2.24 | 95.8 |
| East CCF1 | B–A ^a | 2/27/09 | 7 | 78.7 | 2.53 | 1501 | 32 | 2.13 | 96.0 |
| East CCF2 | G–A ^a | 3/26/09 | 5 | 63.2 | 2.77 | 1447 | 12 | 0.83 | 98.1 |
| East CCF2 | B–D ^a | 3/27/09 | — | 63.0 | 2.78 | 1402 | 0 | 0.00 | 100.0 |
| West CCF | Calcein | 6/12/08 | 5 | 19.1 | 8.63 | 500 | 39 | 7.80 | — |
| Mid-CCF | Calcein | 6/26/08 | 7 | 54.2 | 3.89 | 2647 | 55 | 2.08 | — |
| East CC3 | Calcein | 6/22/09 | 4 | 27.1 | 9.54 | 14413 | 4 | 0.03 | 99.9 |

- a First letter denotes photonic mark colors: B, G, W (blue, green, white). Second letter denotes marked fins per fish: A, C, D, C (anal, caudal, dorsal). All juvenile and adults were calcein marked.
- b Days from release to last recapture.
- c Daily mean over 10 days post-release.

2008 and 2009 occurred during a period of lower water exports and higher residence time in CCF compared to adult experiments (Tables 2, 3). The peak in percent recapture of juveniles occurred just 1 day after the releases, both in the west CCF and mid-CCF (Figure 3A) and in the east CCF (Figure 3B). The juvenile delta smelt group released in June 2009 showed an extremely low percent recapture (0.03%) and extremely high PSL (99.9%).

Daily survival of juvenile delta smelt controls remained consistently high at ambient temperatures below 27 °C for 5 days after the last fish recapture. In contrast, survival declined strongly when maximum water temperatures reached a threshold (27.5 to 28.0 °C). Subsequent decrease in water temperatures below that threshold did not prevent further decline in juvenile survival (Figures 4A, 4B).

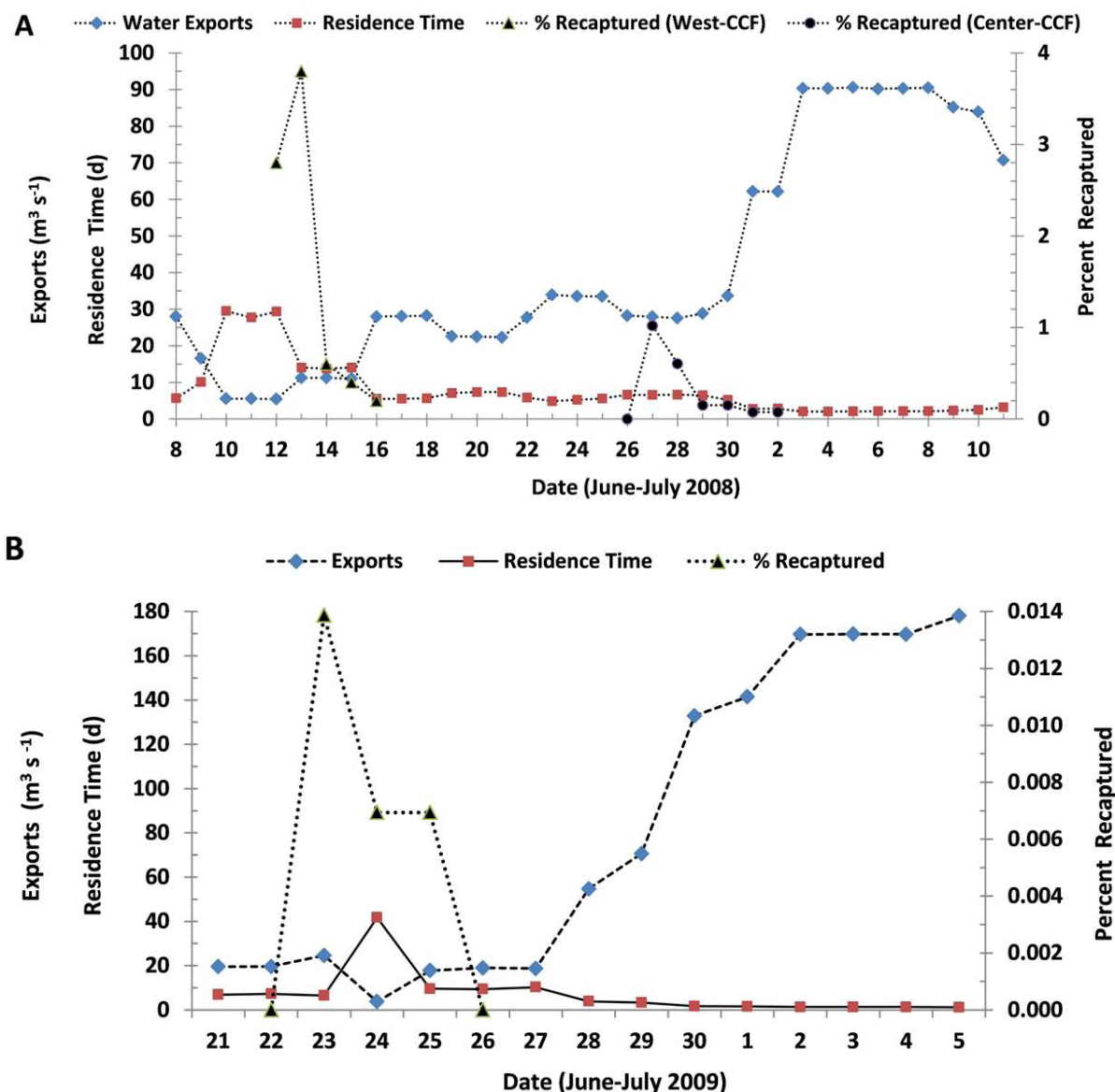


Figure 3 Daily water exports and residence time in Clifton Court Forebay (CCF) in relation to the percent of calcein-marked juvenile delta smelt recaptured at the Skinner Fish Facility: **(A)** Two groups of fish released in the west CCF (intake area) ($n = 500$ fish, June 12, 2008) and mid-CCF ($n = 2,647$ fish, June 26, 2008). **(B)** One group of fish released at the east CCF (entrance area) ($n = 14,413$, June 22, 2009).

