Estimating the percentage of larval-juvenile delta smelt entrained at the Banks and Tracy Pumping Plants

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Summary

We estimated the percentage of larval-juvenile delta smelt (smelt) entrained at the Banks and Tracy export pumping plants. The distribution of larval-juvenile smelt was obtained from the eight biweekly 20 mm surveys conducted beginning in 1995. The percentage of hatched smelt entrained was estimated by combining the distributions with results from the Department of Water Resources Particle Tracking Model. The fraction of delta smelt that had hatched at the time of each survey was estimated using daily water temperature data from stations throughout the range of smelt.

Resulting estimates of total annual percentage of larval-juvenile delta smelt entrained are in Table 1.

This is the "second generation" version of this method of estimating larval-juvenile entrainment of smelt. Previously, we used average Delta-wide water temperature to estimate the fraction of the population hatched by the time of each 20 mm survey. We used equations developed from other Particle Tracking Model (PTM) runs because we did not yet have the capability to run the PTM. For this version we used water temperatures from various stations to better estimate early hatching in parts of the Delta that warm up first.

We now have the capability to run the PTM, so this version uses actual PTM runs.

Background

Delta smelt (smelt) spawn in the Delta and Suisun Bay area beginning in February or March. Spawning begins when water temperatures reach about 12 degrees (Souza 2004). Eggs have an adhesive stalk that attaches to submerged substrate. Eggs hatch in about two weeks, producing 5 to 6 mm larvae. Larvae drift and grow, increasing in length approximately linearly with time (Mager 2004).

Larval-juvenile smelt are entrained at the Banks and Tracy Pumping Plants. Smelt are fragile fish, and essentially none of them survives the salvage and subsequent trucking and release operations. Therefore, for smelt, entrainment equals mortality.

Smelt show up in the salvage facilities at both plants but are not counted and measured until they reach a length of 20 mm. That is, salvage estimates only include smelt of at least 20 mm in length and do not include any larval or early juvenile smelt. So salvage does not provide a basis for estimating entrainment of smelt that are less than 20 mm long. Also, there are no data on the relationship between entrainment and salvage for larvae and juveniles. Therefore, even for smelt greater than 20 mm in length, salvage cannot be converted to entrainment.

Finally, even if it were possible to estimate entrainment, there are no estimates of the population of larval-juvenile smelt.

For the above reasons the percentage of the larval-juvenile population entrained at the export plants cannot be estimated by dividing entrainment by the population. Neither the numerator nor the denominator can be estimated. However, the method described below can be used to estimate percentage larval-juvenile entrainment.

Estimating percentage entrainment using smelt distribution and the Particle Tracking Model

The 20 mm survey has been carried out each spring, beginning in 1995. The survey samples for larval-juvenile smelt throughout the area inhabited by these early life stages. Sampling stations are shown in Figure 1. At least eight surveys were made in all years but one.

The 20 mm survey is not efficient for smaller smelt (Miller 2005a). Figure 2 is a graph of relative efficiency of the 20 mm survey for various sizes of smelt, assuming relative efficiency is 100% for 20 mm smelt. Whatever the actual efficiency is for 20 mm smelt, it is clear that efficiency for smaller sizes is very low. We assumed efficiency does not differ for a particular-sized smelt at different locations in the Delta. Therefore, while the 20 mm survey cannot be used to estimate the population of larval-juvenile smelt, it can be used to estimate the distribution of smelt, that is, the percentage of the total number of larval-juvenile smelt at each station.

The Department of Water Resources developed the Particle Tracking Model. This computer model tracks the fate of neutrally buoyant particles in the Delta-Suisun Bay area. The model can also attribute behavioral characteristics to the particles. We did not use this feature of the model for three reasons: First, the movement of larval smelt, before they start to swim, is similar to that of a neutrally buoyant particle. Second, Particle Tracking Model runs for the South Delta Improvements Program EIS/R (DWR 2005) suggests attribution of behavior to particles reduced their chance of entrainment dramatically. So, assuming neutral buoyancy produces higher entrainment estimates that are environmentally conservative. Third, there are no data to support assumptions about how larval-juvenile smelt would behave.

