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RESEARCH

# Reconsidering the Estimation of Salmon Mortality Caused by the State and Federal Water Export Facilities in the Sacramento–San Joaquin Delta, San Francisco Estuary

Andrew Jahn<sup>\*,1</sup> and William Kier<sup>2</sup>

## ABSTRACT

Combined water exports from Old River in the south end of California’s San Francisco Estuary (estuary) by state and federal pumping facilities entrain small fishes, including out-migrating juvenile salmon. Both export projects have fish salvage facilities that use behavioral barriers (louvers) in combination with screens to guide fish into collection areas from which they are trucked to release points in the western Delta. Sacramento River-origin Chinook Salmon are regularly taken in the projects’ fish salvage operations. Survival has been estimated within the boundaries of both intake structures, but not in Old River. Prevailing methods for estimating fish losses are based on studies of louver efficiency, near-field survival at the state facility, and assumed survival at the federal facility. The efficiency of the fish salvage operations is affected by several factors, including intake velocity, debris build-up on the louvers and trash

racks, and by the omnipresence of predators in front of and within the fish guidance structures. Analysis of existing data suggests that under average conditions, juvenile salmon survive entrainment into the forebay of the state facility at a rate of less than 10%. There is no evidence for better survival at the federal facility. We found no data on predation outside of either the state’s forebay or the federal trash boom, structures which are separated by an approximately 2-km reach of Old River where predation on small fish is thought to be intense. We suggest an improvement to the existing loss estimation, and discuss some features of the studies needed to increase its accuracy and precision.

## KEY WORDS

Chinook Salmon, winter-run, San Francisco Estuary, mortality estimation, State Water Project, Central Valley Project

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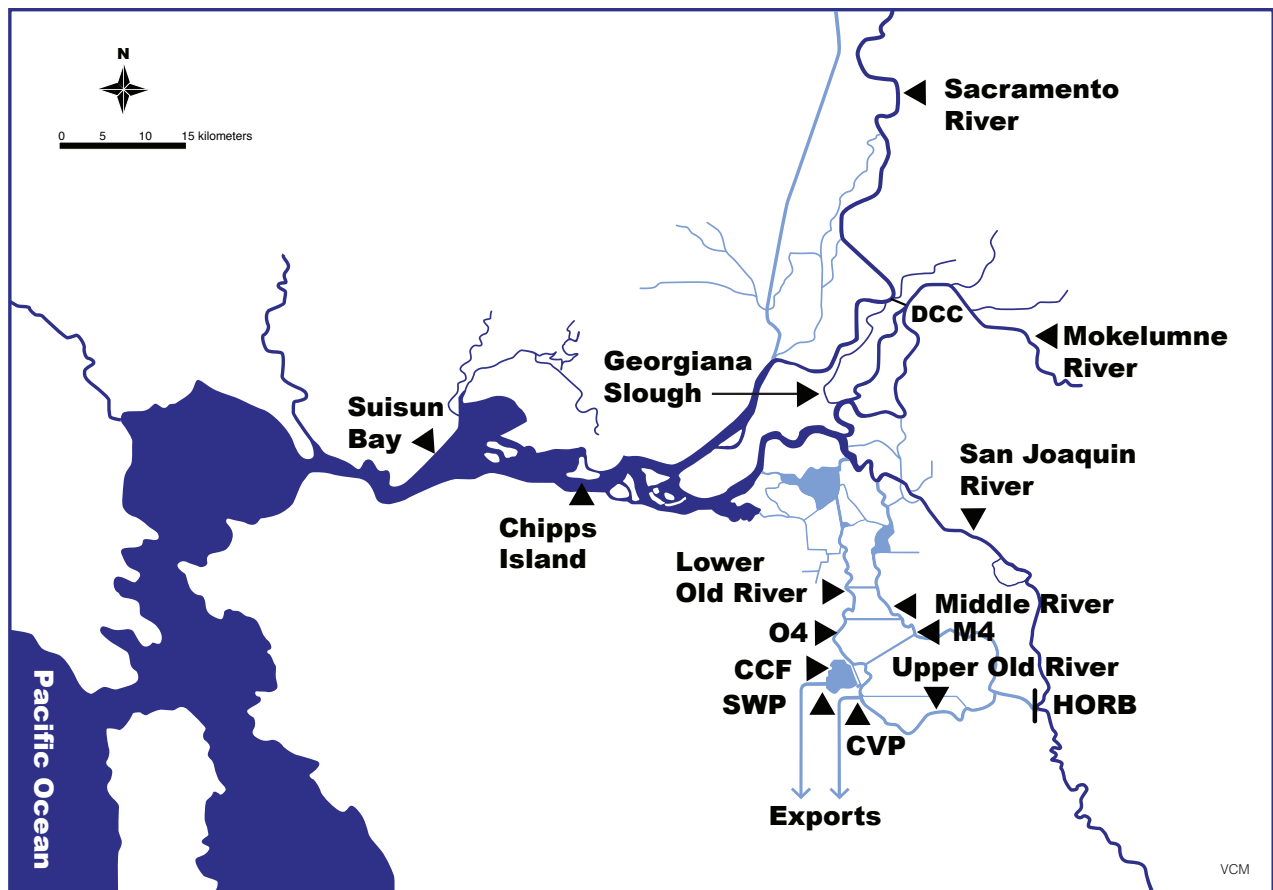
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## INTRODUCTION

California is inhabited by nearly 40 million people, most of whom live in the southern half of the state. Most precipitation falls in the northern half of the state, which is drained by the Sacramento River system. This system, along with the San Joaquin River to the south and streams

that drain the western slope of the Sierra Nevada in between them, all meet in California's Central Valley in a network of channels and islands commonly referred to as the California Delta. The gravitational flow of these rivers is mainly tidal in the South Delta, where the mean seaward flow can be reversed by diversions for agricultural and municipal use. The largest of these diversions are the export facilities of the federal Central Valley Project (CVP) and the State Water Project (SWP) (Figure 1). In recent years, these exports have caused the Old and Middle rivers to flow upstream (as a tidal average; Fleenor et al. 2010), reducing the survival of fish and creating conflict between the users of the exported water and those who advocate for the fish and depend upon the fisheries (SWRCB 2010; Luoma et al. 2015).