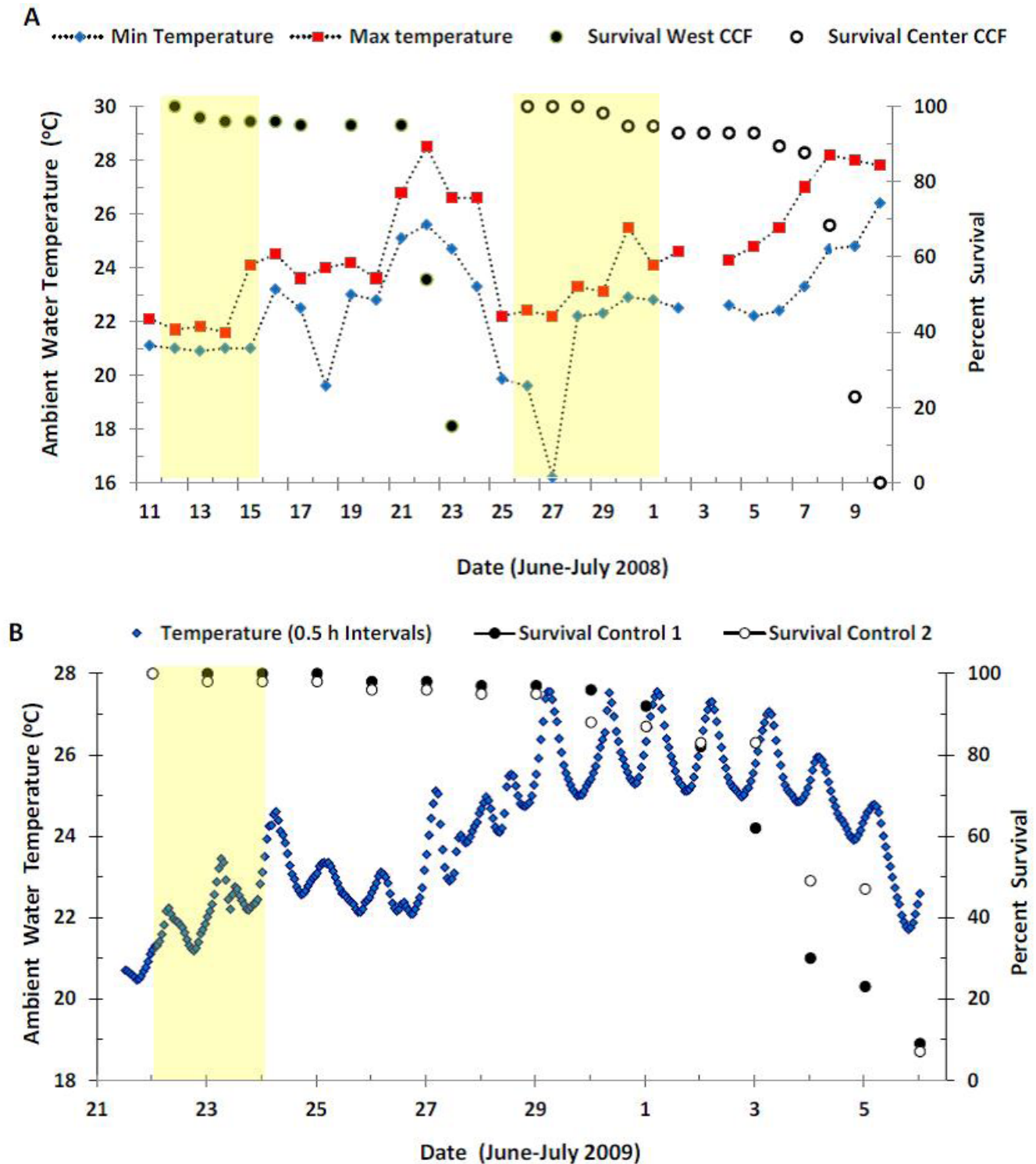


Figure 4 Daily survival of calcein-marked juvenile delta smelt controls exposed to ambient water temperature: **(A)** Controls for releases conducted in the west CCF (intake area) and mid-CCF on June 12 and 26, 2008. **(B)** Controls for the releases conducted in the east CCF (entrance area) on June 22, 2009. Bars denote the period between each field release and the last recapture. Initial number of fish per control was 100 at the time of releases in CCF.

Adult Experiments (February–March 2009)

Photonic-marked fish groups released at the SFF in February and March 2009 had recapture rates ranging from 36% to 89% (Table 2). The average FFE was slightly higher in February (53.2%, SE = 12.2) than in March (44.0%, SE = 1.0). Average FFE for adult delta smelt was 50.2% (SE = 8.0).

The percent recapture for adult delta smelt released at the CCF entrance area over 4 consecutive

days from February 24 to 27, 2009 was very low (mean = 3.01%, SE = 0.78). The peak recapture per group occurred 2 or 3 days after the release and except for one fish, recapture was complete within 10 days (Table 3, Figure 5A). The PSL for the February 2009 release group was very high (mean = 94.3%, SE = 1.5). On the other hand, the survival rate (S) of control marked fish held at the lab remained very high until the control was terminated on March

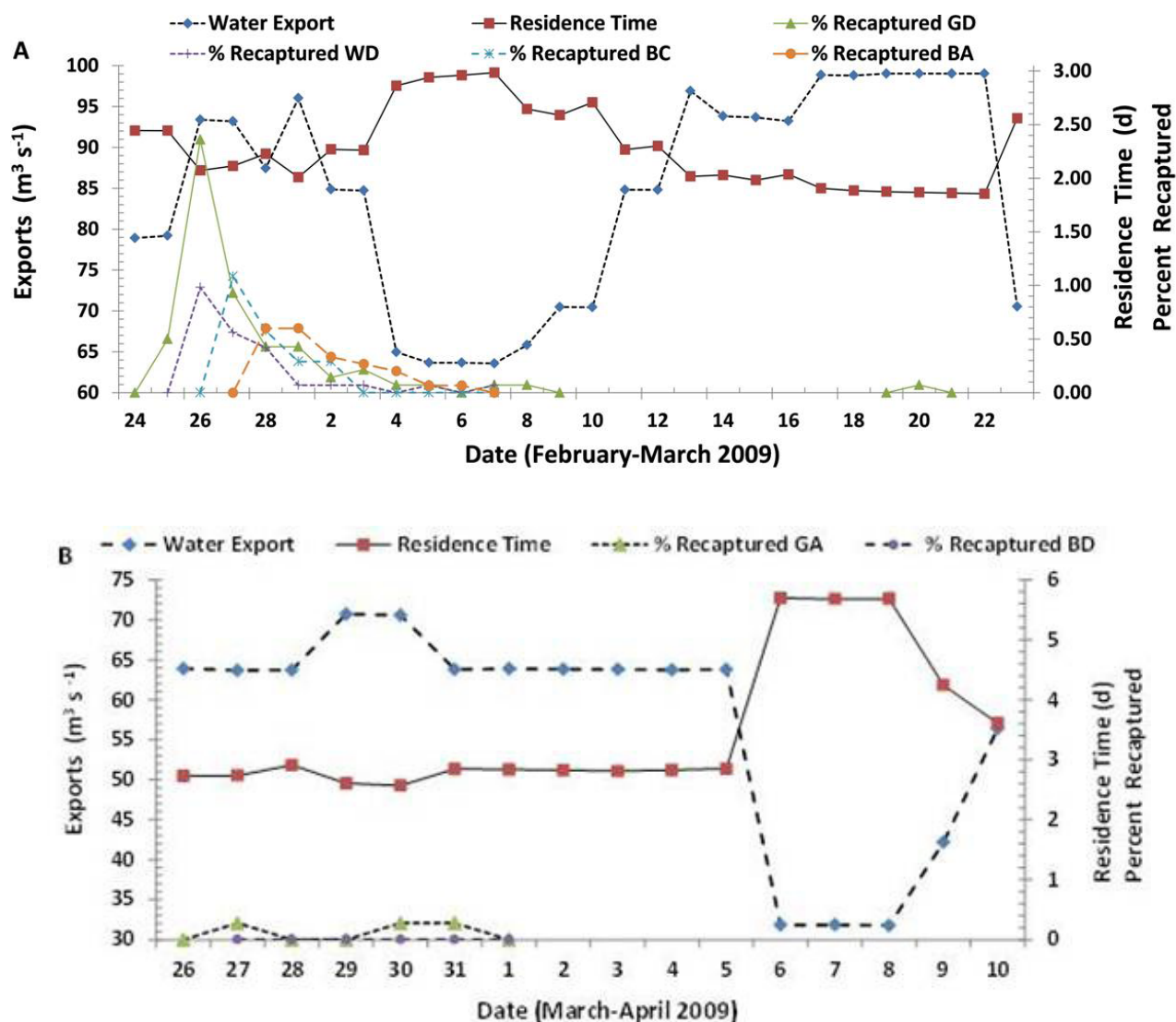


Figure 5 Daily water exports and residence time in Clifton Court Forebay (CCF) in relation to the percent of recaptured calcein- and photonic-marked adult delta smelt released in the east CCF (entrance area): (A) Four fish groups released on February 24–27, 2009. (B) Two fish groups released on March 26–27, 2009. Photonic mark codes are shown in Table 3.