The 20 mm surveys occur over a period of four or five days every two weeks. Each survey produces data on catch per unit effort (CPUE = density) of Delta smelt. We estimated the volume and area represented by each station (Miller 2005b). The product of CPUE and volume for each station estimates relative abundance of smelt in each station's area. Dividing each station's relative abundance by the total relative abundance estimates the percentage of the larval-juvenile population in the area represented by each station.

For each survey, we ran the Particle Tracking Model using average Delta flows and exports in the two weeks beginning with the mid-date of each survey. The Particle Tracking Model estimates the chance of entrainment at the export pumps in two weeks, that is, from one survey to the next.

Next, for each station, we multiplied the percentage of larval-juvenile smelt at each station by the chance of being entrained from that station in two weeks. Summing these products over all stations estimates the percentage of the hatched population entrained from one survey to the next. These data are in Table 2.

Because smelt eggs are attached, they cannot be sampled in the 20 mm survey or entrained at the export pumps or other diversions. If the percentage of hatched smelt entrained from one survey to the next were 50% but only 10% of the population had hatched, the actual entrainment would only be 5% of the population. Therefore, estimates of the percentage of smelt hatched are necessary.

Estimating the fraction of smelt hatched for each 20 mm survey

The fraction hatched at the time of each survey was estimated based on data from Souza (Souza 2004) indicating found that spent females are typically first found at temperatures of 12 degrees C, and Bennett (Bennett 2005), who reported that few hatched smelt survive temperatures above 21 degrees C.

Average Delta water temperature was not used because some parts of the smelt habitat warm up weeks before other parts.[1] Use of average Delta-wide temperature would underestimate the time over which hatching occurred.

Long-term hourly or 15-minute temperature data from stations throughout for larval-juvenile smelt habitat (Figure 3) were used to find average daily temperatures at each station. These daily temperatures had considerable variation from day to day, making it difficult to identify the dates when water temperature reached 12 and 21 degrees C. We smoothed out the variability by using five-day average temperature. Five-day average daily temperature data were used to estimate the date for each year for each temperature station when the water temperature reached 12 degrees and 21 degrees C (Table 3).

Data were missing for some stations (shown in red on Table 3). In fact, entire years were missing in some cases. However, there is an excellent relationship between air temperature at Rio Vista, a centrally located station, and water temperature at nearby stations, with a lag of a few days

[1] We found that the southeastern Delta typically warmed up before other parts of the Delta. Smelt would spawn and hatch there first. This explains why early 20 mm surveys often appear to show that virtually all smelt are in the southeastern Delta when, in fact, most smelt are elsewhere but have not yet hatched because the water has not warmed up enough. Failure to account for this temperature effect has led to misinterpretation of these early 20 mm survey data and caused some to conclude that larval smelt are migrating long distances, from where adults spawned into the southeastern Delta. It has also caused imposition of export curtailments because of the concern raised by this misinterpretation.

between air and water temperature, depending on the station. Figure 4 is an example of this relationship. Air temperature data was used to fill in the missing dates when water temperature reached 12 and 21 degrees C, shown as red numbers in Table 3.

We assumed the following for each area:

- Hatching essentially begins two weeks after the temperature reaches 12 degrees centigrade.
- Hatching essentially ends when the temperature reaches 21 degrees C.
- Hatching proceeds in accordance with a cumulative normal distribution.
- Only 2% of the smelt had already hatched two weeks after the temperature reached 12 degrees.
- 98% had hatched by the time the temperature reached 21 degrees C.

Distribution "tails" of 5% rather than 2% made little difference in the final results.

In this way the fraction hatched for each day can be estimated for each of the eight areas with daily temperature data. Ideally, estimates of fraction hatched for each station should be weighted by the fraction of spawning smelt at each station. Estimates of these fractions are only available for years 2002 through 2005 when Kodiak Spring trawls were carried out for adults. For those years, the distribution of spawning adults for February (Miller 2005c) was used to weight the daily estimates of fraction hatched for each day. We also checked to see how much difference it would make if we assumed smelt were evenly distributed among the eight areas. The differences were not great relative to other uncertainties in this analysis. Therefore, February distributions from the Kodiak Spring trawl were used for years 2002 through 2004. For the years 1995 through 2001 we assumed spawning smelt were evenly distributed among the eight temperature stations.