Anadromous salmonids use the Delta as a migratory pathway between their home streams and the Pacific Ocean, and as rearing habitat (Moyle 2002; NMFS 2009; Williams 2006, 2012). Experimental evidence shows that out-migrating juvenile Chinook Salmon (*Oncorhynchus tshawytscha*) from the Sacramento River follow routes through the Delta in numbers roughly proportional to the flow of Sacramento River water (Perry et al. 2010, 2013), a result Kimmerer and Nobriga (2008) anticipated in discussing particle-tracking results. Survival of out-migrants that follow routes through the South Delta is lower than that of fish that remain in the Sacramento mainstem (Perry et al. 2016, 2018). Fish that enter the South Delta are subject to reversing tidal flows and make slower progress



**Figure 1** Simplified map of the eastern San Francisco Estuary showing the locations of places and facilities mentioned in the text. CCF = Clifton Court Forebay, DCC = Delta Cross Channel, HORB = barrier at head of Old River. O4 and M4 are state Highway 4 crossings of Old and Middle rivers. The SWP and CVP are, respectively, the state and federal water export and fish salvage facilities.

toward the Delta exit at Chipps Island. This prolonged migration increases exposure of the out-migrants to predators and other biotic and abiotic factors that can reduce their fitness and survival (NMFS 2009; Luoma et al. 2015; Grossman 2016; Perry et al. 2018). One source of mortality for fish that enter the South Delta is the previously mentioned water diversions of the SWP and CVP.

The CVP and SWP both include many man-made features, including canals such as the Delta Cross Channel (DCC), which helps move Sacramento River water into the central and South Delta, and movable barriers such as that at the head of Old River (HORB) at the confluence of upper Old River and the San Joaquin River, which is placed at certain times to direct San Joaquin River-origin fish past this entrance to Old River. Unless otherwise noted in what follows, our use of the terms SWP and CVP refers only to the fish salvage facilities in front of the canals that lead to the export pumps.

The CVP and SWP export facilities each use behavioral fish barriers that consist of systems of louvers and bypasses designed to exclude large fish and to direct small ones into a collection area from which they can be captured, transported, and released into the western–downstream–Delta (Hallock et al. 1968; Heubach et al. 1973). Both facilities originally used two sets of louvers, called primary and secondary, to reduce the amount of water that enters the fish collection vessels. At the SWP, a perforated plate replaced the secondary louvers in the early 1980s (Brown et al. 1996; Morinaka 2013), and at the CVP, a traveling screen replaced the secondary louvers in 2014 (Karp et al. 2017). Upstream of the louver arrays are trash racks that capture much of the debris before it can reach the louvers. Upstream of the trash racks are trash booms set at an angle to the flow to deflect large floating debris such as vegetation mats and logs, to reduce clogging of the trash racks. A major difference between the SWP and CVP facilities is the existence of a closeable, open-water feature called Clifton Court Forebay (CCF) at the SWP. The CCF, Old River in the immediate vicinity of the CVP fish facility,

the HORB, and release points in the western Delta have all been identified as “predation hot spots” (Grossman et al. 2013; Grossman 2016).

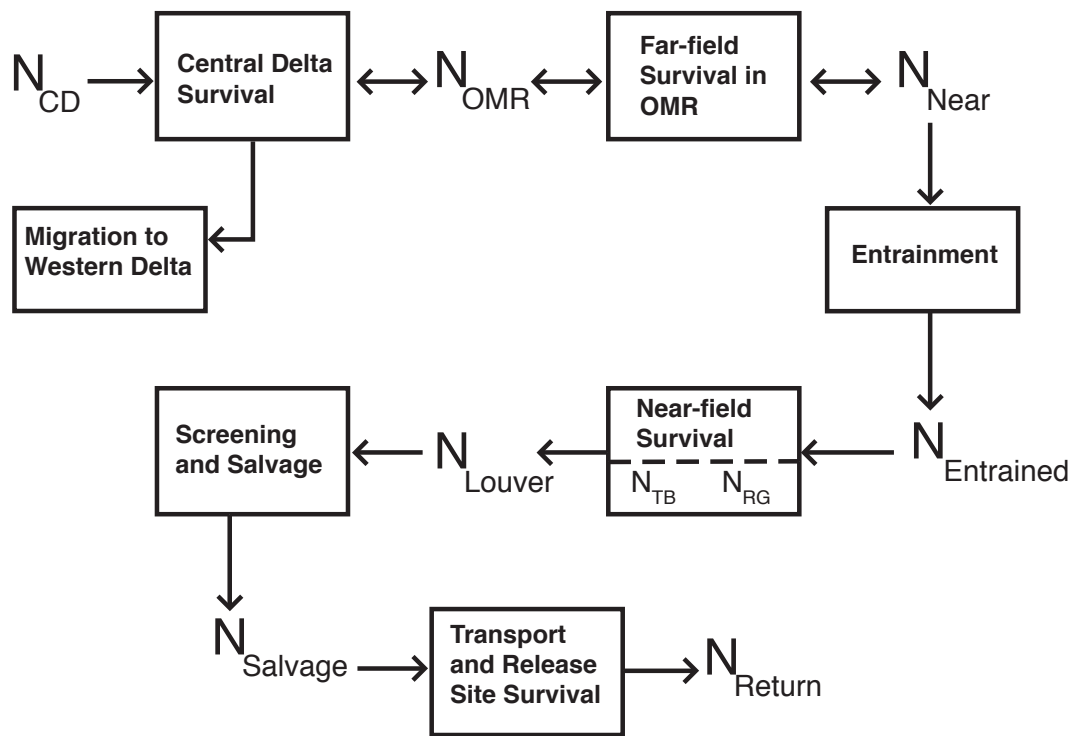
To the degree to which the southward flow induced by the export pumps draws fish out of the safer Sacramento River and into the interior Delta where the probability of survival is lower, the greater mortality experienced by these fish is a result of SWP and CVP operations. This appears to be what some authors refer to as “indirect mortality” (e.g., CDWR and CDFG 1986; SST 2017). In principle, with an estimate of the number of migrating fish, a refined model of route probabilities, and existing or refined estimates of route-specific survival rates (e.g., those of Perry et al. 2018), this contribution of the water projects to juvenile salmon mortality could be estimated. However, our purpose here is only to examine existing studies of juvenile salmon survival in the vicinity of the SWP and CVP facilities, and suggest improvements in the near-field loss estimate. In consideration of indirect evidence of hot spots, we also suggest exploring the possible existence of a zone of above-background predation near the export facilities, and estimating the survival of juvenile salmon within this zone. Such studies could be designed to help alleviate two competing sources of bias in the survival estimate, improve precision, and ensure that the estimates pertain to existing conditions and practices at the facilities. We note bias in the salvage counts, but that will require modeling beyond the scope of this paper.