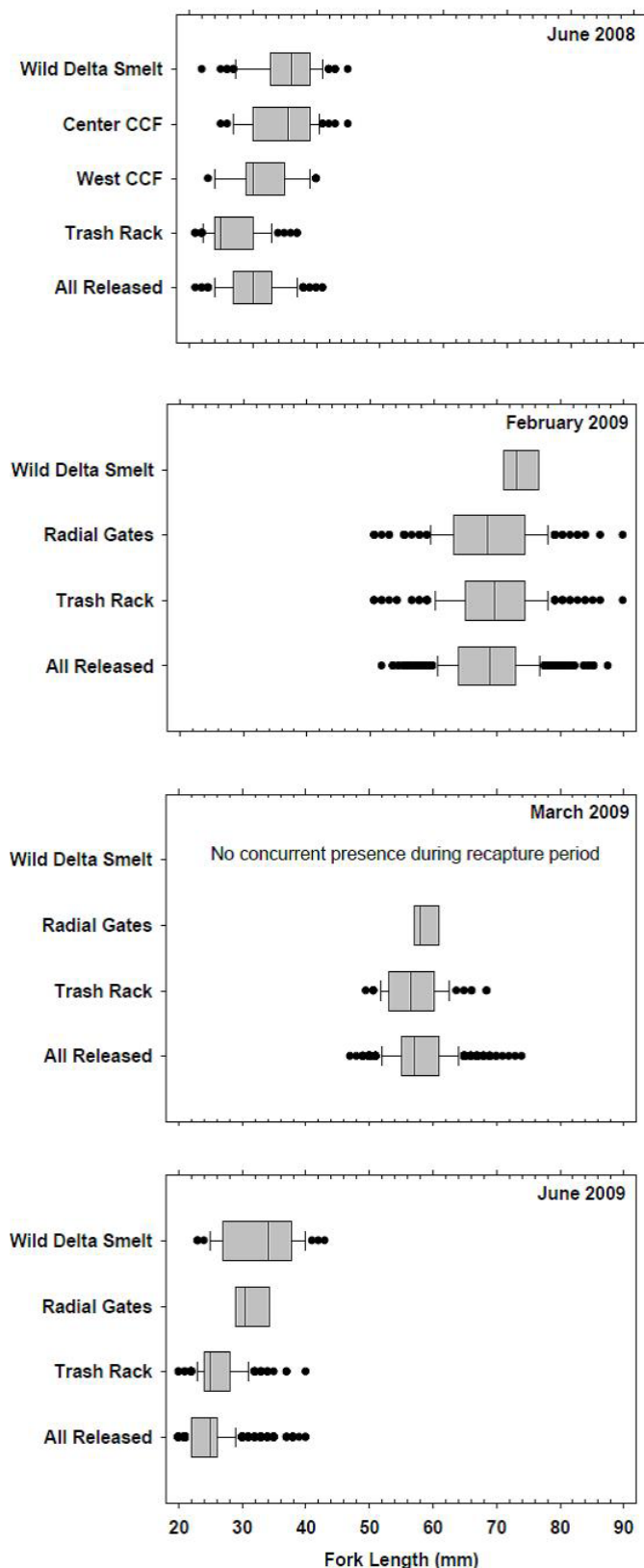
16, 2009 ($S = 99.3\%$, $n = 400$). Thus, the very low recapture cannot be attributed to experimentally induced post-release mortality (i.e., the handling and marking).

Compared to February experiments, the recaptures from releases conducted on March 26 and 27, 2009 at the CCF entrance occurred over a shorter period and only within 5 days from the releases. March experiments coincided with a period of lower exports and higher residence time in CCF (Figure 5B). Despite expanding the number of mark-recaptured fish in CDWR counts, the percent recapture for both fish groups released in March was extremely low (mean = 0.41% , $SE = 0.41$, Table 3), and the estimated PSL for the March 2009 release group was extremely high (mean = 99.1% , $SE = 0.9$). Similar to the February 2009 experiment, the survival rate of the control fish held in the lab in March 2009 was still very high on March 31 ($S = 100\%$, $n = 100$); the last day marked fish were recaptured. Survival was still 98% when the control experiment was terminated on April 20, 2009.

II. Size Composition of Delta Smelt

The size composition of recaptured delta smelt overlapped with that of unmarked wild delta smelt when the later were also reported at the SFF (Figure 6). No obvious differences were observed between the size of fish released and those recaptured for adult delta smelt released either in February or March 2009 (Figure 6). However, recaptured juvenile delta smelt that were released in mid-CCF in June 2008 and in the east CCF in June 2009 were larger relative to the size composition of released fish ($P < 0.001$ Mann-Whitney U test); (Figure 6).

Figure 6 (right column) Size composition of marked (cultured) and unmarked (wild) delta smelt concurrently collected at the Skinner Fish Facility during mark-recapture experiments in June 2008 and 2009 (juveniles) and in February and March 2009 (adults). Size composition before releases is denoted as all released.



III. Factors Influencing Percent Recapture

The percent of recaptured delta smelt at the SFF declined significantly with increasing distance from the release site, both for juvenile releases (Figure 7A) and combined adult and juvenile releases (Figure 7B). Despite the higher FFE for adults than juveniles, the percent recapture for the six groups of adults released at the CCF entrance between February and March 2009 was very low.

The percent recapture of delta smelt declined exponentially, with increasing residence time in CCF for the groups of fish released at the CCF entrance area between February and June 2009 (Figure 8A). Increased exports were associated with higher percent recapture (Figure 8B). Relative to the number of fish released at the CCF entrance in 2009, the number of adult delta smelt recaptured was nearly ten-fold lower from February releases (high exports) to March releases (low exports). A similar ten-fold difference in recapture was observed for juvenile released in June, relative to adults released in March (Figures 8A, 8B).

DISCUSSION

I. Summary and Conclusions

Our results revealed significant spatio-temporal variability in fish recapture. Residence time in CCF and the rate of water export have important influences on the entrainment losses of delta smelt at the SWP. The number of juvenile and adult delta smelt that were recaptured at the SFF was always small compared to the number released into CCF, reflecting consistently high PSLs in CCF. The PSL varied approximately 10- to 100-fold between February and June 2009. The difference in percent recapture of delta smelt released in CCF between February (adults) to March (adults) and then to June (juveniles) is primarily attributed to increased residence time in CCF, which increases exposure time to predators and other potential sources of mortality.

Relative to the February 2009 experiments, the 10-d mean daily water exports from CCF for the March and June 2009 experiments were 22% and 66% lower, respectively.

