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Revisiting Assumptions that Underlie Estimates of Proportional Entrainment of Delta Smelt by State and Federal Water Diversions from the Sacramento–San Joaquin Delta

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ABSTRACT

The delta smelt is a small, endemic fish that resides in the upper San Francisco Estuary. They are listed under state and federal Endangered Species Acts. Since 2002, their abundance has been at record low levels. Delta smelt are entrained at state (Banks) and federal (Jones) pumping plants that export water to much of California. Export cutbacks to limit entrainment have been controversial, making delta smelt arguably the most important fish in California. Kimmerer (2008) published the first estimates of proportional entrainment (mortality relative to population size) of delta smelt at the water export pumping plants, improving on previous estimates of absolute numbers entrained. This paper comments on Kimmerer's estimates, which ranged from 0% to 40% annually with considerable uncertainty reflecting the challenge in estimating the distribution and numbers of this scarce fish. Kimmerer's high estimates in some recent years and his conclusion that entrainment effects could be episodically important are counter to a lack of statistically significant correlation between entrainment and subsequent abundance. My analysis herein justifies estimates of lower proportional entrainment than those Kimmerer suggested. Based on alternative assumptions, his highest annual estimates of adult proportional entrainment would have been no more than 13%, and could even be in the range of 5% to 10%. Most adjustments resulting from alternative assumptions that underlie high estimates of larval–juvenile proportional entrainment cannot be quantified. However, I propose here that eight of ten key assumptions that underlie those estimates resulted in upward bias. Lower estimates of proportional entrainment would be consistent with the lack of statistically significant relationships between entrainment and subsequent abundance in previous studies, and would suggest that assessment of the importance of entrainment awaits additional analyses that narrow uncertainty. My findings presented here suggest that adding more stations and making other adjustments are needed to resolve detection problems with adult and larval–juvenile surveys.

KEY WORDS

delta smelt, *Hypomesus transpacificus*, diversions, entrainment estimates, population ecology

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INTRODUCTION

The delta smelt (*Hypomesus transpacificus*) was listed as a threatened species under state and federal Endangered Species Acts in 1993. State and federal water export pumps, located in the south-eastern extremity of areas occupied by delta smelt, supply water for much of California. Entrainment of delta smelt—i.e., intake of the fish into the export pumping plants, which is assumed to be equal to mortality for this fragile species—has been implicated as an important cause of their recent declining population numbers and has received great attention since indices of delta smelt abundance fell to record low levels in 2002 and to diminishing numbers since then. Kimmerer (2008) provided the first published estimates of proportional entrainment, that is, entrainment mortality relative to the number of delta smelt present. His estimates—that in some recent years up to 40% of the delta smelt population was entrained—supported the assertion that entrainment was threatening the smelt. These estimates were reflected in the biological opinion that resulted in requirements for conserving the species under the Endangered Species Act, by, in part, curtailing state and federal exports to limit entrainment. Kimmerer's methods for estimating entrainment are complicated and involve a number of assumptions. This paper examines those estimates critically and addresses uncertainties in underlying assumptions that could cause bias. It quantifies that bias where it is possible to do so and suggests adjustments in assumptions and analytical methods. The resulting alternative analysis suggests that lower estimates of proportional entrainment can be justified. A by-product of the analyses presented in this paper is the identification of intrinsic problems in the annual surveys that have been used to measure distribution and abundance of adult and larval–juvenile delta smelt. Suggestions for resolving those problems are presented.

Conflicts between human activities and the decline of native species are often difficult to understand and even more difficult to resolve. This is the case for the delta smelt, a small, euryhaline fish in the upper San Francisco Estuary. Almost all (95+%) delta smelt live only one year (Bennett 2005). In winter, adults move into turbid water, typically upstream into the Sacramento–San Joaquin Delta. They spawn once over several weeks, beginning in late February or March (Bennett 2005). Eggs are attached to substratum and hatch into 5- to 6-mm larvae in about 2 weeks (Bennett 2005). By summer, juveniles are generally found in the western Delta, near the confluence of the Sacramento and San Joaquin rivers. After being listed as a threatened species under both state and federal endangered species acts in 1993, abundance of delta smelt increased to a recent high in 1999, then decreased sharply to record low levels in 2002 of only a few percent of that abundance. The persistence of this recent decline has led to great concern about the factors that affect delta smelt abundance in general and that are responsible for the recent sharp decline in particular.

KIMMERER'S APPROACH AND METHODS

Kimmerer (2008) estimated proportional entrainment of adult and larval–juvenile delta smelt at the state and federal water export pumping plants for 1995 through 2006. Those estimates rely heavily on data collected in two surveys: the Kodiak Trawl, which samples for adult delta smelt once per month in January through May, and the 20-mm Survey, which samples for larvae and juveniles every two weeks in March or April through June or July. The Kodiak Trawl began in 2002, and the 20-mm Survey began in 1995. For years before 2002, and in one year (2003), when no January Kodiak Trawl was conducted, Kimmerer used December results from the Fall Midwater Trawl (FMWT), which has sampled for sub-adult delta smelt once per month in September though December since 1967. Figure 1 shows the area of the San Francisco Estuary that delta smelt occupy and also shows sampling stations for the Kodiak Trawl, which are similar in location to those for the 20-mm Survey.

Data from each survey can be used to estimate the abundance of delta smelt close enough to the water export pumps to be entrained, relative to total abundance. Note that this method does not necessarily require an estimate of the actual number of delta

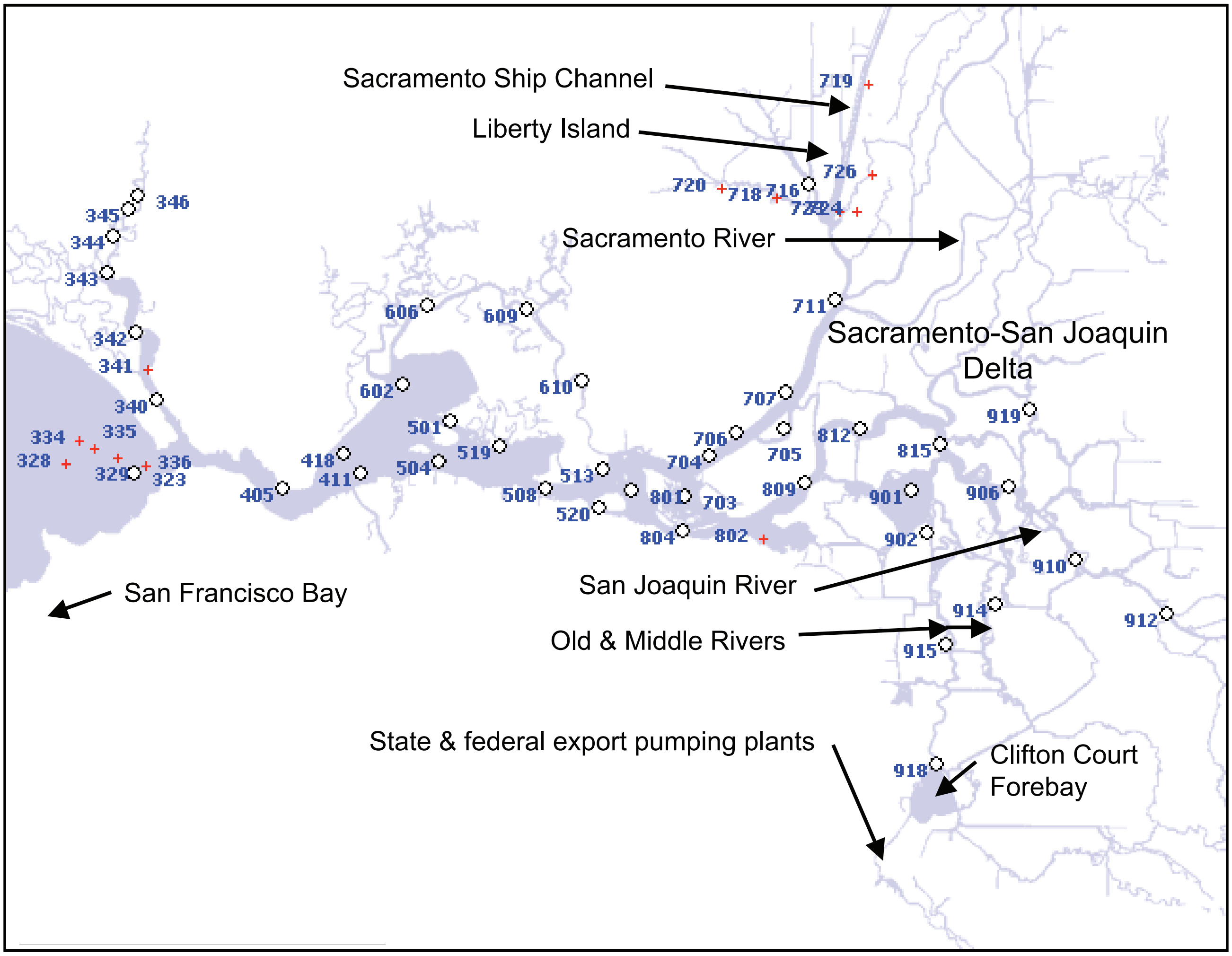

Figure 1 Areas occupied by delta smelt, location map, and sampling stations. For larval–juvenile surveys, open circle indicates station sampled, and plus sign indicates station not sampled.

smelt entrained or the actual number present, as long as entrainment relative to total number present can be reliably estimated. The accuracy of such estimates rests, in part, on sampling in all areas that delta smelt occupy, yet surveys producing the data on which Kimmerer's estimates are based did not always sample in all of those areas, including some areas far removed from the water export pumps. This has implications for estimates of proportional entrainment, which, along with other considerations, are discussed in more detail later in this paper.

Method for Estimating Proportional Entrainment of Adult Delta Smelt

Kimmerer estimated daily adult entrainment by scaling up from daily adult salvage numbers at the pumps. "Salvage" refers to the number of fish that reach salvage tanks at the state and federal pumping plants that export water from the Delta. At these pumping plants, fish are identified, counted, and measured, usually for 10 minutes every 2 hours. These 10-minute counts are used to estimate *what would have been counted* had counting occurred continuously over the sample period. Strictly speaking, this expanded count is "expanded salvage," but is generally, and in this paper, referred to as “salvage.” Salvaged fish are trucked to downstream locations in the Delta and released. Fish that enter the export facilities are “entrained.” Entrained fish die primarily from predation before they reach louvers that divert them to the salvage tanks. Some fish are not diverted because the louvers are not 100% efficient. So, entrainment is always greater than salvage. Because of their fragile nature, all entrained delta smelt are assumed to die in the salvage and trucking process; therefore, for delta smelt, entrainment, which is larger than salvage, is assumed to equal mortality at the export pumping plants.

Kimmerer estimated entrainment from salvage using the estimated ratio, Θ, of sampling efficiency of the Kodiak Trawl to sampling (salvage) efficiency at the two pumping plants, assumed to be the same at each plant. Kimmerer estimated relative abundance of adult delta smelt as the product of density and volume, where density is the average density at all stations sampled in the Kodiak Trawl, and volume is the total volume of water in the upper four meters in areas sampled, to account for the observation that adult smelt reside near the surface. For months when Kodiak Trawl data were not available, he used data from the FMWT, scaling up catch to account for the gear efficiency difference between the FMWT and the Kodiak Trawl.

Kimmerer estimated daily proportional entrainment as the ratio of relative entrainment to total relative abundance, using Θ to relate salvage to abundance estimated from Kodiak Trawl data. He estimated annual proportional entrainment of adults as the accumulation of daily proportional entrainment, adjusting each day’s proportional entrainment to account for adults surviving entrainment on previous days.