The fish salvage facilities afford a relatively easy sampling of the entrained fish populations, and the state and federal agencies both gather extensive data sets of the salvage (e.g., Aasen 2016). Existing salvage-based loss estimates of Sacramento River-origin Chinook Salmon use various estimates of near-field “pre-screen” survival and louver-screen efficiency to build up a partial estimate of near-field loss. The data that underpin the prevailing method (Anonymous 2018) are several decades old and may not apply to present conditions. The formulas in Anonymous (2018) are used by the US Bureau of Reclamation (Reclamation), the California

Department of Fish and Wildlife (CDFW), and the California Department of Water Resources (CDWR) (2020 phone conversation between G. Aasen and A. Jahn, unreferenced, see “Notes”) and others (e.g., SacPAS 2020). In modified form, with some altered parameters, the calculation appears elsewhere (Kimmerer 2008; NMFS 2009; Zeug and Cavallo 2014). Here we re-review the studies on which the data are based, and the method of estimating screen efficiency. We use the existing data to calculate interim estimates of near-field survival, and give an equation for propagating the uncertainty of these estimates into those for near-field loss. New studies of near-field survival could improve the precision—and probably the accuracy—of these estimates. We describe some necessary features of the new studies and, pending their completion, propose an interim loss calculation that is simpler, more true to the existing data than that described in Anonymous (2018), and that gives an approximate standard error for the loss estimate.

### CONCEPTUAL MODEL AND DEFINITIONS

The basic concept here is that fish moving with the tides but with a mean drift southward face an increased probability of entrainment as they approach the export facilities. At some point, their survival is strongly influenced by predation near the facilities, as well as by failure of the behavioral barriers to divert them all from the export canals. After leaving the Sacramento River by any route, some unknown number of fish ( $N_{OMR}$ ) enter Old and Middle rivers (Figure 2 and Table 1). Some of these fish continue tracking southward toward the export projects, and at some point a certain number of them ( $N_{Near}$ ) enter an as-yet-undelimited zone from which they may either return northward or else be entrained into the fish salvage facilities. The entrained fish ( $N_{Entrained}$ ) begin to encounter project-related, near-field mortality. In the current estimation procedure (Anonymous 2018),  $N_{Entrained}$  is simply defined as the number of fish that pass the trash booms (TB) at the CVP, and the radial gates



**Figure 2** Conceptual sketch of numbers of juvenile salmon along the pathway to entrainment, screening, salvage, and release by South Delta water export projects. Numerical terms are defined in Table 1.

**Table 1** Definitions of terms used in the conceptual model of entrainment (see also Figure 2)

Term	Definition
$N_{CD}$	Number of fish that enter the central Delta from the Sacramento River
$N_{Entrained}$	Number of fish that enter a zone of near-field mortality factors and do not return to the central Delta (subset of $N_{Near}$ )
$N_{Export}$	Number of fish that pass through the salvage facility and into the export canal
$N_{Louver}$	Number of fish that reach the primary louvers
$N_{Near}$	Subset of $N_{OMR}$ that enter a zone of increased predation associated with CVP and SWP export facilities
$N_{NFLoss}$	Number of fish lost to near-field mortality factors
$N_{OMR}$	Subset of NCD that enter Old and Middle rivers
$N_{Returned}$	Number of fish that survive salvage, trucking, and release operations
$N_{RG}$	Number of fish that pass the radial gates at the SWP
$N_{Salvage}$	Number of fish captured in a project salvage facility
$N_{TB}$	Number of entrained fish that reach the trash boom
$N_{TR}$	Number of entrained fish that reach the trash rack
$S_{Entrained}$	Fraction of entrained fish diverted to salvage
$S_{Louver}$	Fraction of fish that encounter the primary louvers diverted to salvage
$S_p$	Fraction of entrained fish that reach the primary louvers
$S_{Return}$	Fraction of salvaged fish successfully returned to the western Delta
$S_{RG}$	Fraction of fish that pass the radial gates diverted to salvage
$S_{CCF}$	Pre-trash boom survival = $SRG/STB$
$S_{TB}$	Fraction of fish that pass the trash boom diverted to salvage
$S_{TR}$	Fraction of fish that pass the trash rack diverted to salvage

(RG) at the SWP's entrance to the CCF. If this is correct, then  $N_{Entrained} = N_{TB}$  for the CVP and  $N_{Entrained} = N_{RG}$  for the SWP. There are at least anecdotal observations that suggest a zone of above-background predation in Old River outside

the facilities (Grossman et al. 2013; Vogel 2010, 2011; Karp et al. 2017), in which case  $N_{Entrained}$  will be a larger number for one or both facilities.

Except in experiments, the number of fish in the near-field zone  $N_{Near}$  is an unknown quantity. The double-ended arrows in Figure 2 indicate that, throughout most of the southward route, there is some probability that a fish will reverse course and migrate toward the western Delta. Even in experiments, some number of fish can potentially leave the near-field zone and migrate north toward the San Joaquin River, such that there is some uncertainty in the value of  $N_{Entrained}$ . Fish that leave an experiment in one facility (CVP or SWP) can also be entrained into the other. This challenge in experimental design is more acute with stronger-swimming fish like Steelhead (Clark et al. 2009) than with the smaller Chinook Salmon used in the experiments described here (mean group fork lengths [FLs] < 125 mm). For completeness, we define the term  $N_{Entrained}$  for the near-field fish that do not wander away from the zone of project influence, even though with current knowledge there is no way to distinguish  $N_{Entrained}$  from  $N_{Near}$ .

With an experimentally derived estimate of the survival rate of entrained salmon juveniles at either facility,  $N_{Entrained}$  can be estimated from the number of salvaged individuals of the population of interest (Equation 1), and near-field loss is this number minus the number of fish safely returned to the western Delta (Equation 2). Treating each facility separately, for a given time-period:

$$N_{Entrained} = N_{Salvage} * S_{Entrained}^{-1} \tag{1}$$

$$N_{NFLoss} = N_{Entrained} - N_{Returned} \tag{2}$$

$N_{Returned}$  will be some fraction ( $S_{Return}$ ) of  $N_{Salvage}$ . In Anonymous (2018)  $S_{Return} = 0.98$ , and  $S_{Entrained}$  is partitioned into two parameters, one for louver screen efficiency ( $S_{Louver}$ , Appendix A) and the other for pre-screen survival ( $S_p$ , Appendix B) of entrained salmon. (Potential biases in the survival terms are discussed in a later section.) While it

is natural to envision the salvage sample as the cumulative result of fish surviving far-field, near-field, and guidance-system hazards (Hallock 1968; Anonymous 2018), it is not necessary to build up a loss equation by estimating parameters for each step (Kimmerer 2008; Jahn 2011). That said, studies (e.g., Karp et al. 2017) to find ways to maximize the survival of entrained fish at various steps in the process might still facilitate better management.