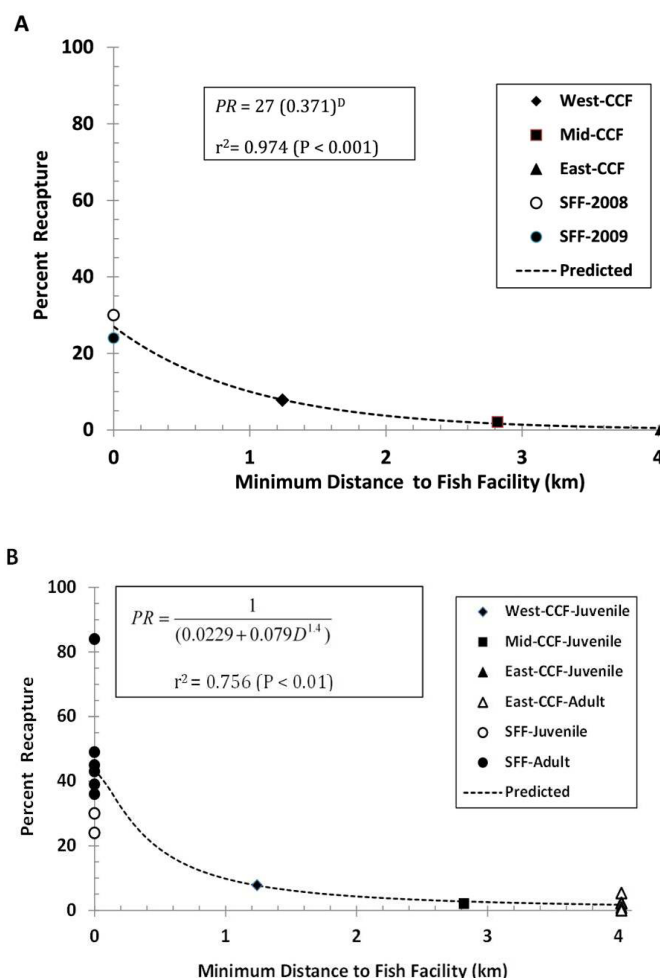


Figure 7 Percent recapture (PR) for delta smelt at the Skinner Fish Facility (SFF) as a function of the minimum distance (D) from each release site to the SFF: (A) Juvenile delta smelt. (B) Combined juvenile and adult delta smelt.

Despite a 19% lower CCF storage volume in June 2009 compared to the February 2009 experiment, the 10-d mean residence time in June was 74% higher than the February experiments. The higher loss of juvenile delta smelt in June 2009 compared to February and March suggests that predation was enhanced by the lower water levels in CCF, and exacerbated by the extensive aquatic vegetation coverage and increasing temperature in CCF relative to the February and March adult mark-recapture experiments in 2009. The FFEs also were lowest in June at the SFF, although this probably reflected the smaller size of the fish.

II. Previous Studies

On a global scale, large numbers of fish are directly lost to water diversions from rivers, lakes, estuaries and coasts by either becoming entrained into water diversion intakes or impinged on intake screens. The sources for such losses are ubiquitous and diverse, including diversions for agriculture (Nobriga and others 2004; Post and others 2006; Baumgartner and others 2009), power plants (Marcy 1975; Michaud and Taft 2000; Newbold and Iovanna 2007) and urban and other uses (Drinkwater and Frank 1994; Arthur and others 1996; Fitzhugh and Richter 2004).

Entrainment studies for other species at the SWP differed from the present work in their use of a combination of fluorescent dye; coded-wire tags; fin clips (Gingras 1997) and PIT tags (Clark and others 2009) to derive PSL estimates; as well as differences in marking methods and, release and recapture locations. Nevertheless, results from all studies show that PSL is always a source of high mortality. Juvenile fish used in previous studies generally had larger mean sizes than delta smelt; and experienced lower average PSL: 86.7% PSL for 88.1 mm FL Chinook salmon; 82% PSL for 53.5 mm FL striped bass (Gingras 1997) and 80% PSL for 217 mm FL steelhead (average PSL of two estimates by Clark and others 2009). The 99% or more losses of delta smelt suggest this species is especially susceptible to such losses.

The FFEs are also low for adult delta smelt, and especially for juvenile delta smelt at the SFF, compared to other species such as juvenile Chinook salmon (Brown and others 1996). Ours is the first empirical study to estimate both PSL and FFE of delta smelt at a water diversion facility. Our mean FFE estimate at the SFF for adult delta smelt was nearly two times higher than the estimated FFE for adult delta smelt at the TFF (22.5 % FFE, M. Bowen and C. Svoboda, U.S. Bureau of Reclamation, unpublished data). Our average adult delta smelt entrainment estimates at the SWP ranged from losses similar to those assumed for adults at SWP-CVP by Kimmerer's (2008) for our February 2009 experiments, to losses nearly 10-fold higher in our March 2009 experiments.

The results of the present experiments reinforce the observations that reservoirs can delay fish migration and increase the role of predation (Gray and Rondorf 1986; Li and others 1987). Our finding of decreased percent recapture of delta smelt with increasing residence time of CCF or decreased exports (Figures 8A, 8B) is consistent with the inverse relations between survival of out-migrating salmonids in impoundments and their residence time (e.g., Trefethen 1968; Mullan 1980) and with the overall pattern of lower water exports from CCF resulting in higher PSL (Gingras 1997). Thus, residence time and exports act as key forcing factors on PSL.

III. Potential Mortality Sources and Study Biases

Several potential mortality sources and experimental biases could individually or in combination influence the PSLs and FFEs reported in our study: (1) predation; (2) starvation; (3) unfavorable physical-hydrodynamic conditions; (4) emigration through CCF intakes; (5) post mark-release-induced mortality; (6) use of cultured fish; and (7) calculation biases.

1. Predation mortality. Previous studies attributed PSLs to predation in CCF (e.g., Kano 1990; Brown and others 1996; Clark and others 2009). The highest population estimates of predators reported by Kano (1990) were white catfish (*Ictalurus catus*, range: 67,000–246,000) and striped bass (*Morone saxatilis*, range: 35,000–118,000). However, predation by striped bass may account for much of the PSL (Kano 1990; Brown and others 1996) because white catfish feed opportunistically on a broader food base, including invertebrates (Turner 1966). Five other species of potential piscivores reported in Kano's (1990) study were: channel catfish (*I. punctatus*), black crappie (*Pomoxis nigromaculatus*), largemouth bass (*Micropterus salmoides*), brown bullhead (*I. nebulosus*), and Sacramento pikeminnow (*Ptychocheilus grandis*). In addition, the potential for avian predation in CCF has also been recognized (Clark and others 2009).