Method for Estimating Proportional Entrainment of Larval and Juvenile Delta Smelt

Kimmerer estimated proportional entrainment of larvae–juveniles based on the proportion of larvae–juveniles sampled at six stations near the pumps in the biweekly 20-mm Survey. He estimated the entrainment that occurred at each biweeklty survey as the product of density and flow, where density is the average density of larvae and juveniles at those six stations, and flow is Old and Middle river (OMR) flow toward the export pumps. He estimated the total population as the product of density and volume, where density is the average density at all stations sampled, and volume is the total volume associated with all stations. He estimated proportional entrainment for each day when a survey occurred as the ratio of entrainment for that day to total population numbers for that day. He interpolated between surveys to estimate this ratio for each day. He estimated gear efficiency for the 20-mm Survey, and adjusted all catch data for gear efficiency. He estimated the fraction of the total population of delta smelt hatched by the time of each survey, and reflected that estimate in proportional entrainment estimates. He accounted for the fact that “natural” (non-entrainment) mortality of larval–juvenile delta smelt is exponential with time by discounting mortality associated with early surveys. As he did for adult proportional entrainment, Kimmerer estimated annual proportional entrainment of larvae–juveniles as the accumulation of daily proportional entrainment, adjusting each day’s proportional entrainment to account for larvae and juveniles that survived entrainment on previous days.

The methods for estimating proportional entrainment of adults and larvae–juveniles involved a number of assumptions. Each assumption is evaluated later in this paper.

ALTERNATIVES TO KIMMERER’S PROPORTIONAL ENTRAINMENT ESTIMATES

Kimmerer’s estimates of annual proportional entrainment of adult and larval–juvenile delta smelt from 1995 to 2006 are shown in Table 1 (Wim Kimmerer, pers. comm., 2009); these data were used in Kimmerer’s estimation of annual proportional entrainment but were not presented in Kimmerer (2008). Note that each year’s estimate of proportional entrainment of larval–juveniles must be discounted to account for the proportion of adults entrained each year. The table indicates that estimates of annual mortality due to pumping range widely, from 3% to 38% of the total population, with the highest estimates in 2002 through 2004. It also indicates that

Table 1 Kimmerer's annual estimates of the proportion of adult and larval–juvenile delta smelt that are entrained

Year	Proportional Entrainment of Adults	Proportional Entrainment of Larvae–Juveniles	Total Proportional Entrainment
1995	18%	0%	18%
1996	3%	1%	3%
1997	3%	14%	16%
1998	1%	0%	1%
1999	3%	7%	10%
2000	5%	13%	17%
2001	5%	19%	23%
2002	16%	26%	38%
2003	22%	17%	35%
2004	19%	21%	36%
2005	9%	3%	12%
2006	3%	0%[a]	3%

[a] Not included in data received from Kimmerer, but known to equal 0% because no larval–juvenile delta smelt were salvaged in 2006. Total proportional entrainment = 1 - (1 - p_A)*(1 - p_J), where p_A = proportional entrainment of adults and p_J = proportional entrainment of juveniles.

estimates of adult proportional entrainment for four years, 1995 and 2002 through 2004, are approximately 20%, and estimates of larval–juvenile proportional entrainment are approximately 20% to 25% for the four years, 2001 through 2004.

Before examining in detail the assumptions underlying Kimmerer's estimates of proportional entrainment of adults, it is useful to consider his estimates from a broader perspective. The percentage of adult delta smelt in each sub-region of the estuary (Figure 2) can be estimated using the same general approach Kimmerer used to estimate the total population of adults and the specific approach referenced in Kimmerer and Nobriga (2008) for juvenile distribution. That is, the density of adult delta smelt at each survey station can be estimated from catch data and volume passing through the sampling net. Sub-region densities can be estimated as the average of station densities in each sub-region. Weighting sub-region densities by the volume of water in the upper four meters (Bennett 2005; Kimmerer 2008) of the sub-region estimates relative abundance of adults in each sub-region. For the Kodiak Trawl, relative abundance estimated in this manner approximates actual population numbers because the Kodiak Trawl fishes for adult delta smelt with gear designed to catch adults. Because the Kodiak Trawl net is towed between two boats, some herding of fish might occur, tending to raise gear efficiency above 100%. However, Hanson Environmental Inc. released salmon smolts directly in front of a towed Kodiak Trawl net and only recovered 90% of these smolts, suggesting that, absent herding, gear efficiency might be slightly less than 100% (Charles Hanson,

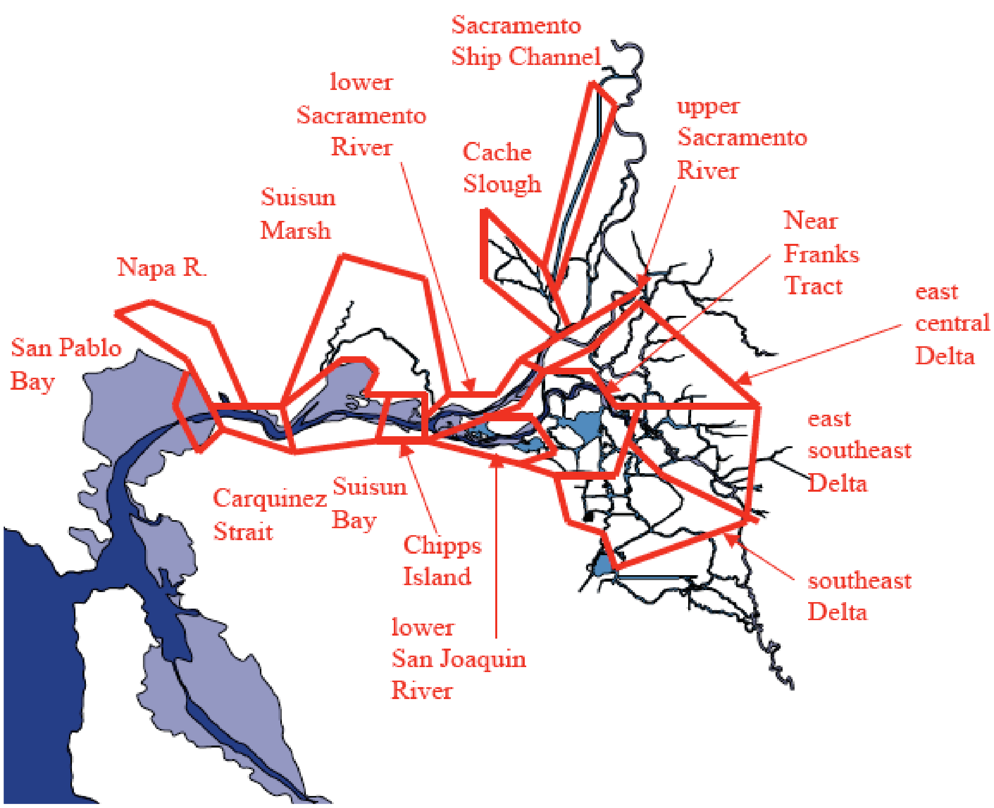

Figure 2 Sub-regions occupied by delta smelt in different parts of the life cycle

Table 2 Number of adult delta smelt in each sub-region and spawning population, assuming Kodiak gear efficiency of 100%

year	survey	survey mid-date	Napa River	Car-quinez Strait	Suisun Bay	Chipps Island	lower Sacra-mento River	lower San Joaquin River	Suisun Marsh	Cache Slough	Sacra-mento Ship Chan-nel	upper Sacra-mento River	near Franks Tract	east central Delta	*south-east Delta*	*east central Delta*	spawning population February
2002	1	8-Jan	0	36,000	83,000	50,000	21,000	147,000	240,000	11,000		0	166,000	5,000	*25,000*	*5,000*	
2002	2	5-Feb	0	15,000	26,000	0	70,000	175,000	459,000	1,000		7,000	216,000	0	*0*	*0*	1,000,000
2002	3	5-Mar	6,000	0	7,000	0	190,000	9,000	144,000	53,000		0	26,000	7,000	*0*	*7,000*	
2003	1	19-Feb	0	0	113,000	67,000	32,000	16,000	59,000	83,000		0	29,000	0	*4,000*	*0*	400,000
2003	2	18-Mar	0	0	132,000	67,000	259,000	0	31,000	104,000		26,000	11,000	12,000	*0*	*12,000*	
2003	3	15-Apr	0	0	9,000	0	61,000	4,000	0	6,000		15,000	91,000	0	*0*	*0*	
2003	4	14-May	0	0	49,000	0	8,000	6,000	0	14,000		0	0	2,000	*0*	*2,000*	
2004	1	13-Jan	6,000	0	12,000	31,000	4,000	180,000	292,000	2,000		0	243,000	2,000	*12,000*	*2,000*	
2004	2	13-Feb	0	0	18,000	5,000	269,000	62,000	217,000	1,000		0	171,000		*0*		700,000
2004	3	10-Mar	0	0	83,000	29,000	124,000	10,000	136,000	0		0	214,000	7,000	*0*	*7,000*	
2004	4	6-Apr	0	0	10,000	5,000	151,000	23,000	0	3,000		7,000	135,000	0	*0*	*0*	
2004	5	5-May	0	0	0	0	10,000	17,000	0	2,000		0	14,000	0	*0*	*0*	
2005	1	26-Jan	0	0	147,000	41,000	210,000	0	142,000	19,000		0	57,000	3,000	*0*	*3,000*	
2005	2	24-Feb	18,000	0	15,000	11,000	45,000	3,000	174,000	21,000	2,000	0	0	0	*0*	*0*	300,000
2005	3	24-Mar	0	0	7,000	14,000	24,000	0	6,000	6,000	14,000	4,000	0	0	*0*	*0*	
2005	4	19-Apr	0	0	7,000	5,000	20,000	0	2,000	3,000	24,000	0	0	0	*0*	*0*	
2006	1	18-Jan	34,000	11,000	15,000	9,000	0	10,000	33,000	2,000	9,000	0	6,000	0	*0*	*0*	
2006	2	15-Feb	65,000	12,000	88,000	14,000	5,000	5,000	40,000	7,000	22,000	0	11,000	2,000	*5,000*	*2,000*	300,000
2006	3	15-Mar	72,000	0	24,000	21,000	7,000	0	8,000	10,000	74,000	0	14,000	1,000	*0*	*1,000*	
2006	4	12-Apr	9,000	0	0	4,000	7,000	5,000	2,000	0	159,000	0	12,000	1,000	*0*	*1,000*	
2006	5	9-May	0	0	12,000	12,000	0	4,000	0	1,000	0	0	0	2,000	*0*	*2,000*	
2007	1	9-Jan	0	0	0	70,000	100,000	15,000	80,000	11,000	19,000	0	31,000	0	*0*	*0*	
2007	2	7-Feb		0	0	70,000	141,000	0	23,000	1,000	177,000	0	0	0	*0*	*0*	400,000
2007	3	8-Mar	0	0	13,000	40,000	24,000	0	63,000	4,000	74,000	0	0	0	*0*	*0*	
2007	4	4-Apr	0	0	0	13,000	39,000	0	7,000	2,000	385,000	0	0	0	*0*	*0*	
2007	5	2-May	0	0	0	0	14,000	0	5,000	0	127,000	0	0	0	*0*	*0*	
2008	1	9-Jan	0	16,000	70,000	46,000	375,000	0	6,000	6,000	126,000	0	7,000	0	*0*	*0*	
2008	2	6-Feb		0	0	13,000	7,000	0	0	9,000	127,000	0	6,000	2,000	*0*	*2,000*	200,000
2008	3	12-Mar	0	0	0	6,000	11,000	0	7,000	3,000	178,000	0	13,000	0	*0*	*0*	
2008	4	9-Apr	0	0	0	0	37,000	0	0	0	57,000	0	0	0	*0*	*0*	
2008	5	7-May	0	0	0	0	10,000	0	0	1,000	27,000	0	0	0	*0*	*0*	

Hanson Environmental, Inc., pers. comm., 2000). Therefore, it is reasonable to assume a gear efficiency of approximately 100% for the Kodiak trawl. If so, estimates of relative abundance in each sub-region approximate the number of adult delta smelt in each sub-region.