We analyze the calculations used in Anonymous (2018) in Appendices A and B. Briefly, the method gives a point estimate of loss using two categories of fish length to regress  $S_{\text{Louver}}$  on the calculated velocity of flow into the primary louvers. The limitations of these regressions are described below and in Appendix A. Near-field survival is then obtained as the product of  $S_{\text{Louver}}$  and a facility-specific value of  $S_p$ .

## CURRENT LOSS ESTIMATES

Existing salvage-based loss estimates of Sacramento River-origin Chinook Salmon are all estimates of near-field loss,  $N_{\text{NLoss}}$  that use various estimates of near-field “pre-screen” survival  $S_p$ , louver survival  $S_{\text{Louver}}$ , and trucking and handling survival  $S_{\text{Return}}$  to build up the estimates (Kimmerer 2008; NMFS 2009; Zeug and Cavallo 2014; Anonymous 2018). This method is described in Equation 3:

$$N_{\text{NLoss}} = N_{\text{Salvage}} * S_{\text{Louver}}^{-1} * S_p^{-1} - N_{\text{Salvage}} * S_{\text{Return}} \quad (3)$$

Laboratory and outdoor flume studies have shown that louvers can achieve fish guidance efficiencies that exceed 90% (Bates and Vinsonhaler 1957; Mainz 1978). However, flow variations, predation, and reaction to predators can decrease the efficacy of these devices. All estimates of  $S_{\text{Louver}}$  must be specific to facilities and conditions (Scruton et al. 2002). Estimates of  $S_{\text{Louver}}$  used in Anonymous (2018) are based on counts of  $N_{\text{Louver}}$  and  $N_{\text{Export}}$  derived from captures of migrating Chinook Salmon juveniles in specially designed nets within the SWP facility (Heubach et al. 1973).

Given an estimate of  $S_{\text{Louver}}$ , it is possible to estimate pre-screen survival  $S_p$  from an inflated salvage count without direct knowledge of the number of fish lost to the export canals. For example, some number of marked fish released experimentally at the radial gates of the CCF will be counted in the salvage, giving

$$S_p = N_{\text{Salvage}} * S_{\text{Louver}}^{-1} * N_{\text{RG}}^{1-} \quad (4)$$

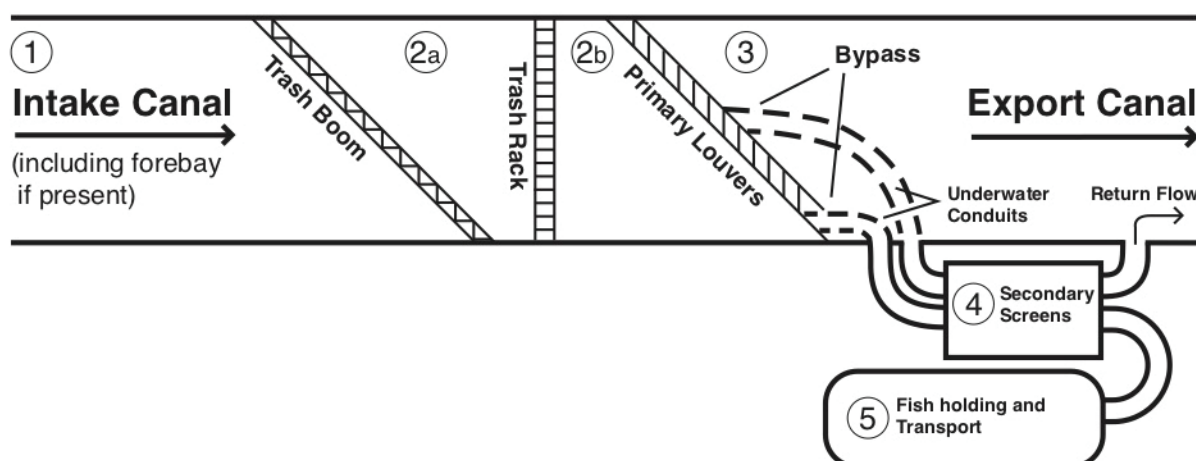
Although Equation 4 is the basis of pre-screen survival estimates used in the loss estimations cited above, use of it to get  $S_p$  creates non-independence of  $S_p$  and  $S_{\text{Louver}}$  in Equation 3.

All the counts and survival values used in the loss equations are estimates. The salvage at both facilities is sampled in time intervals and expanded accordingly. Studies to estimate  $S_p$  (or its complement) that were used in Anonymous 1987 and elsewhere were conducted mainly in CCF, but also on some smaller irrigation facilities, and were based on Equation 4.

## Louver Efficiency, $S_{\text{Louver}}$

Louver arrays used as behavioral barriers are set at an angle to the incoming flow (Figure 3). Fish face into the current and approach the louvers tail-first, avoiding the turbulence induced by the louvers and moving diagonally until they reach a bypass that shunts them to secondary louvers or screens and thence to an area of relative safety (Bates and Vinsonhaler 1957; Ruggles and Ryan 1964; Skinner 1974). Fish can be lost at several places (see numbers on Figure 3). Louver efficiency accounts for fish loss through the primary louvers (3), and to predation within the bypass conduits or loss through the secondary screening structures (4).

Under laboratory conditions, with laminar flow approaching the louvers, louver effectiveness is expected to rise steeply as approach velocity nears the burst swimming speed of the fish. One might then expect a moderate increase of effectiveness at low velocity, a steep and nearly linear rise as burst swimming speed is approached, and then a decrease with increasing



**Figure 3** Generic diagram of SWP or CVP fish facility

velocity until the fish are no longer able to avoid the louvers. For these and other reasons, it is reasonable to expect different survival rates for different species and sizes of fish. Moreover, it is known that turbulence induced by debris as well as chasing and foraging by predators can reduce louver effectiveness (Hallock et al. 1968; Liston et al. 1994; US Congress 1995; Scruton et al. 2002; DeMoyer 2007).

Effects of screen efficiency and pre-screen predation can merge when experimental subjects are introduced in front of the louvers (e.g., Karp et al. 1995, and some of the experiments summarized by Gingras 1997). This is because the efficiency estimate (portion of released fish recovered in the salvage) is confounded by the variable and unmeasured effects of predators near the louvers (see 2b in Figure 3; Hallock et al. 1968; Liston et al. 1994; Bridges et al. 2019). For example, Hallock et al. (1968) wrote, “Fish which could go between the louver slats usually avoid them if they have the swimming strength and desire to do so. Very small fish lack the strength to keep clear and are swept through. Larger fish that have ample strength to avoid the louvers will sometimes go through them. Sometimes they dart through to avoid a predator, sometimes for no apparent reason.” For Chinook Salmon out-migrants that enter the SWP and CVP facilities,  $S_{\text{Louver}}$  is a survival term, because there is no escape from the export canals.