Over 2,000 juvenile striped bass—virtually all of them less than 50 mm FL—were present in the regular CDWR secondary channel flushing when it was examined to remove predators in June 2009. The mean size of striped bass in CDWR counts was

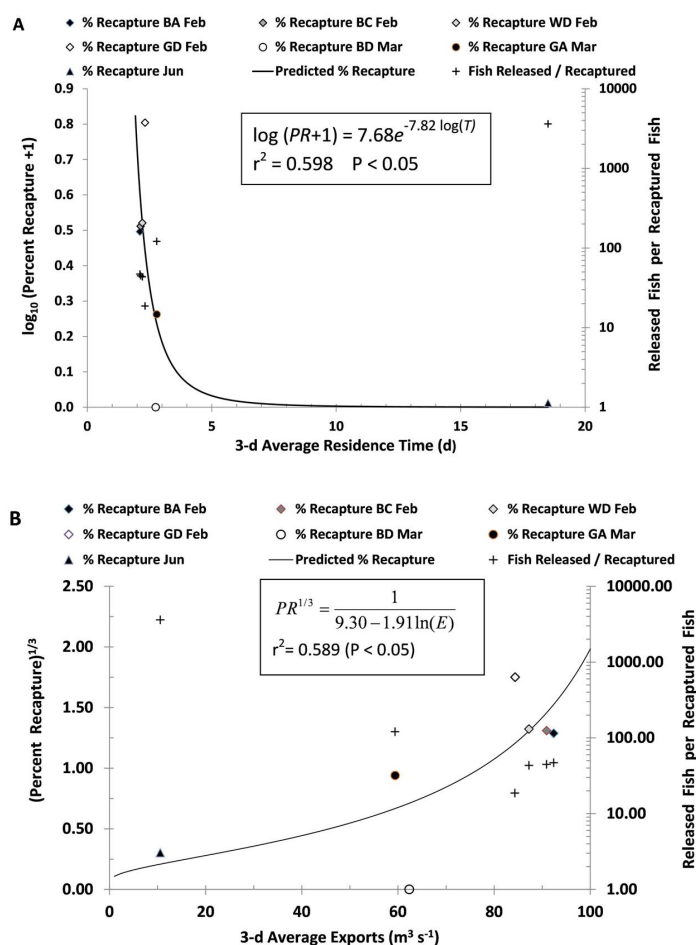


Figure 8 Observed and predicted percent recaptured delta smelt at the Skinner Fish Facility (PR, \log_{10} or cube-root transformed) as a function of: **(A)** residence time (T) and **(B)** exports (E) for the 2009 experiments. The number of released fish per recaptured fish is shown in the right axis (excluding the BD group released in March 2009 with zero recapture).

33.3 mm FL (SE = 1.37) over the juvenile delta smelt mark-recapture period (June 22–26, 2009). Although age-0 striped bass may rely on invertebrates and fish as prey (Stevens 1966), very few larval fish were reported by Bryant and Arnold (2007) among the prey items of age-0 striped bass during the summers of the years 1973 through 2002. In addition, striped bass may not become piscivore until they reach 70 to 100 mm FL in length (R. Fujimura, CDFG, unpublished data). Hence, striped bass may not have preyed greatly upon marked juvenile delta smelt at the SFF in our June experiments. On the other hand, over an

annual period, Kano (1990) reported that the smallest sizes of striped bass in CCF occurred in July (mean = 341 mm FL, SE = 3). Thus, striped bass predation on marked juvenile delta smelt seems more likely in CCF than in the SFF.

2. Starvation. Evidence is lacking to support starvation as a major cause of the high PSLs of delta smelt. There is a regular entrainment of plankton and pelagic organisms to the south Delta export facilities (Jassby and others 2002). Moreover, the period between our fish releases in CCF and subsequent recaptures was short. Although no data on survival of food-deprived delta smelt is available, cod (*Gadus morhua*) juveniles of a size similar to delta smelt (20 mm FL) are able to survive at least a week of food deprivation (Folkvord 1991). Cultured larva and juvenile delta smelt up to 120 days post-hatch are able to switch prey within 2 hours of exposure to zooplankton (L. Sullivan, Romberg Tiburon Center, San Francisco State University, unpublished data). Thus, marked delta smelt in CCF are not likely to have died from starvation within days from their release.

3. Unfavorable physical–hydrodynamic conditions within CCF. Although CCF cannot be considered a physically favorable area for delta smelt, the very high PSL experienced by adult delta smelt in March 2009 (Figure 5B, Table 3) a period of low water temperatures, rules out temperature as the cause of high PSL. For juvenile delta smelt acclimated at 17 °C, Swanson and others (2000) reported 25.4 °C as the critical thermal maxima (loss of equilibrium endpoint). Based on our temperature controls for juvenile delta smelt initially acclimated to temperatures in the range of 20 to 22 °C (Figures 4A, 4B), cumulative exposure to peak daily ambient water temperatures above 27 °C could have significantly reduced juvenile survival. However, all recaptured juvenile fish released at the CCF entrance area in 2009 were recaptured between June 23 and 25, in spite of the fact that most control juvenile fish were still alive by June 30 (Figures 3B, 4B). Temperature gradients in different areas of CCF, if large enough, could have resulted in survival differences for delta smelt, irrespective of their origin (wild or cultured). It is conceivable that increased temperatures in CCF could have interacted synergisti-

cally with predation (e.g., by increasing prey vulnerability and/or predator activity). Whether the salvage of wild juvenile delta smelt observed at the SFF after our last recaptures of marked juveniles in 2008 and 2009 was due to newly, or previously, entrained fish is unknown. Yet, it demonstrates that the timing of our experiments was concurrent with the salvage of wild juvenile delta smelt.

The hydrodynamic characteristics of CCF can also reduce the likelihood that entrained delta smelt will be salvaged, particularly during low export conditions when residence times are longer. Based on simulated 3-D water-circulation patterns for CCF during June 2007 (M. MacWilliams and E. Gross, River Modeling, unpublished data), and drifter trajectory during our June 2008 experiments (C. Ruhl, U.S. Geological Survey, unpublished data) a basin-wide counter-clockwise circulation in CCF seemed a persistent hydrodynamic feature. Conceivably, such a wind-driven circulation pattern in combination with low exports could enhance dispersion and residence time of entrained fish within CCF, increasing the likelihood of PSL. Conversely, during high export and low wind conditions, residence times in CCF are much shorter. Under such conditions, most particles are transported roughly in a straight-line trajectory from the CCF entrance to the SWP pumping plant (M. MacWilliams and E. Gross, River Modeling, unpublished data).

The observed low reservoir level and excessive aquatic vegetation in June 2009 could have contributed to increased mortality through lack of pelagic habitat and by reducing access to the salvage facility. But other potentially lethal conditions such as contaminants or reduced dissolved oxygen, if present, should have also been reflected in lower-than-observed juvenile control survival, making such mechanisms unlikely.

4. Emigration through CCF intakes. Emigration from CCF has been documented for radio-tagged striped bass (mean size: 431 mm FL, Gingras and McGee 1997) and steelhead (mean size: 217 mm FL, Clark and others 2009), two strong swimming species. Water velocity through the CCF entrance often exceeds 300 cm s^{-1} (Kano 1990) and approaches

400 cm s^{-1} at maximum CCF/Old River stage differential (Gingras 1997). In contrast, the critical swimming speed juvenile-adult delta smelt (40 to 60 mm SL) has been estimated to be 25 to 29 cm s^{-1} (Swanson and others 1998, 2000). Hence, potential emigration of delta smelt through the CCF intakes seems unlikely, except toward the end of the water intake period when water velocities decrease significantly. In the case of steelhead, the effect of fish emigration through the CCF entrance was estimated to result in a PSL of 78%, compared to PSL of 82% without accounting for emigration (Clark and others 2009).

5. Potential marking induced mortality. Based on the extremely high survival of control adult fish and the very high survival of juvenile marked fish at temperatures below 27°C , this scenario seems unlikely. Further, laboratory tests designed to evaluate striped bass predation on marked and unmarked delta smelt revealed no significant differences between marked (calcein and photonic marking) and unmarked delta smelt (G. Castillo, U.S. Fish and Wildlife Service, unpublished data). Moreover, those tests suggested no significant differences on predation among the photonic mark colors used in our field experiments.