Table 2 shows the numbers of adult delta smelt by survey and sub-region, and Table 3 shows their distribution for each Kodiak Trawl and also for the December FMWT (for which relative abundance for each sub-region was estimated in a manner similar to that for the Kodiak Trawl). Spawning population estimates are included in Table 2 for discussion later in this paper. The sub-regions labeled "SE Delta" and "E–SE Delta" and italicized are close to the water export pumps. Delta smelt must pass through these two areas to be entrained. Table 3 shows the sum of percentages of adult delta smelt in these two areas. Most of these sums are 0%, in contrast with Kimmerer's estimates of proportional entrainment of adults shown in Table 1. Also note that in Tables 2 and 3, no samples were taken in the Sacramento Deep Water Ship Channel before 2005, and no samples were taken in any years at Liberty Island. As described below, significant numbers of delta smelt have since been found in those two areas.

These estimates of the percent of adult delta smelt near the export pumps (shown in the last column of Table 3) indicate that relatively few adults are located in the sub-regions from which they could be entrained at the export pumps. It is possible that significant fractions of adult delta smelt were near the export pumps between but not during surveys. However, Figure 3, which shows daily adult salvage and mid-dates of the 4- to 5-day Kodiak surveys, indicates surveys were coincidentally conducted dur-

Table 3 Distribution of adult delta smelt by sub-region, also showing the percentage near the export pumps (right column)

year	survey mid-date	Napa River	Car-quinez Strait	Suisun Marsh	Suisun Bay	Chipps Island	lower Sacra-mento River	upper Sacra-mento River	Cache Slough	Sacra-mento Ship Chan-nel	lower San Joaquin River	near Franks Tract	east central Delta	*south-east Delta*	*east south-east Delta*	*sum for SE & E-SE Delta*
2001	10-Dec	0%	0%	0%	0%	0%	78%	2%	7%		8%	6%	0%	*0%*	*0%*	*0%*
2002	8-Jan	0%	5%	30%	11%	6%	3%	0%	1%		19%	21%	1%	*3%*	*0%*	*4%*
2002	5-Feb	0%	2%	47%	3%	0%	7%	1%	0%		18%	22%	0%	*0%*	*0%*	*0%*
2002	5-Mar	1%	0%	32%	2%	0%	42%	0%	12%		2%	6%	2%	*0%*	*3%*	*3%*
2002	8-Dec	0%	0%	12%	65%	14%	6%	0%	4%		0%	0%	0%	*0%*	*0%*	*0%*
2003	19-Feb	0%	0%	14%	27%	16%	8%	0%	20%		4%	7%	0%	*1%*	*2%*	*3%*
2003	18-Mar	0%	0%	5%	21%	10%	40%	4%	16%		0%	2%	2%	*0%*	*0%*	*0%*
2003	15-Apr	0%	0%	0%	5%	0%	33%	8%	3%		2%	49%	0%	*0%*	*0%*	*0%*
2003	14-May	0%	0%	0%	62%	0%	10%	0%	18%		8%	0%	3%	*0%*	*0%*	*0%*
2003	7-Dec	0%	0%	0%	8%	7%	84%	2%	0%		0%	0%	0%	*0%*	*0%*	*0%*
2004	13-Jan	1%	0%	35%	1%	4%	0%	0%	0%		21%	29%	0%	*1%*	*7%*	*8%*
2004	13-Feb	0%	0%	29%	2%	1%	36%	0%	0%		8%	23%		*0%*	*0%*	*0%*
2004	10-Mar	0%	0%	22%	14%	5%	20%	0%	0%		2%	35%	1%	*0%*	*1%*	*1%*
2004	6-Apr	0%	0%	0%	3%	1%	45%	2%	1%		7%	40%	0%	*0%*	*0%*	*0%*
2004	5-May	0%	0%	0%	0%	0%	23%	0%	5%		40%	33%	0%	*0%*	*0%*	*0%*
2004	12-Dec	0%	0%	0%	46%	0%	32%	0%	22%		0%	0%	0%	*0%*	*0%*	*0%*
2005	26-Jan	0%	0%	23%	24%	7%	34%	0%	3%		0%	9%	0%	*0%*	*0%*	*0%*
2005	24-Feb	6%	0%	60%	5%	4%	16%	0%	7%	1%	1%	0%	0%	*0%*	*0%*	*0%*
2005	24-Mar	0%	0%	8%	9%	19%	32%	5%	8%	19%	0%	0%	0%	*0%*	*0%*	*0%*
2005	19-Apr	0%	0%	3%	11%	8%	33%	0%	5%	39%	0%	0%	0%	*0%*	*0%*	*0%*
2005	12-Dec	0%	0%	39%	13%	0%	48%	0%	0%		0%	0%	0%	*0%*	*0%*	*0%*
2006	18-Jan	26%	9%	26%	12%	7%	0%	0%	2%	7%	8%	5%	0%	*0%*	*0%*	*0%*
2006	15-Feb	24%	4%	14%	32%	5%	2%	0%	3%	8%	2%	4%	1%	*2%*	*0%*	*2%*
2006	15-Mar	31%	0%	3%	10%	9%	3%	0%	4%	32%	0%	6%	0%	*0%*	*0%*	*0%*
2006	12-Apr	5%	0%	1%	0%	2%	4%	0%	0%	80%	3%	6%	1%	*0%*	*0%*	*0%*
2006	9-May	0%	0%	0%	39%	39%	0%	0%	3%	0%	13%	0%	6%	*0%*	*0%*	*0%*
2006	11-Dec	0%	0%	100%	0%	0%	0%	0%	0%		0%	0%	0%	*0%*	*0%*	*0%*
2007	9-Jan	0%	0%	25%	0%	21%	31%	0%	3%	6%	5%	10%	0%	*0%*	*0%*	*0%*
2007	7-Feb		0%	6%	0%	17%	34%	0%	0%	43%	0%	0%	0%	*0%*	*0%*	*0%*
2007	8-Mar	0%	0%	29%	6%	18%	11%	0%	2%	34%	0%	0%	0%	*0%*	*0%*	*0%*
2007	4-Apr	0%	0%	2%	0%	3%	9%	0%	0%	86%	0%	0%	0%	*0%*	*0%*	*0%*
2007	2-May	0%	0%	3%	0%	0%	10%	0%	0%	87%	0%	0%	0%	*0%*	*0%*	*0%*
2007	10-Dec	0%	0%	71%	9%	5%	15%	0%	0%		0%	0%	0%	*0%*	*0%*	*0%*
2008	9-Jan	0%	2%	1%	11%	7%	58%	0%	1%	19%	0%	1%	0%	*0%*	*0%*	*0%*
2008	6-Feb		0%	0%	0%	8%	4%	0%	5%	77%	0%	4%	1%	*0%*	*0%*	*0%*
2008	12-Mar	0%	0%	3%	0%	3%	5%	0%	1%	82%	0%	6%	0%	*0%*	*0%*	*0%*
2008	9-Apr	0%	0%	0%	0%	0%	39%	0%	0%	61%	0%	0%	0%	*0%*	*0%*	*0%*
2008	7-May	0%	0%	0%	0%	0%	26%	0%	3%	71%	0%	0%	0%	*0%*	*0%*	*0%*
	avg.	3%	1%	17%	12%	6%	23%	1%	4%	42%	4%	8%	0%	*0%*	*0%*	*1%*

ing times of high salvage, except in December 2002 and January 2003.

The small monthly percentages of adults near the pumps are not consistent with proportional entrainment estimates ranging up to 20+% of the total adult population (see Table 1). One possible explanation for this apparent inconsistency would be that entrainment lowers the densities of delta smelt near the water export pumps, but this is unlikely because the stations at which density is measured are 30+ km from the export pumps themselves. Low turbidity is an alternative explanation for low densities of delta smelt near the water export pumps. Figure 4 shows that Secchi depth is typically high (i.e., turbidity is low) near the export pumps in the southeast Delta, and decreases in sub-regions farther from the pumps (near Franks Tract and lower San Joaquin River sub-regions). This figure also shows that densities of delta smelt are positively associated with the lower Secchi depths that occur away from the water export pumps.

Figure 5 shows the relative catch per sample of adult delta smelt by Secchi depth, from the Kodiak trawl data for 2002 through 2007. (Derivation of this figure is found in Appendix A.) This figure shows that approximately 90% of adult delta smelt are found at Secchi depths of less than 55 cm (i.e., turbidity great-

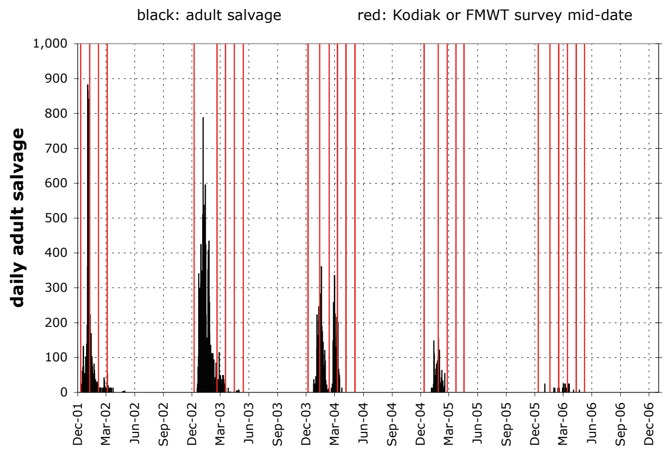

Figure 3 Daily adult salvage and mid-dates for Kodiak and Fall Midwater Trawl (FMWT) surveys

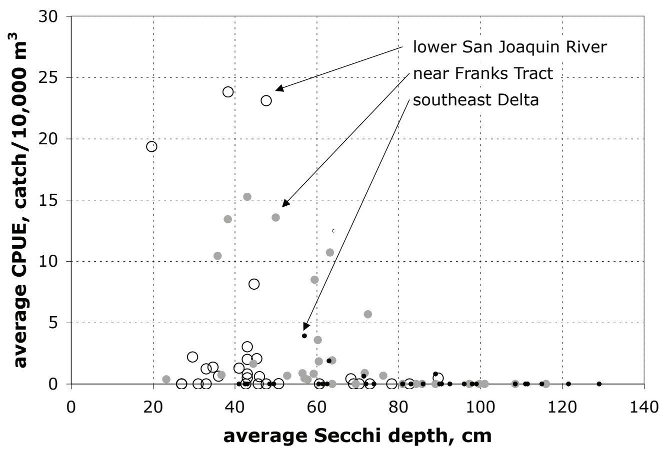

Figure 4 Average density of adult delta smelt and average Secchi depth in three sub-regions of the Delta, one sub-region near the water export pumps (southeast Delta), and two of increasing distance from the water export pumps (near Franks Tract and the lower San Joaquin River)

er than approximately 12 Nephelometric Turbidity Units, NTU), suggesting a preference for turbid water. Moyle's (2002) observation explains this preference: "individual fish apparently hang out in the water column and rely on their small size and transparency to hide them from predators in turbid water." Figure 5 also indicates that relative catch per sample of adult delta smelt increases as Secchi depth decreases. This analysis indicates that low percentages of adult delta smelt near the water export pumps could occur because Secchi depth is too high (turbidity is too low) there.

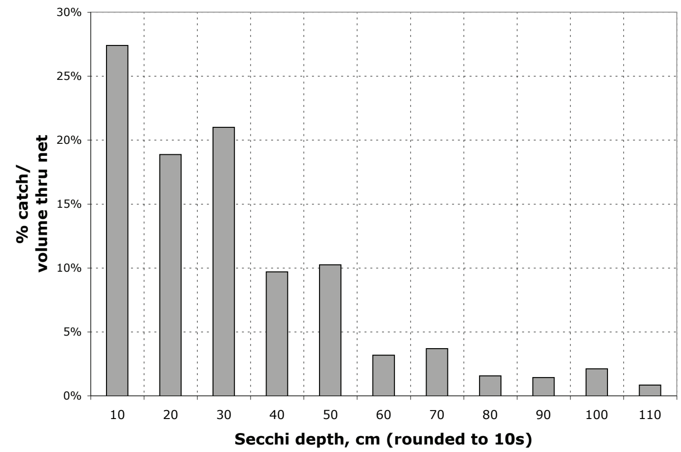

Figure 5 Distribution of adult delta smelt with respect to Secchi depth

Even assuming that all delta smelt near the export pumps are entrained, Kimmerer's finding that up to one-fourth of the adult population was entrained in a few recent years does not appear to be consistent with the overall distribution of delta smelt shown in Table 3. An exception to this observation might have occurred in January 2003, when adult delta smelt salvage was very high, and no Kodiak Trawl sampling occurred. Assuming the monthly sampling distributions are representative of the entire month, and summing those distributions over the months December through March (when most entrainment of adults occurs), would suggest that less than 10% of adults were entrained in the years 2002 through 2006.