### Pre-Screen Survival, $S_p$

Experimental determinations of near-field survival depend first on a definition of the spatial extent of intense pre-screen predation and, second (without telemetry), by the choice of a value of  $S_{\text{Louver}}$ , as expressed in Equation 4.  $S_p$  is the fraction of released fish that are estimated to have reached the face of the louvers. At the SWP facility, the spatial extent of near-field loss is often envisioned as the area within the CCF and intake canal. But the assumption that a concentration of predators extends out no farther than the radial tide gates at the entrance to the forebay (Figure 4) is questionable—and it is not clear that it has been tested. At the CVP facility, the extent of near-field mortality is even less well known, because there are no manmade structures beyond the trash boom, and limited studies of predation outside the trash rack (see 1 and 2a in Figure 3).

### Survival after Salvage, $S_{\text{Return}}$

There is evidence that survival of young salmon exposed to handling and trucking between the salvage facilities and release points can be high, exceeding 95% (Sutphin and Hueth 2015). Some studies, however, have found evidence of predation while fish are en route (Aasen 2013). Most important, survival of these fish upon release in areas of known concentrations of piscivorous fish and birds is unknown and difficult to determine; it is the subject of ongoing research (Miranda et al. 2010; Fullard et al. 2019).





**Figure 4** Vicinity map of state and federal fish facilities near Tracy, California

Like “indirect mortality,” loss from predation at the release points is unaccounted for in present loss evaluations.

## SOURCE MATERIAL

As discussed above, near-field mortality is partitioned into two phases in the calculations: the first an estimate of screen (louver) efficiency, and the second called “pre-screen loss.” There are other steps, such as adjusting for loss during trucking and (at the CVP) for losses during louver cleaning, but the basic calculation proceeds by inflating an expanded sample count by the assumed louver efficiency, then dividing this result by a pre-screen survival parameter  $S_p$  to get an estimate of the number of fish that were entrained. Estimated near-field loss is then the number entrained minus the number salvaged and released alive to the western Delta.

All the experimental data pertinent to the salmon loss equation in current use (Anonymous 2018) are referenced to unpublished memoranda written by California Department of Fish and Game

(CDFG)<sup>1</sup> staff. Experiments in the CCF and SWP fish facility were summarized by Gingras (1997). These experiments were run by introducing marked fish near the radial gates of CCF at times when the current was running strongly into the facility, presumably to minimize the chance that test subjects would leave the area (although most of the data sets were collected over more than one tidal cycle with no mention of radial gate operations). In most of the experiments, fish marked in a different way were introduced near the trash boom, some 100 meters in front of the louver screens.

Although there was some inconsistency in definition of terms, it appeared that only the first two values in the Gingras (1997) summary table were pre-screen loss as defined here. All the work from 1984 onward used a paired release design, apparently to cancel the negative effects on pre-screen survival of introducing naïve fish

1. The name of the California Department of Fish and Game was changed in 2012 to “California Department of Fish and Wildlife.” Since the Department’s studies referenced here predate that name change, the authors have simply stayed with the studies’ original name.

into a novel environment. The pre-trash boom survival was determined from the ratio  $S_{RG}/S_{TB}$ . This formulation cancels out the various values of  $S_{Louver}$  used in the analyses, and may cancel some or all of the effects of introducing unacclimated fish; it does not account for the effects of predation on the fraction of fish that get as far as the trash boom but must still reach the face of the louvers. (For more details, see Appendices A and B).

## SUMMARY OF PARAMETER ANALYSIS

### Screen Efficiency

The official calculation of louver efficiency for salmon has not changed since it was first proposed in 1986. Two different equations are used: one for fish < 101 mm FL, the other for fish > 100 mm (Anonymous 2018). The statistics were not fully explained (Baracco 1984) but the independent variable (velocity) appeared to be extended outside the range of the original data (see Appendix A). For salmon < 101 mm, the regression gives a range of  $S_{Louver}$  from about 0.7 to 0.8 at velocities of 0.5 to 1  $\text{ms}^{-1}$ , and, for the larger size class, the range of  $S_{Louver}$  is about 0.65 to 0.76 for the same range of velocities. The lower efficiencies for larger fish were a surprising result not seen in the secondary louver data for salmon, or in combined efficiency for other species tested (Heubach et al. 1973; Skinner 1974; Appendix A). Skinner (1974) calculated a weighted, cumulative efficiency of about  $S_{Louver} = 0.75$  for salmon of 40 to 125 mm FL (his Figure 15).

The frequent need for predator removals and louver cleaning at both facilities suggests that actual louver efficiencies under normal operating conditions must average lower than indicated in controlled studies. A screen replaced the secondary louvers at the SWP in the early 1980s (Brown et al. 1996; Morinaka 2013) to the effect that juvenile fish cannot pass through the secondary screen, although predation can still occur in the conduits that lead to the secondary screens. Because the work underpinning the Baracco (1984) study was performed before the change in equipment, the relevance of these coefficients today is not certain. The CVP has

different dynamics and design, as well. Better estimates for the CVP will require site-specific study (Scruton et al. 2002).

A recent study (Karp et al. 2017) that used acoustic tags with detectors in the fish facility and its export canal at CVP gives an overall estimate of  $S_{Louver} = 0.77$  for the federal export facility, assuming complete detection of fish that pass into the export canal (Appendix A). These authors used small numbers of fish, and the secondary louvers at CVP were replaced after they completed their field work, so this estimate of  $S_{Louver}$  may also need confirmation.

### Near-Field Survival at SWP

The CDFG memoranda on pre-screen survival are summarized in Appendix B and here, in abbreviated form for salmon only (Table 2). We treat the report of 45 fish salvaged from the radial gate release (Bull 1994) as an expanded number. Kano (1985a, 1985b) used the expression “loss across the forebay” to describe the estimated mortality of marked fish between the radial gate release point and the trash boom (see 1 in Figure 3). As mentioned above, in at least seven cases what Gingras (1997) reported as pre-screen loss in his Table 1 (see also Appendix B) was actually pre-trash boom loss.

To simplify the discussion, we report survival (1 – loss) in Table 2. Because the design and focus of the studies changed through time,  $S_{Louver}$  was not always estimated, and thus  $S_p$  cannot be estimated in all cases. In Appendix B, we show the results of using reasonable ranges of  $S_{Louver}$  for the two Tillman reports, which give estimates of  $S_p$  that, taken together, do not affect the average.