6. Use of cultured fish. The extent to which potential differences between cultured and wild delta smelt may have affected our results is unknown. Predator avoidance in other species seems more developed in fish habituated to predators (e.g., Patten 1977; Healey and Reinhardt 1995; Alvarez and Nicieza 2003). Nevertheless, a mark-recapture test of field-collected juvenile Chinook salmon released in CCF in May 1996 resulted in only 0.32% of the fish being recaptured at the SFF (J. Morinaka, CDFG-Stockton, unpublished data). Thus, results from other species and environments may not be safely extrapolated to our study.

Comparison of secondary louver efficiency at three different speeds between cultured and wild delta smelt revealed no significant differences (M. Bowen, U.S. Bureau of Reclamation, unpublished data). These results lend support to use of cultured delta smelt to approximate the behavior of wild fish to louver systems. On the other hand, the collection, handling,

transport, and release experiments revealed that wild delta smelt experienced higher levels of cortisol response and took longer to recover than cultured delta smelt (V. Afentoulis and A. Rockriver, CDFG, unpublished data). Therefore, cultured and wild delta smelt may differ in their physiological responses to human-induced stress.

7. Calculation biases. The FFEs were estimated a few days before fish released in CCF were recaptured at the SFF. Therefore, short-term changes in FFE could have affected actual PSL but the biases are probably small, considering the magnitude of facility losses relative to the PSL (Tables 1, 2). Our estimated FFEs could have been affected by predation losses within the SFF. Nevertheless, our results should reflect the prevailing FFEs under normal operation conditions. Over the course of our experiments, CDWR operators continued their routine weekly removal of predators from the secondary channel. CDWR operators also continued searching for marked delta smelt in regular counts through the end of the salvage season.

IV. Management Implications

Salvage of delta smelt at the SFF and the TFF is a key tool for monitoring incidental take at the CVP and SWP (USFWS 2008a). However, low population sizes may hinder the ability to evaluate the effectiveness of incidental take (Anderson and others 2011). Our results strongly suggest that salvage is not a consistent index of delta smelt entrainment at the SWP. The extremely high PSLs and the lower recapture of delta smelt as a function of increased residence time in CCF support the rationale for reducing PSL at the SWP (Kano 1990; USFWS 1996; Gingras 1997). Management options supporting such rationale include:

1. Removing predators from CCF (Tillman 1995, but see Gingras and McGee 1997).
2. Establishing export operational criteria that minimize exposure of entrained fish to predators within CCF (Gingras 1997), thus, reducing residence time in CCF.
3. Diverting water through a conveyance channel along the inside of the CCF that leads to the SFF to reduce PSLs (SDFFF 2003a, 2003b).
4. Relocating the fish facility at the entrance of CCF (Kano 1990; SDFFF 2003b).

Among the options listed, options 3 and 4 may contribute most to reducing PSL at the SWP, which should also result in enhanced monitoring of entrained fish in the salvage. In addition, the feasibility of reducing the risk of entrainment for delta smelt and other listed species by a low-flow screened intake at the CCF entrance (e.g., Dorratcague and others 2009) should take into account the species' response (Young and others 2010).

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REFERENCES

Alvarez D, Nicieza AG. 2003. Predator avoidance behaviour in wild and hatchery-reared brown trout: the role of experience and domestication. *Journal of Fish Biology* 63: 1565–1577.

Anderson JJ, Gore AG, Kneib RT, Loran M, Van Sickle J. 2011. Report of the 2011 Independent Review Panel (IRP) on the implementation of reasonable and prudent alternative (RPA) actions affecting the operations criteria and plan (OCAP) for State/Federal Water Operations. Prepared for Delta Science Program. [Internet]. Available from: <http://deltacouncil.ca.gov/science-event/3877>.

Aparicio E, Vargas M, Josep O, Josep M, de Sostoa A. 2000. Decline of native freshwater fishes in a mediterranean watershed on the Iberian Peninsula: a quantitative assessment. *Environmental Biology of Fishes* 59:11–19.

Arthur JF, Ball MD, Baughman SY. 1996. Summary of federal and state water project environmental impacts in the San Francisco Bay-Delta estuary, California. In: Hollibaugh JT, editor. *The San Francisco Bay: The ecosystem. Further investigations into the natural history of San Francisco Bay and Delta with reference to the influence of man*. Altona, Manitoba: Friesen Printers. p 445–495.

Baskerville-Bridges B, Lindberg J, Van Eenennaam J, Doroshov SI. 2004. Delta smelt research and culture program. 5-year Summary, 1998–2003. CALFED Bay-Delta Program contract title: Culture of delta smelt (*Hypomesus transpacificus*) in support of environmental studies and restoration project #2000-B03. USBR agreement #00-FC-20-0113. Davis (CA): University of California, Davis, Department of Animal Science. 57 p.

Bates DW, Logan O, Pesonen EA. 1960. Efficiency evaluation, Tracy Fish Collection Facility, Central Valley Project, California. Seattle (WA): U.S. Fish and Wildlife Service. 70 p.

Baumgartner LJ, Reynoldson NK, Cameron L, Stanger JG. 2009. Effects of irrigation pumps on riverine fish. *Fisheries Management and Ecology* 16:429–437.

Bennett WA. 2005. Critical assessment of delta smelt in the San Francisco Estuary, California. *San Francisco Estuary and Watershed Science* [Internet]. Available from: <http://www.escholarship.org/uc/item/0725n5vk>.

Bennett WA, Moyle PB. 1996. Where have all the fishes gone? Interactive factors producing fish declines in the Sacramento-San Joaquin Estuary. In: Hollibaugh JT, editor. *The San Francisco Bay: the ecosystem. Further investigations into the natural history of San Francisco Bay and Delta with reference to the influence of man*. Altona, Manitoba: Friesen Printers. p 519–542.

Bowen MD, Baskerville-Bridges BB, Frizell KW, Hess L, Karp CA, Siegfried SM, Wynn SL. 2004. Empirical and experimental analyses of secondary louver efficiency at the Tracy Fish Collection Facility, March 1996 to November 1997. Technical report. Tracy Fish Facility Studies, Volume 11. Denver (CO): Bureau of Reclamation, Mid-Pacific Region, Denver Technical Service Center. 33 p.

Brown R, Greene S, Coulston P, Barrow P. 1996. An evaluation of the effectiveness of fish salvage operations at the intake to the California Aqueduct, 1979–1993. In: Hollibaugh JT, editor. *The San Francisco Bay: the ecosystem*. Altona, Manitoba: Friesen Printers. p 497–518.

Bryant ME and JD Arnold. 2007. Diets of age-0 striped bass in the San Francisco Estuary, 1973–2002. *California Fish and Game* 93:1–22.

[CDWR] California Department of Water Resources. 2010. Dayflow: an estimate of daily average Delta outflow [website]. Available from: <http://www.water.ca.gov/dayflow/>.

Clark KW, Bowen MD, Mayfield RB, Zehfuss KP, Taplin JD, Hanson CH. 2009. Quantification of pre-screen loss of juvenile steelhead in Clifton Court Forebay. State of California. Sacramento (CA): California Department of Water Resources, Bay-Delta Office Fishery, Improvements Section. 119 p.

Drinkwater KF, Frank KT. 1994. Effects of river regulation and diversion on marine fish and invertebrates. *Aquatic Conservation: Freshwater and Marine Ecosystems* 4:135-151.

Dorratcague B, Gatton D, Hamaker T. 2009. Low-flow intake technical analysis. Prepared for California Department of Water Resources, Bay-Delta Office, Fishery Improvements Section. Sacramento (CA): CH2M HILL. Available from: http://baydeltaoffice.water.ca.gov/announcement/LFI_TA_12082009revised12610.pdf.