Analysis of Assumptions Underlying Estimates of Proportional Entrainment of Adult Delta Smelt

Each assumption that could be a possible source of bias in estimates of proportional entrainment of adult delta smelt is discussed below, followed by an analysis of its effect on proportional entrainment estimates.

Assumption 1: The Kodiak trawl survey takes a representative sample of the adult delta smelt population. Routine Kodiak Trawl sampling in the Sacramento Ship Channel did not begin until 2005. Kimmerer used data from the December FMWT survey to estimate adult population in years before 2002, and the

FMWT survey does not sample in the ship channel. The ship channel was not sampled during most of the years Kimmerer used to estimate proportional entrainment. Kimmerer did not use the ship channel data in 2005 and 2006 because he confined the analysis to stations continuously sampled for all years. When Kodiak Trawl sampling began in the ship channel in 2005, as shown in Table 3, a single station, 719, was sampled approximately one-third of the way up the channel. Because this "man–made" channel is relatively homogeneous, it would not be unreasonable to assume that densities at this single station are representative of most of the ship channel. Adults have not been sampled in other parts of the ship channel, but juveniles were sampled at several stations in two surveys in June 2009. In one of these surveys, a density of 13 per 1,000 m^3 was observed at Station 719, and densities of 9 and 23 per 1,000 m^3 were observed at stations 3 miles south and 5 miles north, respectively. In another survey, a density of 11 per 1,000 m^3 was observed at Station 719, and 26 and 5 per 1,000 m^3 were observed at stations 5 and 11 miles north, respectively (California Department of Fish and Game [CDFG], unpublished data). Because it is unlikely that larval and juvenile delta smelt migrated up the ship channel, it is reasonable to assume that the delta smelt caught there in June were present because adults were there earlier. These data, though meager, suggest that densities of adults at station 719 provide some indication of densities throughout most of the ship channel. Based on this assumption, shown in Table 3, an average of 40% of adult delta smelt were in the ship channel in January through April, the months Kimmerer used. If a significant percentage of adults were in the ship channel but not sampled, Kimmerer's estimates of total population could be low, making estimates of proportional entrainment correspondingly high.

Another area where significant numbers of delta smelt have been found was also not sampled. A resident population of delta smelt was recently reported on Liberty Island, shown in Figure 1 (Sommer and others 2009). The island flooded in 1998. This area was not sampled in the Kodiak Trawl or FMWT in the years Kimmerer considered. Failure to sample this area would also cause some upward bias in the estimated proportion near the export pumps, and a similar upward bias in estimated proportional entrainment of adults, although that effect cannot be quantified because no samples, from which abundance estimates could be derived, were taken on Liberty Island.

An assumption reflecting the fact that some areas occupied by delta smelt were not sampled might read:

> *The Kodiak trawl survey takes a representative sample of the adult delta smelt population in the area sampled, but must be adjusted to account for delta smelt in areas not sampled.*

The required adjustment, considering only the ship channel, can be estimated for 2005 and 2006 using data on the distribution of delta smelt shown in Table 3. No data are available on the percentage of delta smelt on Liberty Island for 1998 (the year the island flooded) through 2006.

Figure 6 shows evidence that upstream movement of weak–swimming adult delta smelt into Cache Slough and the Sacramento Ship Channel increases as Delta outflow decreases. This figure suggests that lower Delta outflows in the preceding 30 days are a necessary but insufficient condition for the presence of higher percentages of adult delta smelt in these two upstream areas. The range of Delta outflow, below which higher percentages of delta smelt are found in the ship channel, is 30,000 to 50,000 ft^3 sec^{-1}. In 2002 through 2004, when Kimmerer estimated relatively high proportional entrainment (see Table 1), monthly average Delta outflow was less than 30,000 to 50,000 ft^3 sec^{-1} in 9 of the 12 December through March monthly periods. Therefore, it is possible that a significant proportion of adult delta smelt were in the unsampled ship channel in those years, and unknown additional numbers were in Liberty Island. Based on assumptions that underlie estimates in Table 3 and the similarity in flows in years before the ship channel was sampled, the percentage of delta smelt in the ship channel in 2002 through 2004 can be assumed to approximately equal the percentage there in 2005 through 2008, that is, in the range of 20% to 60%. If so, actual entrainment in 2002 through 2004 would be only 40% to

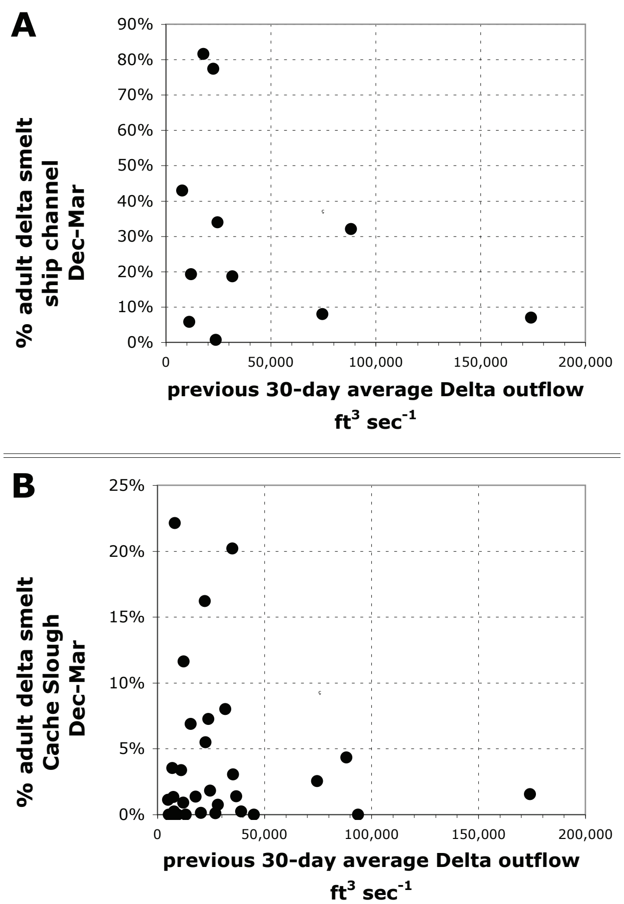

Figure 6 Relationship between the monthly percentage of adult delta smelt in the Sacramento Ship Channel (A) and Cache Slough (B) in January–March and Delta outflow averaged over the previous 30 days. (50,000 $ft^3 sec^{-1}$ = 1,400 $m^3 sec^{-1}$, 100,000 $ft^3 sec^{-1}$ = 2,800 $m^3 sec^{-1}$)

80% of that estimated by Kimmerer, based solely on the percentage of delta smelt in the unsampled ship channel, without taking into consideration any delta smelt at Liberty Island beginning in 1998.

Assumption 2: Entrainment is proportional to the combined southward flow in Old and Middle rivers. The observation that most adult delta smelt move upstream against substantial Delta outflows before they spawn suggests that they are not neutrally buoyant particles. If adult delta smelt do not "go with the (tidally averaged) flow," the assumption that flux to the export pumps (entrainment) is the product of smelt density and OMR flow toward the pumps will result in estimates that are biased upward. Furthermore, factors other than flow affect the distribution of delta smelt.

As discussed above, adult delta smelt prefer turbid water. Therefore, unless water with Secchi depth less than about 55 cm exists between the export pumps and where adults occur, entrainment would not be likely. Conversely, if water is turbid near the export pumps, and also turbid between the export pumps and where adult delta smelt occur, entrainment would be expected regardless of the magnitude and direction of flow in OMR. This could explain the occurrence of salvage when OMR flow was positive, as shown in Kimmerer's Figure 4 (Kimmerer 2008).

Figure 7 shows relationships between salvage and the 7-day average of both OMR flow and turbidity at Clifton Court Forebay at the Banks (state) Pumping Plant and at the Jones (federal) Pumping Plant. These data indicate that high values of relative salvage are associated with OMR flows of less than -142 m^3sec^{-1} ($-5{,}000$ ft^3 sec^{-1}) and turbidity greater than approximately 20 NTU at Banks Pumping Plant. Both of these conditions are necessary but insufficient for higher relative salvage to occur. No such relationships are apparent at Jones Pumping Plant. These data indicate that higher relative salvage, a rough measure of proportional entrainment, is affected by both OMR flow and turbidity near the export pumps, at least at the Banks Pumping Plant, but the association with OMR is not determinative. If adult delta smelt entrainment is not proportional to OMR flow but is actually less than that predicted by OMR flow, Kimmerer's estimates of Θ are too high. Because his estimated proportional entrainment of adults is proportional to Θ, high estimates of Θ result in proportional entrainment estimates that are biased upward by amounts that cannot be quantified.

Assumption 3: Monthly estimates of population based on Kodiak or FMWT survey catch apply for the entire month when sampling occurred. If delta smelt are entrained, the population would decline, and estimates of proportional entrainment that did not account for this decline until the next survey would be biased downward. This assumption could be revised as follows:

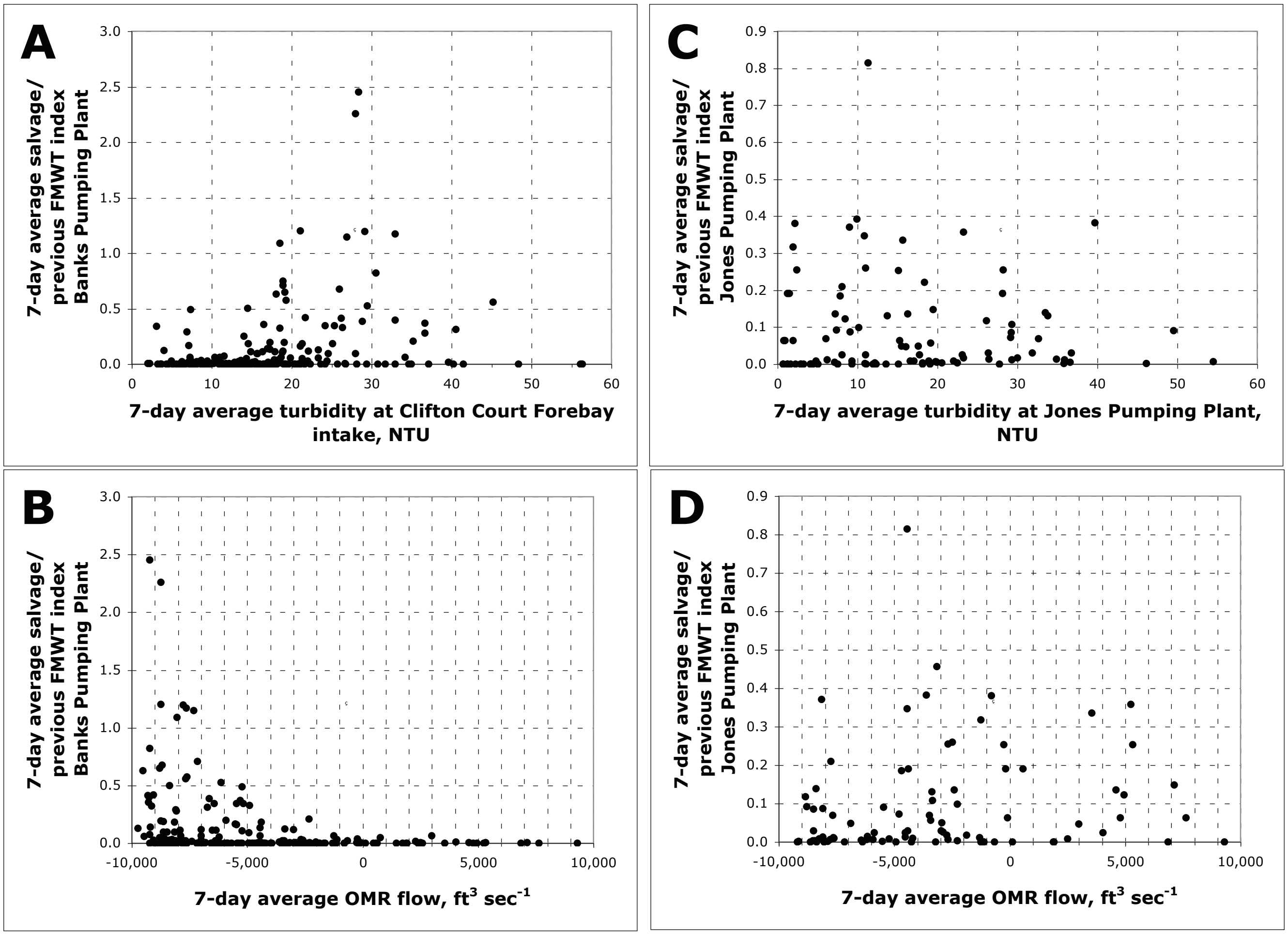

Figure 7 Relationship between relative salvage (salvage divided by previous fall abundance index) and turbidity at the Banks Pumping Plant (A) and Jones Pumping Plant (C) and relative salvage and OMR flow at the Banks (state) Pumping Plant (B) and the Jones Pumping Plant (D)