In our view, the most useful parameter from Table 2, estimable in all cases, is mean near-field survival as estimated from the radial gate releases ( $S_{RG}$ ), which has a mean of 0.08 with a standard error of 0.03. Possible and known biases in  $S_{RG}$ , and the difficulties of estimating project-specific near-field survival, are discussed below. Five certainly, and probably six, of the pre-screen loss values tabulated by Gingras were the complement

**Table 2** Revised summary of SWP pre-screen loss experiments for juvenile Chinook Salmon originally summarized by Gingras (1997)

Reference	Date of experiment	FL (mm)	$S_{\text{Louver}}$	$S_P$	$S_{\text{CCF}}$	$S_{\text{RG}}$
Schaffter 1978	1976 / Oct	114	0.67	0.028	—	0.019
Hall 1980	1978 / Oct	87	0.81	0.123	0.14	0.099
Kano 1985a	1984 / Apr	79	0.74	0.332	0.37	0.245
Kano 1985b	1985 / Apr	44	0.69	0.132	0.25	0.091
Bull 1992	1992 / May	77	0.69	0.004	0.01	0.003
Tillman 1993a <sup>a</sup>	1992 / Dec	121	—	—	0.22	0.160
Tillman 1993b <sup>b</sup>	1993 / Apr	66	—	—	0.05	0.012
Bull 1994 <sup>b</sup>	1993 / Nov	117	—	—	—	0.004
				Mean	0.175	0.079
				SE	0.054	0.031

a. Reference seen but marked "DRAFT COPY ONLY."

b. Reference not seen.

of the ratio  $S_{\text{TB}}/S_{\text{RG}}$ , an estimate of pre-trash boom loss with (some of) the bias for the effect of unacclimated fish factored out. The ratio is also calculable from Hall's (1980) data, and the seven values give a mean survival term  $S_{\text{CCF}} = 0.15$  with a standard error of  $= 0.05$ . This partial estimate of pre-screen survival must be used along with an estimate of  $S_{\text{Louver}}$  to produce a loss estimate with unknown standard error, albeit one that omits loss between the trash boom and the face of the louvers.

### Near-Field Survival at CVP

Relevant estimates of  $S_P$  for the CVP facility post-date the work that supports Anonymous (2018). As explained in Appendix B, a "placeholder" value of  $S_P = 0.85$  was derived from early survival estimates made between the trash boom and the louvers ( $S_{\text{TB}}$ ) at other facilities (see 2a and 2b in Figure 3). With the completion of a series of experiments at SWP, mean  $S_{\text{TB}}$  at SWP now stands at 0.48 with a standard error of 0.10 (Appendix B). Three recent point estimates of  $S_{\text{TB}}$  at the CVP facilities are all  $< 0.5$ , if marked fish that were unaccounted for are all considered lost to near-field predation or to the export canal. There are no estimates of predation near, but outside of, the immediate vicinity of the CVP trash boom, although Vogel (2010, 2011) reported

a concentration of apparently defecated acoustic tags from San Joaquin River salmon in the area. In this regard, Karp et al. (2017) wrote, "The high number of unknown fates, particularly for Steelhead, influenced estimates of facility efficiency and pre-screen loss. These estimates would improve with development of reliable equipment and methods to determine predation events, as well as installation of additional acoustic equipment upstream of the trash boom." As observed by Kimmerer (2008), the only evidence that juvenile salmon entrained into the CVP enjoy a higher survival rate than those that enter the SWP is the circumstance that the state facility has a forebay.

If survival at CVP is substantially greater than at SWP, one should expect a higher salvage rate of salmon per unit volume of exported water, assuming both projects draw from the same pool of fish in Old River. In a memorandum from CDWR to CDFG, Brown (1988) reported salvage of salmon normalized to export volume as the ratio SWP/CVP (Table 3). Brown expected an average ratio of "about 0.2" and was surprised by the results, stating, "The ratios indicate that in general (20 of 27 times) the State facility salvages more salmon per acre-foot than does the federal facility. This...increased salvage at the state plant is...even more surprising because both plants receive the majority of their salmon from the San Joaquin River...thus the CVP gets the first chance at them." Brown saw in this a suggestion that pre-screen loss at the SWP had been over-estimated. However, as subsequent studies showed, estimated near-field survival (as  $S_{\text{RG}}$ ) remained very low at SWP, averaging  $< 8\%$  in four experiments performed after his 1988 memo (Table 2).

As indicated by Brown (quoted above), there may be differences in the mix and abundance of species entrained into the SWP and CVP facilities. However, as the intakes are  $< 2\text{ km}$  apart, over time they must be reasonably similar. For example, Nobriga and Cadrett (2001) found that SWP salvage was a necessary factor in a linear model that predicted CVP salvage of Steelhead. Predators, too, appear to be shared in common. Kano (1990), Gingras and McGee (1997), and Vogel

**Table 3** Ratios (SWP/CVP) of salvaged Chinook Salmon per unit volume of exported water. From Brown’s (1988) Table 2.

Year	Month		
	April	May	June
1978	NA <sup>a</sup>	2.0	7.0
1979	0.56	1.5	7.7
1980	0.52	1.0	3.0
1981	1.7	2.3	1.0
1982	2.4	1.2	1.5
1983	NA <sup>a</sup>	0.08	1.9
1984	0.35	0.55	23.5
1985	0.72	1.6	5.0
1986	2.7	0.93	2.0
1987	1.4	3.6	NA <sup>a</sup>

a. NA indicates that no ratio was calculable.

(2010, 2011) all reported Striped Bass entering and exiting the radial gates of the CCF. We interpret Table 3, with a median ratio of 1.6, to strongly indicate that the approach to the CVP intakes is no less perilous for out-migrating Chinook Salmon than that to the SWP. As suggested by Karp et al. (2017), this can be studied by extending a network of telemetry stations further out from the project(s). As the Old River between CVP and SWP has many more exits than the CCF, these studies will demand more resources than those at the CCF, although as indicated by Clark et al. (2009), the “non-participation” of tagged fish released near the radial gates is a complication even at the state facility.