Dynesius M, Nilsson C. 1994. Fragmentation and flow regulation of river systems in the northern 3rd of the world. *Science* 266:753-762.

Erkkila LF, Moffet JW, Cope OB, Smith BR, Nelson RS. 1950. Sacramento-San Joaquin Delta fishery resources: Effects of Tracy Pumping Plant and the Delta Cross Channel. U.S. Fish and Wildlife Service Special Scientific Report 56.

Federal Register. 2010. Endangered and threatened wildlife and plants; 12-month finding on a petition to reclassify the delta smelt from threatened to endangered throughout its range. Wednesday, April 7, 2010. Proposed Rules 75(66):17667.

Feyrer F, Nobriga ML, Sommer TR. 2007. Multidecadal trends for three declining fish species: habitat patterns and mechanisms in the San Francisco Estuary, California, USA. *Canadian Journal of Fisheries and Aquatic Sciences* 64:723-734.

Fitzhugh TW, Richter BD. 2004. Quenching urban thirst: growing cities and their impacts on freshwater ecosystems. *BioScience* 54:741-754.

Folkvord A. 1991. Growth, survival and cannibalism of cod juveniles (*Gadus morhua* L.): effects of feed type, starvation and fish size. *Aquaculture* 97:41-59.

Gingras M. 1997. Mark-recapture experiments at Clifton Court Forebay to estimate pre-screening loss to juvenile fishes: 1976-1993. Interagency Ecological Program. Technical Report 55. Sacramento (CA): California Department of Water Resources. 22 p.

Gingras M, McGee M. 1997. A telemetry study of striped bass emigration from Clifton Court Forebay: Implications for predator enumeration and control. Interagency Ecological Program for the San Francisco Bay-Delta Estuary. Technical Report 54. Sacramento (CA): California Department of Water Resources. 30 p.

Gray G, Rondorf D. 1986. Predation on juvenile salmonids in Columbia Basin reservoirs. in: Hall G, Van Den Avyle M, editors. Reservoir fisheries management strategies for the 80's. Bethesda (MD): Southern Division American Fisheries Society. p 178-185.

Grimaldo LF, Sommer T, Van Ark N, Jones G, Holland E, Moyle PB, Herbold B, Smith P. 2009. Factors affecting fish entrainment into massive water diversions in a tidal freshwater estuary: can fish losses be managed? *North American Journal of Fisheries Management* 29:1253-1270.

Gumpinger C, Scheder C. 2008. Decline of biodiversity as a result of various human impacts related to river regulation—exemplified by several small river catchments (Austria). *Transylvanian Review of Systematical and Ecological Research* 6:141-148.

Healey MC, Reinhardt U. 1995. Predator avoidance in naive and experienced juvenile Chinook and coho salmon. *Canadian Journal of Fisheries and Aquatic Sciences* 52:614-622.

Heubach W. [ca. 1973]. Further observation of the densities of king salmon, striped bass, and white catfish collected at the Federal and State Fish Facilities. Stockton (CA): California Department of Fish and Game. 11 p.

- Hobbs JA, Castillo G, Tigan G, Lindberg J, Ikemiyagi N, Ramos G. 2012. Tagging the next generation: validation of trans-generational chemical tagging for an endangered fish. *Environmental Biology of Fishes* 95(4):463-468. doi 10.1007/s10641-012-0034-1. Available from: <http://link.springer.com/article/10.1007%2Fs10641-012-0034-1>.
- Hymanson ZP, Brown LR. 2006. Fulfilling a paradoxical mandate: can the Environmental Water Account ensure the reliability of freshwater exports from the Sacramento-San Joaquin Delta and simultaneously protect delta smelt (*Hypomesus transpacificus*) from excessive entrainment? Interagency Ecological Program of the San Francisco Estuary. IEP Newsletter 19:28-49. [Internet]. Available from: http://www.water.ca.gov/iep/newsletters/2006/IEPNewsletter_Winter2006final6.pdf.
- Jassby AD, Cloern JE, Cole BE. 2002. Annual primary production: Patterns and mechanisms of change in a nutrient-rich tidal Ecosystem. *Limnology and Oceanography* 47:698-712.
- Kano RM. 1990. Occurrence and abundance of predator fish in Clifton Court Forebay, California. Interagency Ecological Study Program for the Sacramento-San Joaquin Estuary Technical Report 24. Sacramento (CA): California Department of Water Resources. 13 p. Available from: <https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentVersionID=59833>.
- Kennish MJ. 2002. Environmental threats and environmental future of estuaries. *Environmental Conservation* 29:78-107.
- Kimmerer W. 2008. Losses of Sacramento River Chinook salmon and delta smelt to entrainment in water diversions in the Sacramento-San Joaquin Delta. *San Francisco Estuary and Watershed Science* [Internet]. Available from: <http://www.escholarship.org/uc/item/7v92h6fs>.
- Li H, Schreck C, Bond C, Rexstad E. 1987. Factors influencing changes in fish assemblages of Pacific Northwest streams. In: Matthews W, Heins D, editors. *Community and evolutionary ecology of North American stream fishes*. Norman (OK): University of Oklahoma Press. p 193-202.
- Lund JR, Hanak E, Fleenor WE, Bennett WA, Howitt RE, Mount JF, Moyle PB. 2010. Comparing futures for the Sacramento-San Joaquin Delta. Berkeley (CA): University of California Press. 231 p.
- Marcy BC. 1975. Entrainment of organisms at power plants, with emphasis on fishes—an overview. In: Saila SB, editor. *Fisheries and energy production: a symposium*. D.C. Lexington (MA): Heath & Co. p 89-106.
- Michaud DT, Taft EP. 2000. Recent evaluations of physical and behavioral barriers for reducing fish entrainment at hydroelectric plants in the upper midwest. *Environmental Science and Policy* 3:499-512.
- Miranda JR, Padilla R, Aasen G, Mefford B, Sisneros D, Boutwell J. 2010. Evaluation of mortality and injury in a fish release pipe. California Natural Resources Agency. Department of Water Resources. 79 p.
- Messineo J, Fish M, Contreras D, Hieb K, Afentoulis V. 2010. 2009 Fishes annual status and trends report for the San Francisco Estuary. Interagency Ecological Program for the San Francisco Estuary. IEP Newsletter 23:49-72. [Internet]. Available from: http://www.water.ca.gov/iep/newsletters/2010/IEPNewsletter_FINALSpring2010.pdf.
- Morinaka J. In press. Acute mortality and injury of delta smelt associated with collection, handling, transport, and release at State Water Project fish salvage facility. Interagency Ecological Program of the Sacramento-San Joaquin Estuary Technical Report. Sacramento (CA): California Department of Water Resources.
- Moyle PB, Herbold B, Stevens DE, Miller LW. 1992. Life history and status of delta smelt in the Sacramento-San Joaquin Estuary, California. *Transactions of the American Fisheries Society* 121:67-77.
- Moyle PB, Lund JR, Bennett WA, Fleenor WE, Lund JR. 2010. Habitat variability and complexity in the upper San Francisco Estuary. *San Francisco Estuary and Watershed Science* [Internet]. Available from: <http://www.escholarship.org/uc/item/0kf0d32x>.

Moyle PB, Williams JE. 1990. Biodiversity loss in the temperate zone: Decline of the native fish fauna of California. *Conservation Biology* 4:275-284.

Mullan J. 1980. Fish predation on salmonid smolts in the Columbia River system in relation to the Endangered Species Act. Leavenworth (WA): U.S. Fish and Wildlife Service, Fisheries Assistance Office. 24 p.