> *Monthly estimates of population based on Kodiak or FMWT survey catch apply for days when sampling occurred, and should be adjusted for other days before or after sampling occurred, to account for significant entrainment if such entrainment occurs.*

The only years that exhibit estimated proportional entrainment of adults high enough to warrant consideration of this correction are 1995, and 2002 through 2005. Kimmerer estimated adult population size for 1995 from December FMWT data, scaled up to make it comparable to Kodiak catch data. About 80% of adult salvage in 1995 occurred from mid-January to early February, and, as a result, about 80% of proportional entrainment also occurred then. If actual proportional entrainment was about 18%, as Kimmerer estimated, the number of adults would be about 14% fewer after taking into account that 80% of the entrainment occurred in early February. The 20% of estimated proportional entrainment occurring after early February would be about 16% higher than Kimmerer estimated, resulting in total proportional entrainment of about 3% higher, which, considering other errors in these estimates, would not be important. As shown in Figure 3, salvage peaks occurred just before Kodiak trawls in 2002 through 2005, so the trawl following the peak salvage would have reflected previous proportional entrainment, making any necessary corrections very small. This assumption would appear to result in small, downward bias in estimates of proportional entrainment.

Assumption 4: The ratio of Kodiak Trawl gear efficiency to salvage efficiency can be estimated assuming the probability that the total number of fish caught at four stations in or near OMR has a Poisson distribution with mean value:

$$(V_{SD}/\ \Theta_{SD})\Theta(N_1 + N_2)$$

where,

V_{SD} = volume of water sampled at the four stations

Θ_{SD} = rate of flow toward the export pumps in OMR

N_i = salvage at pumping plant i

i = 1 for state pumping plant, 2 for federal pumping plant

Θ = ratio of Kodiak Trawl gear efficiency to salvage efficiency.

Kimmerer assumed that the volume of water sampled at each of the four stations was the average volume sampled per station for all surveys. He also assumed that the relevant rate of flow toward the export pumps and total adult salvage equaled the flow and salvage on the day of the Kodiak trawl. Based on those assumptions, the relationship between total catch and the function above is as shown in Figure 8. Theta, estimated as the slope of the line of best fit, is 16, compared to Kimmerer's estimated value of 29.

In addition, 14 trawls sampled the four stations in or near OMR that produced the total catch per trawl correlated with the above function to estimate Θ. Of the 56 samples, 43 had zero catch. Five or fewer delta smelt were caught in the remaining samples (with one exception, a catch of 17 fish at Station 906 in January 2001). For all Kodiak Trawl data, only 1.3% of samples form the San Joaquin River had a catch as high as 17. This single, unusual catch had considerable influence on the estimate of Θ as seen in Figure 8, and suggests that the Θ value of 16 might be biased upward by this event.

Furthermore, it is not clear how Kimmerer used a Poisson distribution to estimate Θ. There are sampling errors in N_1 and N_2, as well as in the catch at the four sampling stations, so sampling errors in the

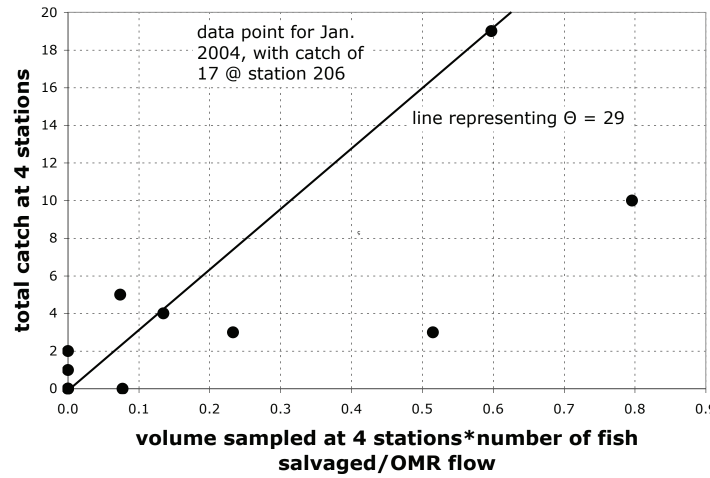

Figure 8 Relationship between total catch at four stations near the water export pumps and the ratio of the product of volume sampled and number of fish caught in the survey to OMR flow toward the water export pumps, based on Kimmerer's assumptions for these variables.

Poisson mean values shown above must be allowed for, as well as sampling errors in the Poisson term. Also, Kimmerer refers to 13 degrees of freedom for estimating Θ, using a generalized linear model, but 7 of the 14 values of $N_1 + N_2$ are zero, with the result that the corresponding Poisson means are zero and, therefore, uninformative.

The four stations are far from the export pumps, and travel time to the pumps can be approximately one week given OMR flows typical of those occurring when surveys were made. Salvage of adult delta smelt would also occur over similar periods. Accordingly, OMR flow should be averaged over the number of days after each survey equal to the travel time to the export pumps, and salvage should be averaged over the same number of days. Also, actual sample volumes are known for each station for each survey, so these should be used rather than a survey–wide average. With these adjustments, the data in Figure 8 appear as in Figure 9, and the value of Θ based on a linear regression would be approximately 18. If the single large catch of 17 delta smelt at Station 906 in January of 2001 had been, for example, five, which was the next largest catch, the value of Θ would be 12.

The parameter Θ is important because it relates daily salvage to daily entrainment and the total number

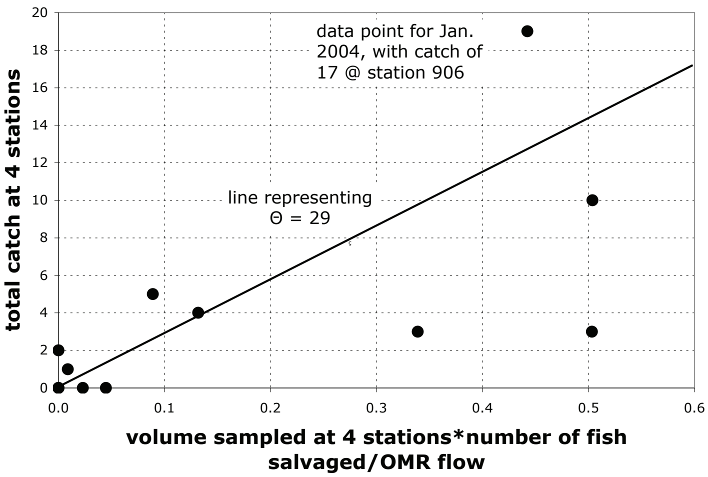

Figure 9 Relationship between total catch at four stations near the water export pumps and the ratio of the product of volume sampled and number of fish caught in the survey to OMR flow toward the water export pumps, based on values considering travel time to the pumps.

of delta smelt, as measured by the Kodiak Trawl catch or the FMWT catch, adjusted to be compared to the more efficient Kodiak catch. Kimmerer estimated Θ at 29, so all daily salvage values would be expanded that factor. Therefore, Kimmerer's estimates of proportional entrainment of adult delta smelt are approximately proportional to Θ, and Θ is approximately 18 or less, rather than 29. If so, Kimmerer's estimates of proportional entrainment of adults are much higher than they should be, and should be reduced by 40% or more. Furthermore, it is clear that there is great uncertainty in whatever estimate of Θ is derived from these data.

In summary, this alternative analysis indicates that biases in assumptions that underlie the estimates of proportional entrainment of adult delta smelt could result in an overestimate of that entrainment. Kimmerer's estimates could be reduced by at least 40% to be consistent with modified estimates of Θ. An additional reduction of 20% to 60% could be attributed to modifications related to location of routine sampling stations and neutral buoyancy. The former adjustment would reduce Kimmerer's high estimate of 22% adult proportional entrainment in 2003 to ~13%, and the latter adjustment could further reduce that estimate to 5% to 10% or less.

Analysis of Assumptions Underlying Estimates of Proportional Entrainment of Larval–Juvenile Delta Smelt

Each assumption that is a possible source of bias in estimates of proportional entrainment of larval–juvenile delta smelt is discussed, followed by an analysis of its effect on proportional entrainment estimates.

Assumption 1: Delta smelt arriving in the vicinity of the export facilities are lost from the population. If larval–juvenile delta smelt do not move as neutrally buoyant particles, their arrival in the vicinity of the export pumps—that is, at Stations 902, 906, 910, 914, 915, and 918—would not necessarily result in their being entrained; and this could produce an upward bias in estimates of proportional entrainment. The three most remote stations (902, 906, and 910), are 30+ km from the export pumps. Another of Kimmerer's assumptions is that young delta smelt swim downstream when water temperatures become too high, holding their position until then. This assumption is inconsistent with the notion that these smelt are neutrally buoyant. If they were not neutrally buoyant, they would not necessarily be entrained from stations 30+ km distant from the export pumps. Furthermore, Mager and others (2004) reports swimming behavior for three-day-old larvae.

Assumption 2: The six stations listed above provide estimates of catch per unit (of fishing) effort [CPUE] that represent the part of the population in the water going to the export facilities. Figure 10 compares salvage of delta smelt between 20-mm Surveys to the product of average OMR flow toward the export pumps between surveys and each survey's abundance of delta smelt at the six stations listed above. Abundance was estimated by correcting catch for gear efficiency using Kimmerer's gear correction factors, and excluding all smelt less than 20 mm long, because smelt smaller than that are not counted at the salvage facilities. While juvenile salvage is an uncertain estimator of juvenile entrainment, if the entrainment measure is restricted to fish of the same length as measured in salvage, there should be some relationship between salvage and flux to the pumps (estimated as the product of the number of delta smelt at the six stations and OMR flow). No relationship is apparent.

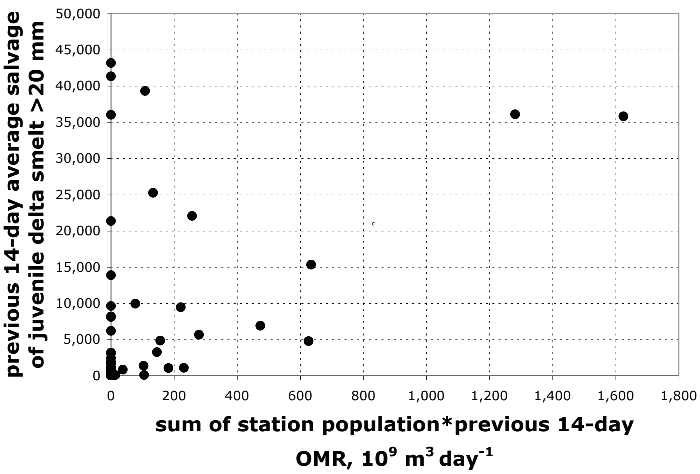

Figure 10 Comparison of salvage between 20-mm Surveys of delta smelt juveniles >20 mm long and the product of abundance of juvenile delta smelt at the six stations near the export pumps, corrected for gear efficiency, and average flow in Old and Middle rivers between 20-mm Surveys

This apparent lack of a relationship, coupled with analysis presented for Assumption 1 above, suggests that this assumption can produce estimates of entrainment, and therefore, proportional entrainment that are biased upward.