### ESTIMATING NEAR-FIELD LOSS

With an estimate of near-field survival, Equation 3 can be simplified to Equation 5.

$$N_{NFIoss} = N_{Salvage} * S_{Near}^{-1} - N_{Salvage} * S_{Return} \quad (5)$$

There are currently two choices for the estimate of  $S_{Near}$  at the SWP: our preference is to use  $S_{RG} = 0.08$  with  $S_E = 0.03$ , but one could use the product  $S_{Lower} * S_{CCF} \approx 0.11$  with an unknown standard error and the fraction of loss between trash boom and louvers unaccounted for. For

the CVP, again our choice is  $S_{RG}$  from Table 2, but pending further study one could get a point estimate of loss by using some value  $S_{TB} < 0.5$  from Appendix B as a perhaps-generous estimate of  $S_{Near}$ . If estimates of  $S_{Return}$  remain near one, the focus for managers will remain on the accuracy and precision of the estimates of  $N_{Entrained}$  ( $N_{Salvage} / S_{Near}$ ) and  $S_{Near}$ . These, in turn, lead to an approximate estimate of the precision of the loss estimate, e.g., by the delta method (Equation 6). Simplifying the notation and using  $L$  for loss,  $S$  for near-field survival,  $N$  for mean of the expanded salvage per sampling period (usually a day) over some time-period of interest, and estimated entrainment  $G = N/S$ , we rewrite Equation 2 as  $L = G - S$  (from Anderson et al. 2013) and use the result of Equation 6 to estimate the standard error of  $L$  (Equation 7):

$$SE(G) = G * \sqrt{\left[ \left( \frac{SE(N)}{N} \right)^2 + \left( \frac{SE(S)}{S} \right)^2 - 2COV(N, S) \right]} \quad (6)$$

$$SE(L) = \sqrt{\left[ (SE(G))^2 + (SE(N))^2 - 2COV(G, N) \right]} \quad (7)$$

The daily salvage of salmon of a particular genetic group will often be in single digits, and frequently zero in individual 2-hourly counts, even during peak migration season. Even so, calculating its variance is relatively straightforward: sample size is large when the time-period of interest is a month or longer, and consequently the standard error of  $N$  will generally have less influence than  $SE(S)$  in Equation 6 (Jahn 2011). A problem with using the salvage facilities as a sampler of the entrained population (a purpose for which they were not designed) was broached by Anderson et al. (2013), who observed that the estimated entrainment is biased low because of the large number of zeros in the sample counts. That is, the salvage can be zero when both survival and  $N_{Entrained}$  are non-zero. In an example used in Anonymous (2018), the minimum number of entrained fish in a 2-hr sampling period that is likely to produce a non-zero count in a 10-minute salvage sample (at  $S_{RG} = S_{Lower} * S_P = 0.17$ ) is 70, i.e. 35 fish per hour. At a lesser flux of fish or lower survival rate, the

expanded salvage counts will produce many false zeros in estimated  $N_{\text{Entrained}}$ . For example, with  $S_{\text{RG}} = 0.08$ , if eight fish enter the forebay with an independent chance of being salvaged, the probability of getting a zero count in the salvage is  $(1 - 0.08)^8 = 0.51$ . The accumulated bias over many sampling periods can substantially affect the loss estimate. Other sources of bias in the counts are missing fish during periods of heavy debris loads in the salvage (a negative bias) and mis-assignment of wild salmon to their genetic run membership (either positive or negative bias; Perry et al. 2016).

As for error in the estimation of near-field survival, there is an 80-fold variation in the eight individual estimates of  $S_{\text{RG}}$  in Table 2. This suggests very large changes in near-field survival through time. Anderson et al. (2013) noted that it is unrealistic to expect a constant survival term through time and that, if the true value does vary through time, use of a constant parameter in the loss equation will lead to an underestimate. In this regard, Vogel (2011) wrote, "A fundamental question associated with the salmon survival estimates in the Delta is the stationarity of the predator field and, by association, the stationarity of the survival estimates. If the predators are highly mobile or congregate in different regions in the Delta at different times of the year, then the survival estimates will vary depending on the spatial and temporal variability of the predator fields." The  $S_{\text{RG}}$  values in Table 2 are right-skew, such that a log-normal distribution fits them somewhat better than a normal. Small samples from such non-random distributions can produce misleading estimates of population parameters. An accommodation for such samples, which often result when data acquisition is expensive, is an asymmetric confidence interval (CI), such as that given by Equation 8 (from Jahn and Smith 1987):

$$CI = m * \exp \left\{ \pm t_{\alpha} \sqrt{\ln \left( 1 + \frac{SE^2}{m^2} \right)} \right\} \quad (8)$$

where  $m$  is the sample mean,  $SE$  the standard error of  $m$ , and  $t$  the critical value of student's  $t$ -distribution for the appropriate degrees of

freedom and type-one error rate  $\alpha$ . Using  $S_{\text{RG}}$  and its standard error from Table 2 for  $m$  and  $SE$  with  $\alpha = 0.05$ , Equation 8 gives a 95% confidence interval for  $S_{\text{RG}}$  from 0.03 to 0.19. Any value of  $S_{\text{RG}}$  (or a product of  $S_{\text{Louver}}$  and  $S_P$  or  $S_{\text{Louver}}$  and  $S_{\text{CCF}}$ ) outside these limits is poorly supported by the existing data.

Because the data in Table 2 were generated with the use of experimental introductions of unacclimated fish into the CCF, Gingras (1997) listed reasons, including temperature shock and altered salinity and "light regime," why predator avoidance might be reduced in comparison to migrating juveniles acclimated to Old River. The effects of non-acclimation should have cancelled out in most of the pre-screen loss values reported by Gingras, because as mentioned above, most of them were calculated from trash boom-released controls, which should have experienced about the same effects of the sudden introduction to the new environment as the radial gate releases. Regardless, in consideration of the factors listed by Gingras, Greene (2008), calculating a 15% pre-screen survival rate based on his report, made a 67% adjustment to a supposed 25% survival rate for acclimated fish. This leads directly to a 67% deflation in the estimated entrainment, most of which goes to estimated loss. Fish released at the trash boom experienced pre-screen predation for a shorter time than those released at the radial gates, although the majority of recoveries from both groups generally occurred in the first day after release. Depending on time to acclimation, the paired release method may not have fully accounted for the effects of introducing non-acclimated fish. However, Greene's adjustment is at least partly redundant, and there was no mechanistic consideration of the expected duration or severity of the listed sources of degradation in predator avoidance. This adds uncertainty to the magnitude of her adjustment to the pre-screen survival estimate.

Beyond performance of unacclimated fish, there are other questions about experimental estimates of near-field survival. The tendency of some fish to leave the study area (Clark et al. 2009; Karp et al. 2017) might negatively bias the near-field

survival estimate if such fish escape northward to the general population of migrants in the Delta. The premise that elevated predation pressure from the SWP is confined to the forebay is a likely positive bias in the estimate of  $S_{\text{Near}}$  as  $S_{\text{RG}}$ . Striped Bass have been observed to pass through the radial gates in both directions (Kano 1990; Gingras and McGee 1997; Vogel 2010, 2011). It is therefore a fair presumption that predator fish are concentrated outside the fish facilities, at least at times. How far this above-background concentration extends should be investigated. If, as seems likely, elevated predation occurs before fish enter the forebay, then the experimentally estimated  $S_P$  and  $S_{\text{RG}}$  do not account for all pre-screen loss.