Newbold SC, Iovanna R. 2007. Population level impacts of cooling water withdrawals on harvested fish stocks. *Environmental Science & Technology* 41:2108-2114.

Nobriga ML, Matica Z, Hymanson ZP. 2004. Evaluating entrainment vulnerability to agricultural irrigation diversions: A comparison among open-water fishes. *American Fisheries Society Symposium* 39:281-295.

Nobriga ML, Sommer TR, Feyrer F, Fleming K. 2008. Long-term trends in summertime habitat suitability for delta smelt, *Hypomesus transpacificus*. *San Francisco Estuary and Watershed Science* [Internet]. Available from: <http://www.escholarship.org/uc/item/5xd3q8tx>.

Patten BG. 1977. Body size and learned avoidance as factors affecting predation on coho salmon (*Oncorhynchus kisutch*) fry by torrent sculpin (*Cottus rhotheus*). *Fishery Bulletin* 75:453-459.

Post JR, Van Poorten VT, Rhodes T, Askey P, Paul A. 2006. Fish entrainment into irrigation canals: an analytical approach and application to the Bow River, Alberta, Canada. *North American Journal of Fisheries Management* 26:875-887.

[SDFFF] South Delta Fish Facility Forum. 2003a. Meeting summary and action items dated January 29, 2003. Available from: http://calwater.ca.gov/calfed/library/Archive_Conveyance.html.

[SDFFF] South Delta Fish Facility Forum. 2003b. Where do we go from here? Meeting presentation - agenda dated November 3, 2003. Available from: http://calwater.ca.gov/calfed/library/Archive_Conveyance.html.

Sommer T, Armor C, Baxter R, Breuer R, Brown L, Chotkowski M, Culberson S, Feyrer F, Gingras M, Herbold B, Kimmerer W, Mueller-Solger A, Nobriga M, Souza K. 2007. The collapse of pelagic fishes in the upper San Francisco Estuary. *Fisheries* 32:270-277.

Stevens DE. 1966. Food habits of striped bass, *Roccus saxatilis*, in the Sacramento-San Joaquin Delta. In: Turner J, Kelley DW, compilers. *Ecological studies of the Sacramento-San Joaquin Delta. Part II: Fishes of the Delta*. California Department of Fish and Game. Fish Bulletin 136:68-96.

Stevens DE, Miller LW. 1983. Effects of river flow on abundance of young Chinook salmon, American shad, longfin smelt, and delta smelt in the Sacramento-San Joaquin River system. *North American Journal of Fisheries Management* 3:425-437.

Sutphin ZA. 2008. High pressure injection of a photonic marking agent: Mark retention and effects on survival of juvenile striped bass, *Morone saxatilis*, and adult delta smelt, *Hypomesus transpacificus*. Technical report. Tracy Fish Facility Studies Volume 34. Byron (CA): U.S. Bureau of Reclamation, Department of the Interior. 21 p.

Sutphin Z, Morinaka J. 2010. Evaluation of calcein immersion for batch-marking fish: survivability and mark retention in delta smelt and Sacramento splittail. *Tracy Technical Bulletin* 2010-1. Byron (CA): U.S. Bureau of Reclamation, Department of the Interior. 13 p.

Swanson C, Reid T, Young PS, Cech JJ. 2000. Comparative environmental tolerances of threatened delta smelt (*Hypomesus transpacificus*) and introduced wakasagi (*H. nipponensis*) in an altered California estuary. *Oecologia* 123:384-390.

Swanson C, Young PS, Cech JJ. 1998. Swimming performance of delta smelt: maximum performance, and behavioral kinematic limitations on swimming at submaximal velocities. *Journal of Experimental Biology* 201:333-345.

SAN FRANCISCO ESTUARY & WATERSHED SCIENCE

- Tillman T. 1993. December 1992 estimates of pre-screen mortality of juvenile Chinook salmon at Clifton Court Forebay; State Water Project. Byron, California. DFG Memorandum Report. Bay-Delta Project. Stockton, CA.
- Tillman T. 1995. Clifton Court Forebay predator-predation control. Program activities of the Interagency Ecological Program of the Sacramento-San Joaquin Estuary dated May 1, 1995. Available from: http://www.water.ca.gov/iep/activities/monitor/prescreen_loss.cfm.
- Trefethen PS. 1968. Fish passage research. Review of progress, 1961-66. U.S. Fish and Wildlife Service Bureau of Commercial Fisheries Circular Report 254.
- Turner JL. 1966. Distribution and food habits of Ictalurid fishes in the Sacramento-San Joaquin Delta. In: Turner J, Kelley DW, compilers. Ecological studies of the Sacramento-San Joaquin Delta. Part II: Fishes of the Delta. California Department of Fish and Game Fish Bulletin 136:130-143.
- [USFWS] U.S. Fish and Wildlife Service. 1996. Sacramento-San Joaquin Delta native fishes recovery plan. Portland (OR): U.S. Fish and Wildlife Service. 195 p.
- [USFWS] U.S. Fish and Wildlife Service. 2008a. Formal Endangered Species Act consultation on the proposed coordinated operations of the Central Valley Project (CVP) and State Water Project (SWP). Sacramento (CA): U.S. Fish and Wildlife Service, California and Nevada Region. 396 p.
- [USFWS] U.S. Fish and Wildlife Service. 2008b. Study protocol for a compassionate aquaculture investigational new animal drug (INAD) exemption for calcein (SE-MARK™), (INAD #10-987). Bozeman (MT): Aquatic Animal Drug Approval Partnership Program. 18 p.
- Young PS, Swanson C, Cech JJ. 2010. Close encounters with a fish screen III: behavior, performance, physiological stress responses, and recovery of adult delta smelt exposed to two-vector flows near a fish screen. Transactions of the American Fisheries Society 139:713-726.
- Vörösmarty CJ, McIntyre PB, Gessner MO, Dudgeon D, Prusevich A, Green P, Glidden S, Bunn SE, Sullivan CA, Reidy Liermann C, Davies PM. 2010. Global threats to human water security and river biodiversity. Nature 467:555-561.

APPENDIX A: COMPUTATION OF PRIMARY AND SECONDARY BYPASS RATIOS

Primary Bypass Ratio Calculations

$$\text{Primary flow per bay} = \frac{\text{Primary channel flow}}{\text{No. of bays in use}}$$

$$\text{Primary channel approach velocity} = \frac{(\text{Primary flow per bay} \times \text{No. of bays in use})}{(\text{Total width of primary bays in use} \times \text{Primary channel depth})}$$

$$\text{Water velocity at primary bypass opening} = \frac{(\text{Secondary channel flow})}{(\text{Primary channel depth} \times \text{Width of 2 primary bypass openings})}$$

$$\text{Primary bypass ratio} = \frac{(\text{Water velocity at primary bypass opening})}{(\text{Primary channel approach velocity})}$$

Secondary Bypass Ratio Calculations

$$\text{Secondary channel approach velocity} = \frac{(\text{Secondary channel flow})}{(\text{Width of secondary channel} \times \text{Secondary channel depth})}$$

$$\text{Water velocity at secondary bypass opening} = \frac{(\text{Flow into the holding tank building})}{(\text{Secondary channel depth} \times \text{Width of secondary bypass opening(s)})}$$

$$\text{Secondary bypass ratio} = \frac{(\text{Water velocity at secondary bypass opening})}{(\text{Secondary channel approach velocity})}$$