Assumption 3: Mean CPUE in all stations represents the entire population. There are three reasons to question this assumption. Each of these reasons is discussed in further detail.

1. The 20-mm gear does not reliably detect small larvae, particularly those less than approximately 10 mm long.
2. The 20-mm Survey tends not to detect delta smelt in downstream areas.
3. The 20-mm Survey did not sample where large percentages of larval–juvenile delta smelt reside.

Failure to reliably detect small larvae. Efficiency of the 20-mm Survey gear at catching small (4-mm to 9-mm) larvae suggests that application of gear correction factors to the catch of these small larvae is questionable. Comparing the number of small larvae caught with the number present gives some idea of how important this problem is. The number of 5-mm larvae can be roughly estimated from the number of spawning adults, the number of eggs produced per adult, and survival of eggs that grow to become 5-mm larvae. Delta smelt begin spawning in late February or March (Moyle 2002), making the February population in Table 2 the best estimate of adult spawning population. Starting with an estimate of the number of spawning adults, an estimate ten times the number of larvae can be made based on the following assumptions:

1. Half of adult delta smelt are female. (Actually, 62% of adults caught in the Kodiak Trawl from 2002 through 2007 were female.)
2. Each female produces 2,000 eggs. Bennett (2005) reports that egg production increases with female size, beginning at approximately 2,000 eggs per female for smaller females, and ranging up to 4,000 for larger one-year-olds.
3. Fertilization success is 20%. Mager (1996) reports success in aquaculture of 20% to 40%.
4. Hatching success is 30%. Mager (1996) reports hatching success of 30% to 80% in aquaculture.

Based on these assumptions, 100,000 spawning adults would produce approximately six million 5-mm larvae, which would begin to die at a rate of 3% to 5% per day (Kimmerer 2008). Table 2 indicates that the spawning population varied upward from approximately 300,000 adults for the years Kimmerer used. If so, tens of millions of 5-mm larvae were present. However, the one-hundred and eleven 20-mm Surveys conducted in those years caught only 42 delta smelt 5-mm in length. Figure 11 shows the catch from these 20-mm Surveys from 1995 through 2007 and illustrates the problem. The small graph is the same as the large one with a different scale on the Y-axis.

For smelt of about 9 mm or less in length, the probability of detection is so small that if a single small larva, of the millions present, is caught at a 20-mm Survey station (catch of a single larva is not unusual), it is probable that many were present, and this possibility also exists if no 4-mm to 9-mm smelt are caught in the survey. This uncertainty would be especially high for 20-mm Surveys early in spring, when most larvae are less than 10 mm long. As mentioned

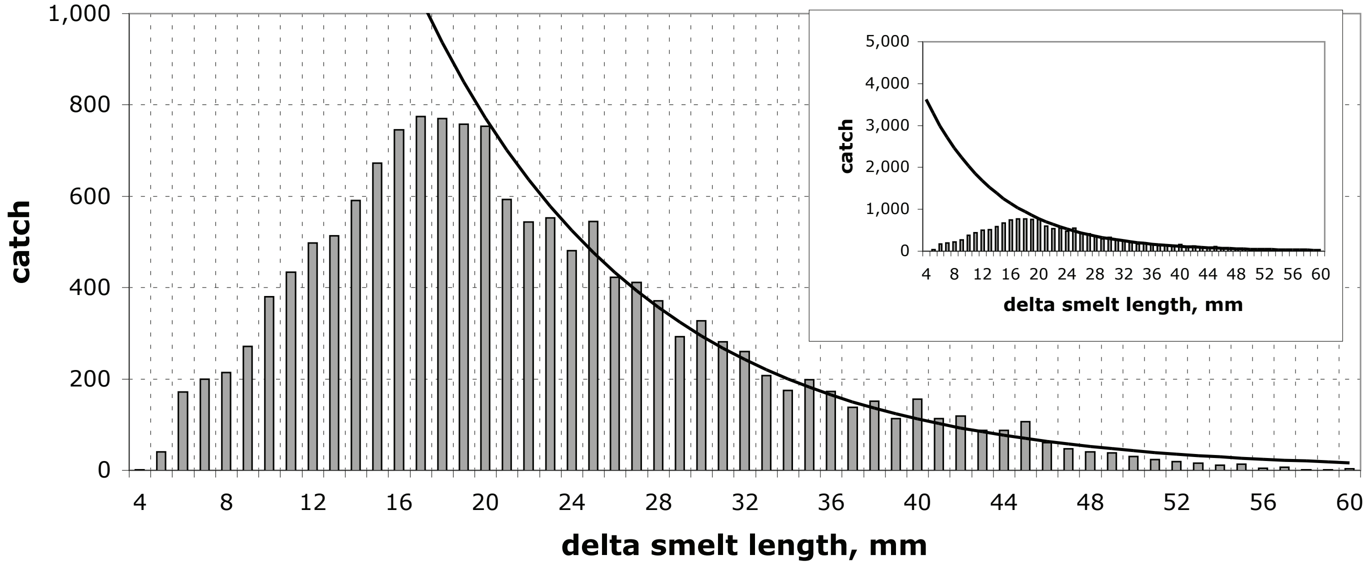

Figure 11 Catch by length of delta smelt in 20-mm Surveys, 1995–2007. Assuming 20-mm Survey gear is relatively efficient for smelt greater than about 20 mm, the line approximates the number of smaller smelt an efficient net would have caught.

above, Kimmerer estimated gear efficiency for delta smelt of all sizes, but problems with detection, as described above, make the concept of gear efficiency for delta smelt <10 mm long questionable. Gear efficiency can be corrected confidently if the gear detects significant numbers of fish, relative to the number in the water through which the net passes, when they are present. However, if the gear catches no fish when millions are present, *any* catch is a rare, random occurrence. Further, to estimate gear efficiency correction factors and to perform catch correction using these factors can impute unwarranted certainty.

This does not necessarily mean that data from early surveys are biased toward higher or lower estimates of proportional entrainment, but simply that those data are so uncertain that proportional entrainment estimates from those surveys are probably uninformative.

Tendency not to detect larvae and juveniles in downstream areas. The second reason is the tendency of the 20 mm Survey to fail to detect delta smelt in downstream areas. Catch data from sequential 20-mm Surveys 4 and 5 in 2001 shown in Table 4 demonstrate the problem. (See Figure 2 for sub-region boundaries.)

Only one delta smelt was caught in the lower Sacramento River and Cache Slough areas in Survey 4, and no smelt were caught downstream. Yet, two weeks later, 47 smelt were caught in the lower Sacramento River and Cache Slough areas. Kimmerer estimated that larvae grow at the rate of about 0.3 mm per day, so the smelt caught in Survey 5 were too large to have hatched in the lower Sacramento River and Cache Slough areas between surveys. It is also unlikely that smelt moved from the Franks Tract area downstream to the lower Sacramento River or, especially, upstream to Cache Slough. More smelt than indicated by the single catch in Survey 4 were most likely there at that time, but not detected.

Failure to detect delta smelt when—based on catch and location of catch in the subsequent survey—they were present, often occurred in areas downstream, away from the export pumps, and did not occur near the export pumps or in other upstream areas. Why would it be more difficult to detect larval and juvenile smelt in downstream stations? Is there an essential difference in upstream and downstream sampling stations that might produce a difference in detection of delta smelt? A possible explanation is an obser-

Table 4 Catch by length in 20-mm Surveys 4 and 5 in 2001

	delta smelt length, mm	lower Sacramento River	Cache Slough	lower San Joaquin River	near Franks Tract	SE Delta	E-SE Delta	E-Central Delta
Survey 4 3-May	4							
	5				1		4	
	6				1		1	1
	7			3	4			
	8			2	4			1
	9				8		2	1
	10				9		2	
	11			1	8	1	1	
	12				5	1	2	
	13				1	1	1	
	14			1	4	1	2	1
	15		1			1		
	16							
	17							
	18					1	1	
	19						1	
	20							
	21						1	
Survey 5 16-May	4							
	5							
	6				5			1
	7				18			
	8				12			
	9	1			11			1
	10	3			8		2	
	11	4			8			1
	12	1			3	1	1	2
	13	2			6			1
	14	5			8			3
	15	6			5	1		1
	16	3			7			
	17	1			9			
	18	2			4			
	19	4	1		1			
	20	1	1		1			
	21	1						
	22		1		1			
	23	2	1		1			
	24	2	1					
	25	1	1					
	26	2			1			
	27							
	28				1			

vation by Bennett that delta smelt tend to congregate where the pitch of channel depth is steep, i.e., between near-shore shoals and deeper mid-channel areas (William A. Bennett, University of California, Davis, pers. comm., 2009). As shown in Figure 1, downstream stations are generally located in wide channels or bays, whereas upstream stations tend to be located in narrow channels. Upstream sampling stations in narrow channels are more likely to be near areas where depth varies across the channel, because areas where depth varies comprise a greater proportion of total channel width. Downstream stations tend to be in areas where depth does not vary, because areas where depth varies are only a small proportion of the total downstream waters. If delta smelt are not detected in areas away from the export pumps, the estimated proportion of delta smelt near the export pumps—and, therefore, estimated proportional entrainment—would be too high. Surveys in which this occurred are summarized in Table 5.

Failure to sample areas with large percentages of larval–juvenile delta smelt. The third reason relates to inadequate sampling of areas away from the export pumps, where large numbers of delta smelt are known to occur, such as Liberty Island and the Sacramento Ship Channel, shown on Figure 1.

As discussed above for adult delta smelt, a resident population of delta smelt was recently reported on flooded Liberty Island (Sommer and others 2009). This area was not sampled in the 20-mm Survey in the years Kimmerer used. If delta smelt reside at Liberty Island but are not sampled in the 20-mm Survey, there would be an upward bias in the estimated proportion near the export pumps. Similarly, the Sacramento Ship Channel was not sampled in the 20-mm Survey until 2008. Once sampling began, relatively high densities of delta smelt were found in the ship channel. Table 6 shows data from 2008 and 2009, when the ship channel was routinely sampled. In six of the 17 surveys, the highest densities of delta smelt at all sampled stations occurred in the ship channel. In 2009, densities in the ship channel were among the highest observed in all 15 years of 20-mm Surveys.

Delta smelt eggs are attached to substrata, and there is essentially no net, advective flow into the north end of and down the ship channel. Therefore, if a high percentage of adult delta smelt are in the ship channel, a high percentage of larval smelt would be expected there as well, consistent with the relatively high CPUEs observed in the ship channel in the 20-mm Survey. As shown in Table 3, the percentage of adult delta smelt there is typically larger than in any other sub-region, subject to uncertainties arising from the single sampling station in the ship channel discussed above.

If the percentage of adult smelt in the ship channel is a predictor of the percentage of larvae and juveniles there, and considering the unsampled resident population in Liberty Island, it would be reasonable to assume that a significant percentage of larval–juvenile delta smelt were located in unsampled areas in the years that were represented in Kimmerer's analysis.

Table 5 shows surveys in which one or more of the above three phenomena occurred, for all surveys in which delta smelt were caught in the six stations Kimmerer used for all years with larval–juvenile proportional entrainment estimates greater than 3%.

Detailed data that underlies this table is found in Appendix B. The file presents catch data by sub-region and length for each year in which Kimmerer estimated larval–juvenile entrainment greater than 3%. Only those surveys where delta smelt were caught at stations that contributed to Kimmerer's estimates are shown. Occurrences of the three phenomena described above are super-imposed on survey catch data.

Assumption 4: The relevant flow toward the export facilities is the southward flow in Old and Middle rivers. Southward flow in OMR is more relevant than, for example, exports alone or upstream flow in the lower San Joaquin River. However, as discussed above, if larval–juvenile delta smelt can hold their position and there is no relation between salvage and the product of the number of smelt longer than 20 mm long and OMR flow toward the pumps, this assumption would tend to produce estimates of entrainment and proportional entrainment that are biased upward by unquantifiable amounts.