Anderson et al. (2013) proposed a way to account for the aforementioned counting bias in the estimation of  $N_{\text{Entrained}}$ . But in the absence of studies to quantify the other biases, accepting the estimated survival as is, with error ( $S_{\text{RG}}=0.08$ ,  $\text{SE}=0.03$ ) seems preferable, pending further studies. At any rate, like the  $S_{\text{Louver}}$  estimates for both facilities, it is likely that estimates of the various measures of near-field survival do not represent current conditions, especially at the SWP, where most of the experimental work predates structural (secondary screens) and operational (pumping rate) changes.

Finally, there are at least two reasons to increase the number of experimental trials that have to do with the precision of the estimates. The first and most obvious is to minimize the standard error of whichever measure is used to estimate  $S_{\text{Near}}$ . In addition, as noted by Anderson et al. (2013), there is good reason to expect positive covariance between the salvage and near-field survival if, as appears likely, the surviving fraction of entrained fish varies in time. At present, there is no way to estimate the covariance, but setting it to zero very likely overestimates the standard error of the number of entrained fish (Equation 6). Experiments performed in such a way as to estimate the covariance between  $N_{\text{Salvage}}$  and  $S_{\text{Near}}$  could reduce the error, and this should be of interest to managers who must keep an eye on the upper confidence limit of the loss estimate.

## DISCUSSION

As fish migrate southward in Old and Middle rivers, their chance of entrainment into SWP and CVP facilities increases. Vogel (2002) released radio-tagged juveniles in Old River some 14 km north of the SWP and inferred export-related mortality but did not observe it because of technical difficulties. Under what he termed “medium export” conditions (combined CVP and SWP exports of 200 to 300 m<sup>3</sup>s<sup>-1</sup>), most (64%) of the fish were considered to have been entrained into the export projects. Another 20% were presumed predated, and 16% remained in the channels or were unaccounted for at the end of the experiment. In contrast, under low export conditions (combined SWP and CVP exports of about 60 to 85 m<sup>3</sup>s<sup>-1</sup>), most of the tagged fish (68%) remained in the channels or were unaccounted for, and only 28% were considered lost to the projects. Vogel noted that the medium exports damped the tidal movements such that the fish “experienced minimal or no positive (downstream) flow on the first day whereas fish in releases 3 and 4 (low export) experienced long periods of high positive flow.” Vogel (2004) found that, similarly, fish that entered the interior Delta from the San Joaquin River tended not to return to the San Joaquin, and many of them tracked southward in Middle River under conditions of “reverse flow.” San Joaquin River-origin salmon are not Sacramento River-origin salmon, but we assume that salmon juveniles from any source, once entrained well into Old and Middle rivers, are transitioning into a zone of strong influence from the export facilities. The true extent of project influence is amenable to study by use of electronic-tagged fish with a network of fixed telemetry stations, possibly augmented with mobile tracking.

Clark et al. (2009) showed and Karp et al. (1995, 2017) suggested that test subjects at one facility wandered away, becoming “non-participants” in the experiments. Presumably, some fraction of these fish are entrained at the other facility (SWP or CVP) or lost to predators somewhere in between. Reporting on mark-recapture studies at the CVP, Karp et al. (2017) wrote, “there were high numbers of fish with unknown fates (23.2%

Chinook Salmon, 73.8% Steelhead), which reduced the precision of the pre-screen loss and facility efficiency estimates. In the future, estimates of these facility parameters would improve with development of reliable equipment and methods to definitively determine predation events, as well as installation of additional receivers and hydrophones upstream of the trash boom to reduce the proportion of unknown fates.”

The Old River near the CVP is more difficult to monitor than the CCF, but both projects share this source of water and fish (possibly to varying degrees). As suggested by Gingras (1997), release of tagged fish some distance north in Old and Middle rivers would ensure that the fish are acclimated to local conditions before they reached the CCF. This would be a complex and expensive undertaking, but coordinated studies of fish released in Old and Middle rivers (perhaps at the Highway 4 crossings; [Figure 1](#)) at both facilities simultaneously could provide cost sharing. If set up to estimate survival in short reaches between the release points and the export canals, such studies might lead to some consensus on the extent of a near-field zone of elevated predation associated with the facilities.

## CONCLUSIONS

Except for the pilot-scale study by Karp et al. (2017), none of the experiments discussed here were specifically designed to estimate total mortality from SWP or CVP operations, a topic of great interest to fish biologists and conservation agencies, as well as to the water export agencies. Rather, they were intended either to demonstrate the efficacy of the guidance systems or to shed light on various aspects of facilities and operations that might be improved. To these ends, much of the work has been successful. On the other hand, as a basis for estimating project effects under average, modern conditions on entrained populations of threatened and endangered salmon runs, the work leaves much to be done.

The evidence that near-field survival at CVP is greater than at SWP is not compelling.

Regarding his take estimate of winter-run by the export facilities, Kimmerer (2008) wrote, “From a population maintenance stand-point, the calculated loss rate at the export facilities would be a significant component of direct anthropogenic mortality.” The conventional loss calculation (Anonymous 2018) differs considerably from the central tendency of existing SWP survival data. Its adjustment for application to the CVP adds uncertainties that are especially important considering the conservation status of some of the Sacramento River salmon runs. It has been more than a decade since Williams (2006) wrote, “The estimated forebay mortality is large and plays an important role in the calculation of the take of winter-run Chinook, so it seems that more effort should be made to characterize it well.” Continuing improvements in run identification and studies of the general design suggested in the discussion above could improve both the accuracy and the precision of salmon loss estimates from the SWP and CVP exports.

The simplified loss calculation is a traditional application of sampling theory in which near-field survival is estimated as a fixed parameter. It is more true to existing data than the equations currently in use (Anonymous 2018), and like the older method, it is easily understood. It has the further advantage of giving an indication of the precision of the estimate. We suggest that [Equations 5 through 7](#) be used with  $S_{RG}$  from [Table 2](#) both for the present and retrospectively, until updated and more comprehensive studies are performed. For this purpose, estimating covariance between salvage and survival should be incorporated into future experiments. Recently, Anderson et al. (2013) and others (Tepley and Ceder 2013; Simonis et al. 2016) have suggested a different approach to the loss evaluation through modeling the mortality and associated parameters as random variables. Even if these suggestions are incorporated into practice, our recommendation for extending the spatial scale of the experiments and performing them cooperatively for both facilities would apply to any future approach.

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## NOTES

- Aasen G. 2020. Phone conversation with AJ (possibly June 5). Aasen said "everyone" uses the calculation method described in Anonymous (2018).
- Odenweller D. 2011. In-person conversation with AJ on Mar 18, 2011. Odenweller loaned AJ his hard copy of Heubach et al. (1973) and said the data files for this 1970–71 project were all lost.