Table 5 Summary of problems with larval–juvenile proportional entrainment estimates

Year	Kimmerer's % larval-juvenile entrain-ment	surveys contri-buting to % entrain-ment	smelt not detected away from pumps when must have been present	smelt not sampled in Liberty Island and Ship Channel	catch data unreliable, larvae <10 mm	Net effect on estimates of proportional entrainment
1997	14%	1		X	X	Most entrainment in Survey 2. Entrainment unreliable for 1 & 2, too high for 2.
		2	X	X	X	
		3		X		
		4		X		
1999	7%	1		X	X	Most entrainment in Surveys 1, 4, & 5. Entrainment unreliable for 1 & 2. No samples in Napa R for 2 & 4.
		2		X	X	
		3		X		
		4		X		
		5		X		
		6		X		
2000	13%	1	X	X	X	Almost all entrainment in Surveys 3-5. Entrainment unreliable for 1-3, too high for 1 & 5.
		2		X	X	
		3		X	X	
		4		X		
		5	X	X		
2001	19%	2		X	X	Most entrainment in Survey 4, but other surveys important. Entrainment unreliable for 2 & 3, too high for 3 & 4.
		3	X	X	X	
		4	X	X		
		5		X		
2002	26%	2	X	X	X	Most entrainment in Surveys 2 & 3. Entrainment unreliable for first 2 surveys and too high for Surveys 2 & 4.
		3		X	X	
		4	X	X		
		5		X		
2003	17%	1		X	X	All surveys relatively important. Entrainment unreliable for first four surveys and too high for 3 and 4.
		2		X	X	
		3	X	X	X	
		4	X	X	X	
		5		X		
		6		X		
		7		X		
2004	21%	1		X	X	Most entrainment in Survey 3. Entrainment unreliable for Surveys 1-3, too high for 3.
		2		X	X	
		3	X	X	X	
		4		X		
		5		X		
		6		X		

Assumption 5: Daily entrainment equals the product of average density at six stations near the export pumps and daily flow to the export pumps in OMR. This assumption is questionable for the same reason that Figure 10 shows no relationship. The abscissa of that graph can be transformed to the product of average density at six stations near the export pumps and daily OMR flow toward the export pumps by dividing by the volume of water sampled at the six stations, which Kimmerer assumes is approximately the same for all stations. There would still be no relationship, suggesting that this assumption introduces an unquantifiable upward bias in estimates of proportional entrainment.

Assumption 6: Daily mortality is constant from the beginning of the hatch period until the last survey. If natural mortality is higher near the export pumps

Table 6 Catch per unit effort (relative density, CPUE) at Station 719 in the Sacramento Ship Channel and at the other station with the highest CPUE

year	20 mm Survey number	survey mid-date	catch per unit effort (relative density) at station 719 in Sacramento Ship Channel	next highest catch per unit effort (relative density)	station where next highest occurred	sub-region where next highest occurred
2008	1	19-Mar	0	0		
2008	2	2-Apr	0	0		
2008	3	16-Apr	0	27	720	Cache Slough
2008	4	30-Apr	7	26	718	Cache Slough
2008	5	14-May	34	7	707	
2008	6	28-May	no sample	no sample	no sample	
2008	7	11-Jun	41	248	704	lower Sacramento River
2008	8	25-Jun	6	85	513	Chipps Island
2008	9	9-Jul	38	22	706	lower Sacramento River
2009	1	11-Mar	0	5	519	Chipps Island
2009	2	25-Mar	3.3	0		
2009	3	8-Apr	6.6	15.9	809	lower San Joaquin River
2009	4	22-Apr	41	8.4	720	Cache Slough
2009	5	6-May	276	17.7	703	lower Sacramento River
2009	6	20-May	108	19.5	716	Cache Slough
2009	7	2-Jun	126	230	799	
2009	8	16-Jun	114	259	797	
2009	9	30-Jun	43	72	704	lower Sacramento River

and not accounted for, this would produce estimates of proportional mortality that were biased upward. Although temperature is higher near the export pumps, as evidenced by temperature data collected as part of the 20-mm Survey, temperatures do not rise to levels that are commonly associated with the absence of delta smelt. Secchi depth, which varies inversely with turbidity, does increase to levels not typically associated with the presence of larval and juvenile delta smelt. Figure 12 shows the catch per sample of different-sized delta smelt for Secchi depth, based on analysis of 20-mm Survey data.

Catch per sample for larvae less than 10-mm long varies little for Secchi depths between 15 and 85 cm, bounding the catch/sample of 85% of them. Seventy-five percent of the catch per sample of 10- to 20-mm delta smelt occurs in water with Secchi depth readings of 75 cm or less, and 90% of the catch per sample of delta smelt longer than 20 mm occurs in water with a Secchi depth of less than 65 cm. Baskerville–Bridges (2004) and Lindberg and Baskerville–Bridges (2006) found that feeding success of larval delta smelt in the presence of adequate food was adversely affected when turbidity was less than 10 to 15 NTU (Secchi depth greater than 45 to 70 cm).

Table 7 shows Secchi depth measurements for each 20-mm Survey, including supplemental surveys that are labeled with two-digit survey numbers, averaged over sub-regions occupied by larval and juvenile delta smelt in spring. Sub-regions are noted as column headings. Surveys for which Kimmerer estimated high proportional entrainment are shaded. Secchi values in light shading are in the range 45 to 75 cm, and darker shading indicates Secchi values greater than 75 cm. (See Figure 2 for locations of sub-regions.) This table shows that all other factors being equal, more larval delta smelt would die near the export pumps than elsewhere because Secchi

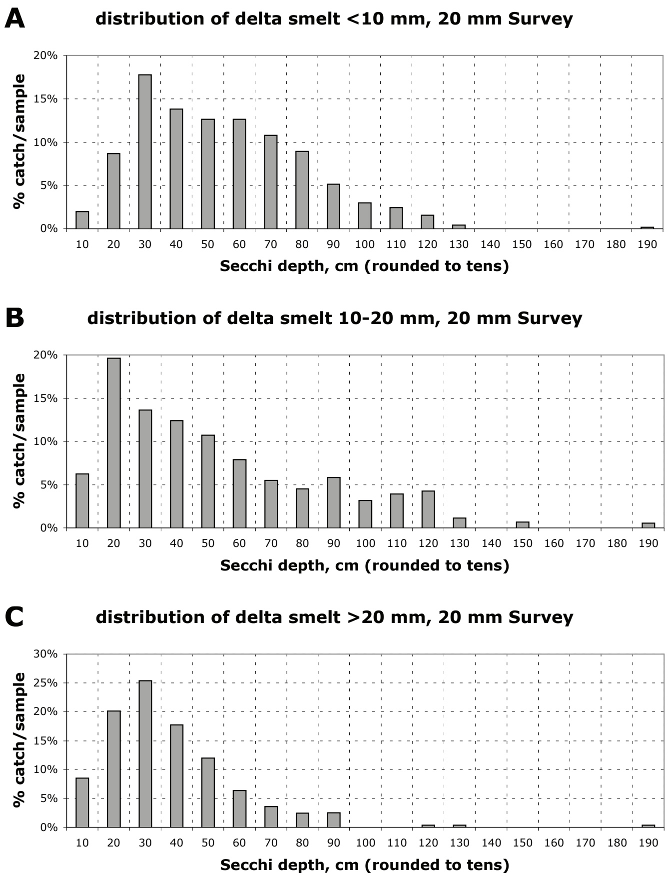

Figure 12 Percentage catch per volume sampled for larval-juvenile delta smelt: (A) <10 mm long, (B) 10 to 20 mm long, and (C) >20 mm long

depth is more likely to be in the range where larval feeding success is adversely affected. The assumption that natural mortality rates are constant for all delta smelt is not consistent with these data, and that assumption tends to produce estimates of proportional entrainment that are biased upward.

Other important assumptions that underlie proportional entrainment estimates for both adults and larvae–juveniles did not appear to produce bias in those estimates (Table 8).

To summarize the analysis of assumptions that underlie estimates of larval–juvenile proportional entrainment, only one of eight assumptions that appear to produce bias in estimates of proportional entrainment can be quantified—the one related to the mean CPUE that represents the entire population (Assumption 3)—and the magnitude of that bias is uncertain. If the proportion of larvae and juveniles in the ship channel equals the percentage of adults there, and if the percentage of adults there is comparable to the percentages there in 2005 and 2006, actual entrainment in those years would be only 40% to 80% of that estimated by Kimmerer, lowering the high estimate of 38% in 2002 to 15% to 30%. None of the other biases can be quantified, but they could be important enough to substantially reduce estimates of proportional entrainment.

Summary of Analysis of Assumptions Underlying Adult and Larval–Juvenile Proportional Entrainment Estimates

Table 9 summarizes the analysis of Kimmerer's assumptions. Of the 18 assumptions, 12 would appear to cause some bias in estimates of proportional entrainment, and 11 of those most likely result in upward bias.

IMPLICATIONS OF KIMMERER'S ESTIMATES AND THE BIAS IN THOSE ESTIMATES

Kimmerer's (2008) estimates that up to 40% of delta smelt were entrained in some recent years have had important influence on the management of state and federal exports to reduce entrainment. Kimmerer noted that the variation in effects of other factors, including food limitation, were so large as to make losses to entrainment difficult to detect through correlation. Presumably because his estimates of proportional entrainment were so large, he suggested they should not be dismissed as unimportant but, because they were episodic, their effects should be calculated instead of inferred from correlative analysis. The U.S. Fish and Wildlife Service (USFWS 2009) noted that published analyses did not support the hypothesis that entrainment drives population dynamics year in and year out, but, apparently drawing on Kimmerer's interpretations, concluded that delta smelt entrainment could best be characterized as a "sporadically significant" influence on population dynamics. This conclusion, in turn, led to prescriptions that caused significant curtailment in exports from the Sacramento–San Joaquin Delta, to minimize entrain-

Table 7 Secchi depths in sub-regions where the 1995–2006 average proportion of larval–juvenile delta smelt was more than about 10%

year-survey	survey mid-date	Suisun Marsh	lower Sacramento River	lower San Joaquin River	south-east Delta	east-south-east Delta
1995-1	26-Apr	24	52	63	55	54
1995-2	10-May	25	42	73	79	51
1995-3	24-May	21	62	80	85	62
1995-4	7-Jun	29	65	70	67	59
1995-5	21-Jun	30	71	78	56	53
1995-6	6-Jul	25	82	65	59	60
1995-7	20-Jul	35	69	67	58	59
1995-8	4-Aug	32	52	65	64	57
1996-1	13-Apr	26	65	70	76	72
1996-2	27-Apr	24	78	89	103	88
1996-3	11-May	21	59	64	85	66
1996-4	25-May	21	47	62	78	64
1996-5	11-Jun	16	42	50	69	54
1996-6	26-Jun	17	51	48	77	47
1996-7	10-Jul	16	32	34	65	58
1996-8	24-Jul	30	36	48	77	73
1997-1	2-Apr	15		50	76	71
1997-2	16-Apr	13	47	45	57	59
1997-3	30-Apr	16	32	43	64	73
1997-4	14-May	28	44	47	69	64
1997-5	29-May	18	41	35	65	52
1997-6	11-Jun	38	41	41	68	56
1997-7	26-Jun	46	37	37	67	46
1997-8	10-Jul	50	52	53	77	62
1997-9	24-Jul	43	46	45	88	79
1998-1	8-Apr	26	35	57	51	58
1998-2	23-Apr	21	55	53	62	58
1998-3	6-May	25	76	62	49	59
1998-4	20-May	26	51	58	45	45
1998-5	3-Jun	25	37	65	43	36
1998-6	17-Jun	35	34	47	40	45
1998-7	30-Jun	21	46	53	32	35
1998-8	15-Jul	21	50	48	32	35
1998-9	30-Jul	19	41	35	40	39
1999-1	14-Apr	20	52	56	76	71
1999-10	2-Jun			35		
1999-11	14-Jun			40		
1999-12	28-Jun				49	
1999-2	28-Apr	16	28	43	64	51
1999-3	12-May	16	43	43	66	62
1999-4	25-May	17	39	28	54	56
1999-5	9-Jun	14	51	38	21	24
1999-6	23-Jun	13	27	31	54	49
1999-7	8-Jul	21	40	31	54	50
1999-8	21-Jul	25	42	30	42	51
2000-1	22-Mar	19	34	31	55	52
2000-10	8-May	11	38	33	63	51
2000-11	23-May	19	47	63	80	55
2000-12	6-Jun	17	20	23	47	32
2000-2	5-Apr	14	37	42	70	55
2000-3	19-Apr	14	51	62	70	58
2000-4	3-May	15	43	42	71	66
2000-5	17-May	17	42	42	63	45
2000-6	31-May	14	36	29	71	55
2000-7	14-Jun	20	33	43	79	60
2000-8	28-Jun	20	35	27	73	54
2000-9	12-Jul	23	32	23	66	57
2001-1	21-Mar	28	37	21	63	69
2001-2	4-Apr	22	31	33	63	68
2001-3	18-Apr	26	50	28	76	78
2001-4	3-May	18	47	23	70	65
2001-5	16-May	26	34	33	55	64
2001-6	1-Jun	34	22	22	48	49
2001-7	13-Jun	42	29	30	62	43
2001-8	27-Jun	38	34	39	62	54
2001-9	9-Jul				65	
2002-1	20-Mar	23	62	63	85	83
2002-2	4-Apr	29	48	44	100	86
2002-3	17-Apr	21	43	40	73	73
2002-4	1-May	23	31	21	73	68
2002-5	15-May	29	29	39	66	60
2002-6	30-May	35	27	36	60	49
2002-7	12-Jun	27	30	26	39	49
2002-8	26-Jun	32	33	20	65	55
2003-1	26-Mar	19	37	29	104	67
2003-2	9-Apr	33	49	39	81	60
2003-3	23-Apr	26	51	40	88	64
2003-4	7-May	22	38	44	97	83
2003-5	21-May	25	46	48	78	67
2003-6	4-Jun	14	40	36	64	54
2003-7	18-Jun	13	34	36	63	67
2003-8	1-Jul	25	51	38	86	68
2004-1	31-Mar	23	64	39	99	88
2004-2	14-Apr	20	50	46	92	79
2004-3	28-Apr	25	68	52	94	79
2004-4	12-May	20	61	31	54	65
2004-5	26-May	26	34	67	87	63
2004-6	10-Jun	36	32	36	56	71
2004-7	23-Jun	41	41	47	73	66
2004-8	8-Jul	34	35	39	60	61
2005-1	16-Mar	28	62	70	92	73
2005-2	30-Mar	22	33	40	80	52
2005-3	13-Apr	30	52	67	104	73
2005-4	27-Apr	26	47	87	85	79
2005-5	11-May	29	59	92		62
2005-6	25-May	24	32	44	66	57
2005-7	8-Jun	27	52	62	73	73
2005-8	22-Jun	16	51	70	85	58
2005-9	8-Jul	16	51	50	93	62
2006-1	22-Mar	23	46	52	121	63
2006-2	5-Apr	27	41	33	103	48
2006-3	19-Apr	16	21	57	57	66
2006-4	3-May	27	42	83	67	78
2006-5	17-May	24	47	50	72	81
2006-6	1-Jun	25	51	72	65	85
2006-7	14-Jun	22	53	53	65	66
2006-8	28-Jun	21	52	62	78	60
2006-9	13-Jul	17	40	56	68	60

Table 8 Assumptions that did not appear to produce bias in estimates of proportional entrainment of adult or larval–juvenile delta smelt

Life Stage	Assumptions	Comments
Adults	Salvage efficiency, the ratio of salvage to entrainment, is the same at both pumping plants.	Assumption results in uncertainty, but no bias is apparent.
	All delta smelt entrained toward the export facilities are lost from the population.	This is a generally accepted characterization of the fate of entrained adults.
	Efficiency of sampling by the fish salvage facilities is constant.	Higher pumping rates and more negative OMR flow would be expected to reduce mortality occurring before the louvers that divert fish into salvage facilities, but would increase mortality due to lower efficiency, resulting in uncertainty but no apparent bias.
	Population size throughout the habitat is the mean catch per m3 multiplied by the volume of habitat shallower than 4 meters, about 0.9×10^9 m^3.	A reasonable assumption not associated with bias in proportional entrainment estimates, although estimation of total population size in areas sampled could be improved by summing estimates of population for sub-regions.
Larvae–Juveniles	Capture efficiency of the 20-mm net can be described by a logistic function increasing from 0 to 100% as fish length increases.	Detection problems for smaller larvae using the 20 mm Survey gear suggests that use of gear correction factors for larvae less than 10 mm in length imputes unjustified certainty.
	Fish hatch at a constant daily rate over some time period.	There is some evidence that fraction hatched is sigmoidal with time (Bennett 2005), but given the uncertainty in estimates of the fraction hatched, the assumption of constant daily hatching rate seems appropriate.
	Fish remain in the Delta until some date (or temperature) rather than moving to higher salinity at a certain age.	A reasonable assumption.
	Fish hatch at a length of 5 mm and grow at a rate of ~0.3 m d^1.	Growth rates are likely to be lower near the export pumps because of adverse effects of lower turbidity (higher Secchi depth) there on larval feeding success. Estimates of the magnitude of this effect probably cannon be made based on existing data.

ment effects. These curtailments have aggravated serious water shortages already occurring in much of California due to a multi-year drought.

Lower estimates of proportional entrainment would be consistent with correlative analysis (Manly and Chotkowski 2006; Kimmerer 2008; Manly 2006a, 2006b) that show no important, statistically significant effects of various measures of entrainment or proportional entrainment on subsequent abundance. Lower estimates of proportional entrainment also raise questions about curtailment of exports to minimize entrainment because of population–level consequences to delta smelt. Analyses presented here suggest that assessment of the importance of proportional entrainment awaits further analyses that narrow uncertainty, address questions of bias, and consider effects of other factors to place entrainment effects in context.

This analysis also suggests some modifications in surveys that sample adult and larval–juvenile delta smelt. First, sampling stations should be added for Liberty Island and the Sacramento Ship Channel to better define the distribution and numbers of adults and larvae–juveniles in those two areas. Second, research should address the problem of lack of detection of larvae less than 10-mm long in the 20-mm Survey and the intermittent failure of the 20-mm Survey to detect smelt in downstream circumstances, wide channels, and bays.

Table 9 Summary of analysis of Kimmerer's explicit and implicit assumptions that underlie the estimation of proportional entrainment of adult and larval–juvenile delta smelt.

	Assumption	Brief description	Problem	Resulting bias in estimates of proportional entrainment	Correction
adult proportional entrainment	1	Kodiak takes representative sample	No samples taken where significant fraction of population existed	Biases upward	Adjust proportional entrainment downward to account for unsampled, occupied areas
	2	Entrainment proportional to OMR	Delta smelt do not necessarily "go with the flow."	Biases upward	Adjustment cannot be quantified
	3	Monthly estimates of population size apply to entire month	Estimates not adjusted downward to account for significant entrainment	Biases downward	Adjust monthly population size down if significant entrainment occurs
	4	Salvage efficiency same at both pumping plants	Highly uncertain	No apparent bias	None
	5	All entrained smelt lost from population	None	None	None
	6	Salvage efficiency is constant	Components of salvage efficiency vary with export rate	None	None
	7	Number of adults = average density*volume of water in upper 4 meters	None	None	None
	8	Θ estimated as Poisson error function	Inappropriate estimation method produces overestimate of entrainment relative to salvage	Biases upward	Modify method, recalculate, and apply new value
larval-juvenile proportional entrainment	1	Delta smelt in vicinity of export pumps are lost from population	Larval-juvenile delta smelt are not neutrally buoyant particles	Biases upward	Adjustment cannot be quantified
	2	Six stations in southeast Delta provide estimates of delta smelt entrained	Abundance at those six stations not related to salvage	Biases upward	Adjustment cannot be quantified
	3	Mean CPUE represents entire population	Small larvae not detected, smelt in downstream areas sometimes not detected, significant proportion of population not sampled	Biases upward	Some adjustment can be quantified
	4	OMR is relevant flow toward export pumps	Larval-juvenile delta smelt are not neutrally buoyant particles	Biases upward	Adjustment cannot be quantified
	5	Daily entrainment equals product of density at six stations and OMR flow	Larval-juvenile delta smelt are not neutrally buoyant particles	Biases upward	Adjustment cannot be quantified
	6	Gear efficiency for 20 mm Survey is logistic function	Gear efficiency correction inappropriate for delta smelt <10 mm	Biases upward	Adjustment cannot be quantified
	7	Delta smelt hatch at constant rate	No serious problems	None	None
	8	Daily mortality is constant	Mortality likely higher near export pumps	Biases upward	Adjustment cannot be quantified
	9	Fish movement from Delta triggered by time or temperature rather than fish size	No problems	None	None
	10	Delta smelt hatch at 5 mm length and grow at constant rate	Growth rate likely lower near export pumps	Biases upward	Adjustment cannot be quantified

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REFERENCES

Baskerville–Bridges B, Lindberg JC, Doroshov SI. 2004. The effect of light intensity, alga concentration, and prey density on the feeding behavior of delta smelt larvae. American Fisheries Society Symposium 39:219–227.

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

Kimmerer WJ. 2008. Losses of Sacramento River chinook salmon and delta smelt (*Hypomesus transpacificus*) to entrainment in water diversions in the Sacramento–San Joaquin Delta. San Francisco Estuary and Watershed Science [Internet]. Available from: *http://escholarship.org/uc/item/7v92h6fs*.

Kimmerer W, Nobriga M. 2008. Investigating particle transport and fate in the Sacramento–San Joaquin Delta using a particle tracking model. San Francisco Estuary and Watershed Science [Internet]. Available from: *http://www.escholarship.org/uc/item/547917gn*.

Lindberg JC, Baskerville–Bridges B. 2006. Factors influencing growth and development of delta smelt, and other topics. Presentation to Estuarine Ecology Team of Interagency Ecological Program, San Francisco Bay–Delta Estuary.

Mager RC, Doroshov SI, Van Eenennaam JP, Brown RL. 2004. Early life stages of delta smelt. In: Feyrer F, Brown LR, Brown RL, Orsi JJ, editors. Early life history of fishes in the San Francisco Estuary and watershed. American Fisheries Society Symposium 39. Bethesda (MD): American Fisheries Society. p. 169–180.

Mager R. 1996. Gametogenisis, reproduction, and artificial propagation of delta smelt, *Hypomesus transpacificus* [PhD dissertation]. Available from: University of California, Davis.

Manly BFJ. 2006a. Review of analyses presented at the Environmental Water Account meeting; December 7–8, 2005. Western EcoSystems report. Version dated 19 July 2006.

Manly BFJ. 2006b. Review of searching for effects of state and federal exports on delta smelt abundance. Western EcoSystems Technology report to the San Luis and Delta–Mendota Water Authority. Version dated 7 September 2006.

Manly BFJ, Chotkowski M. 2006. Two new methods for regime change analyses. Archive fur Hydrobiology 167:593–607.

Miller WJ. 2008. Smelt, food, and other factors, presentation to Interagency Ecological Program Estuarine Ecology Team, February 2008.

Moyle PB. 2002. Inland fishes of California. Revised and expanded. Berkeley (CA): University of California Press.

Sommer T, Reece K, Mejia F, Nobriga M. 2009. Delta smelt life–history contingents: a possible upstream rearing strategy? Interagency Ecological Program Newsletter [Internet]. Winter 2009. Sacramento (CA): Dept. of Water Resources. Available from: *http://www.water.ca.gov/iep/newsletters/2009/IEPNewsletter_FINALWinter2009.pdf*.

[USFWS] U.S. Fish and Wildlife Service. 2009. Biological opinion on coordinated operations of the Central Valley Project and State Water Project and the operational criteria and plan to address potential critical habitat issues. Service file 81420–2008–F–1481–5.