Summing the eight estimates for each day estimates the fraction hatched each day as shown in Figure 5. Estimates of percentage hatched for each 20 mm survey are in Table 4.

Estimates of percentage hatched were combined with estimates of the percentage of hatched smelt entrained from Table 2. The resulting estimates of the percentage entrainment of the population present at the time of each survey are in Table 5.

Estimating the total percentage larval-juvenile entrainment for the year

The total annual percentage larval-juvenile entrainment is not the sum of the estimates for each survey. If the total population entrained for three consecutive surveys were 50%, adding these estimates produces the ridiculous result that 150% of the population was entrained.

Each survey's estimate of larval-juvenile entrainment must be discounted by the percentage entrainment that occurred in previous surveys. For example, if 10% of the population is entrained from survey one to survey two, only

90% of the population is subject to entrainment from survey two to survey three. Applying these discount factors produces estimates of the total larval-juvenile entrainment for each year. These estimates are in Table 1.

Figure 1
20 mm survey sampling stations

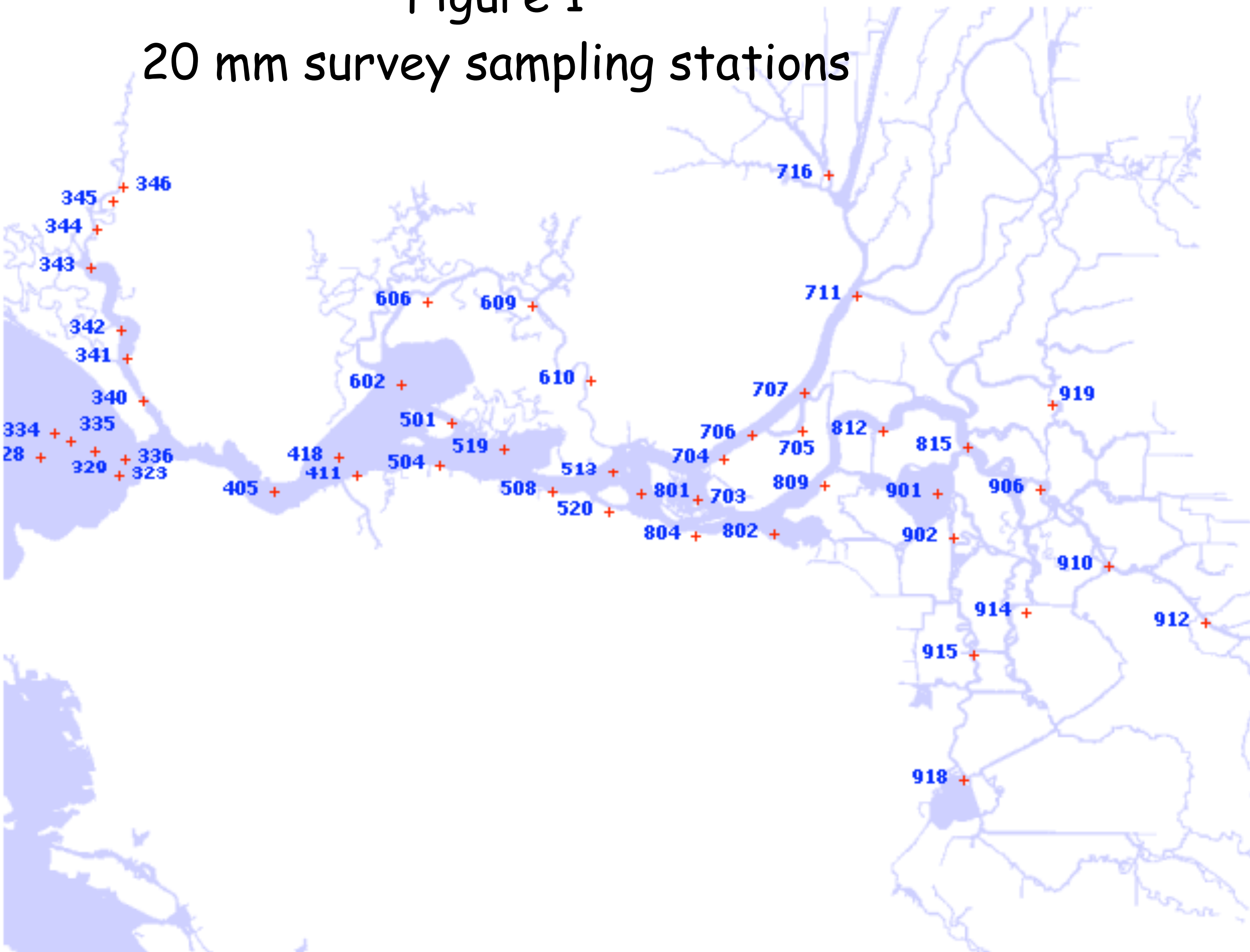

Figure 2
Family of relative efficiency curves

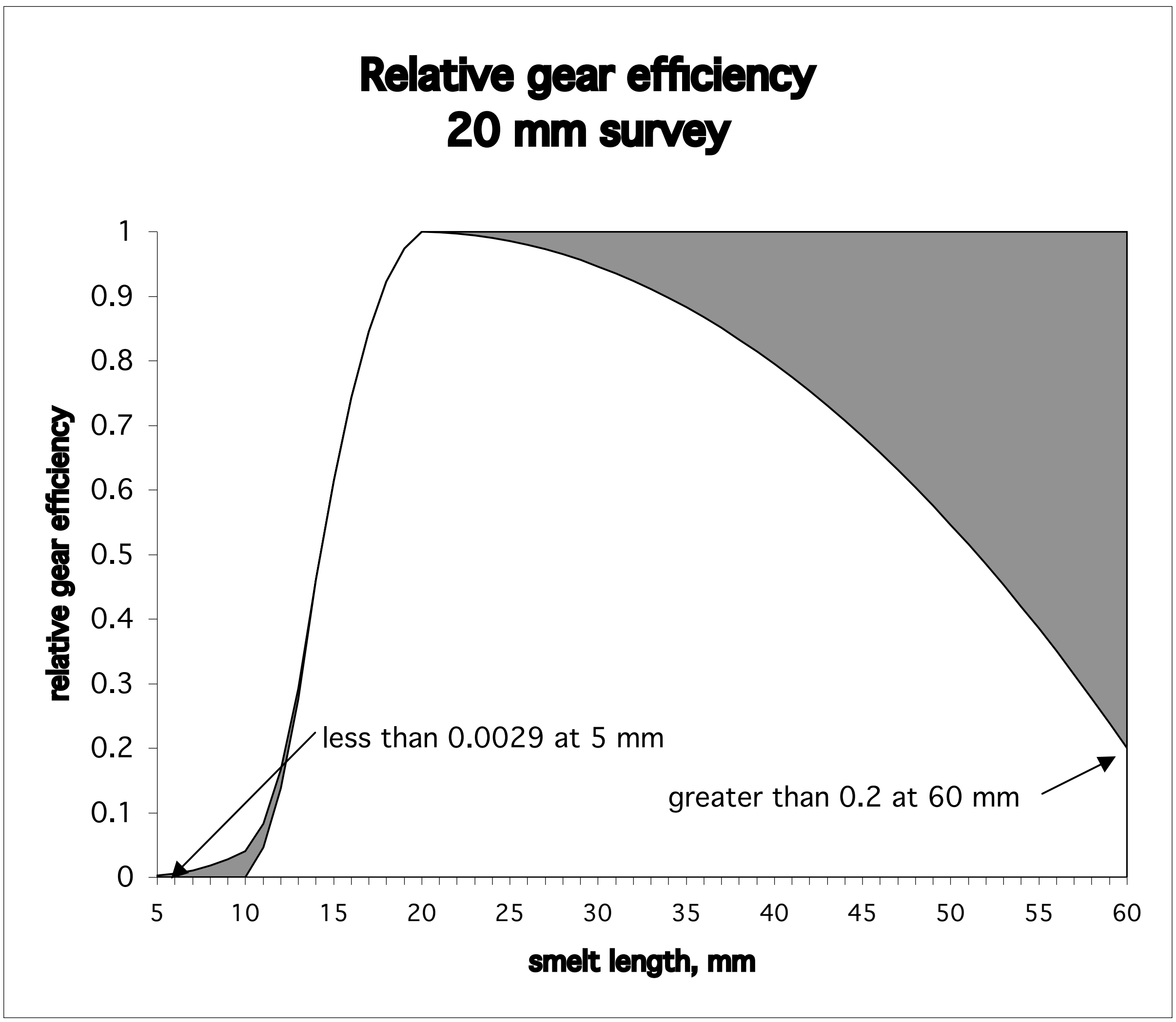

Figure 3
Water temperature stations

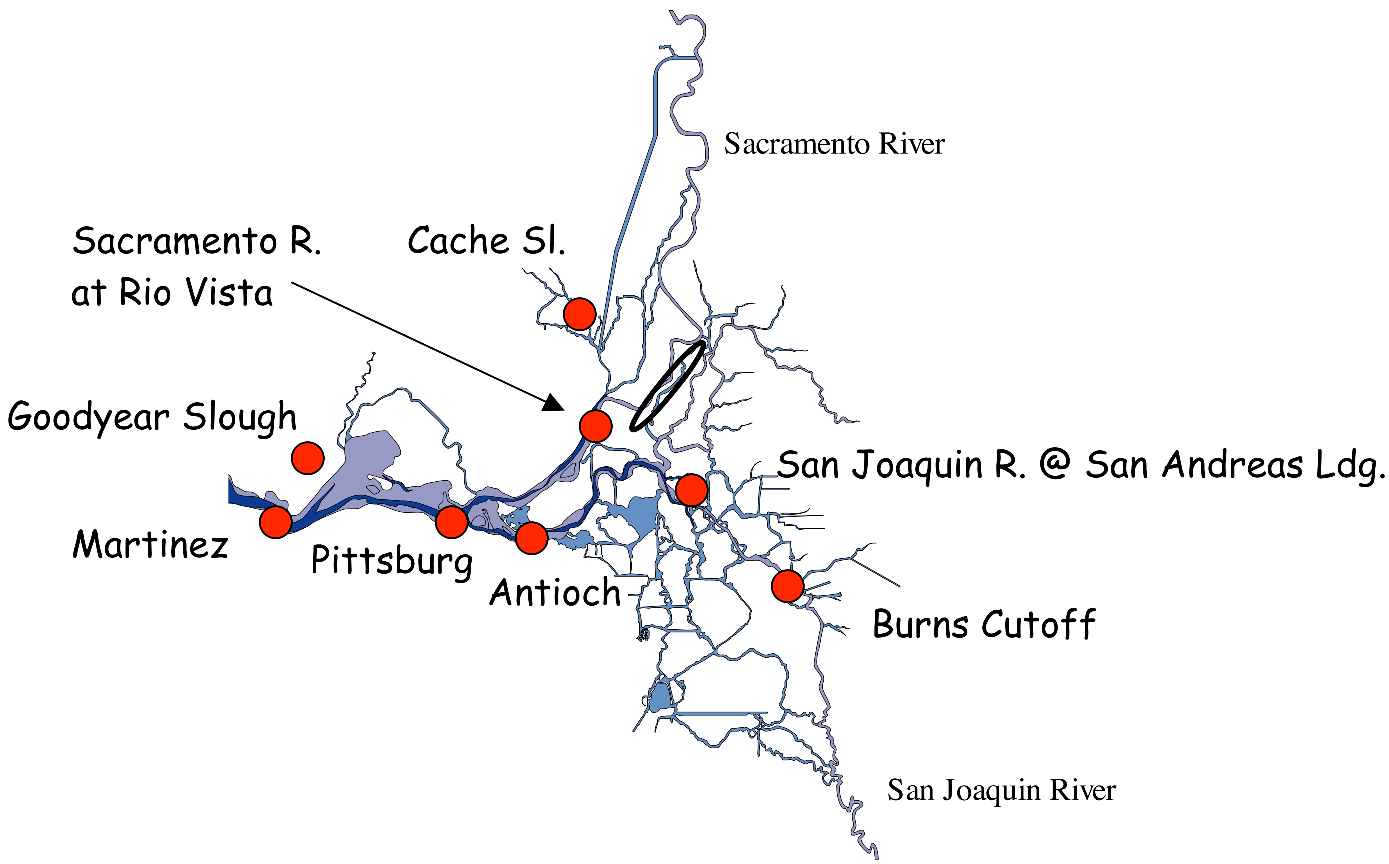

Figure 4
comparison of air and water temperatures at nearby stations

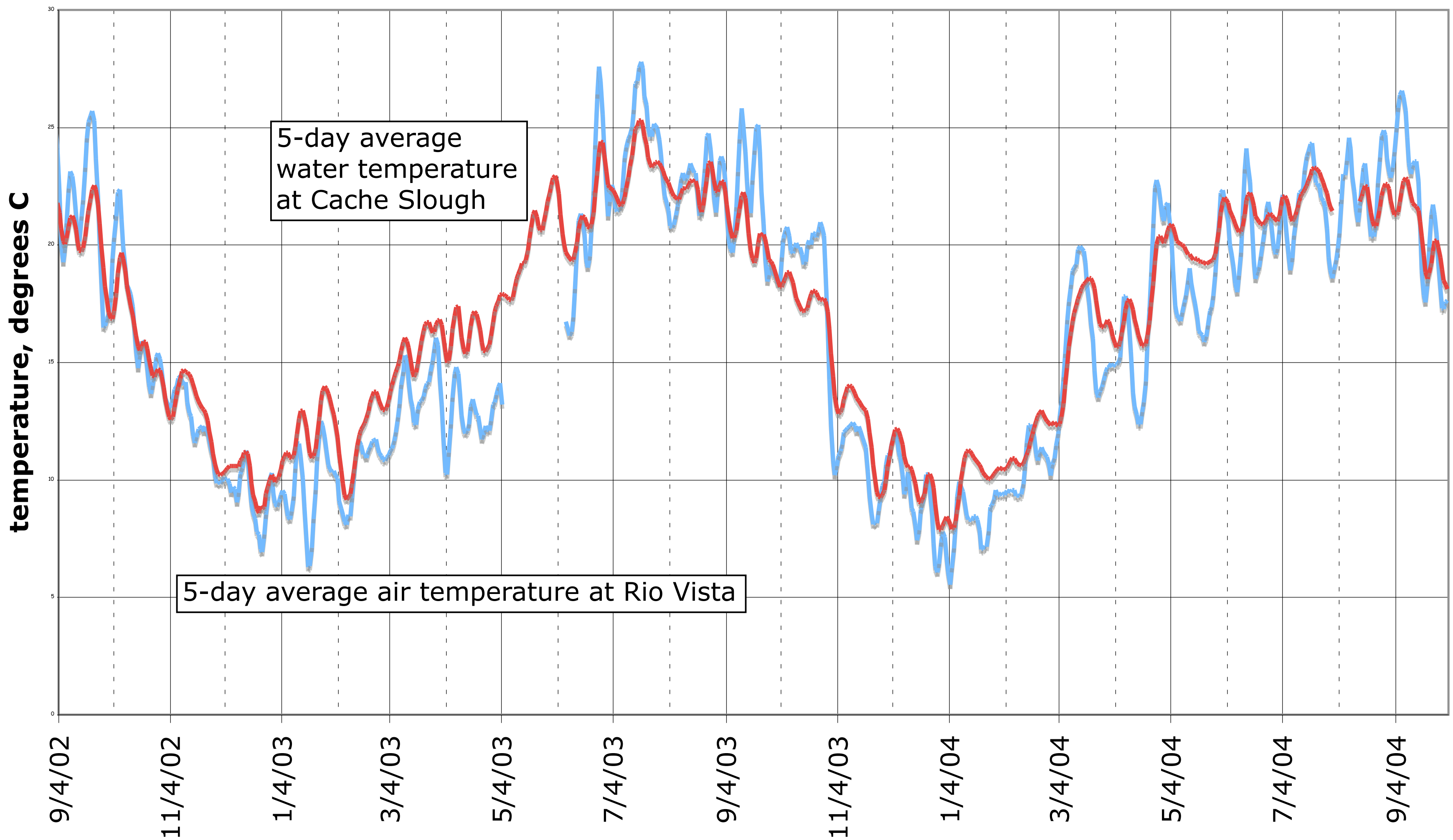

Figure 5
Estimates of percentage of larval-juvenile delta smelt hatched

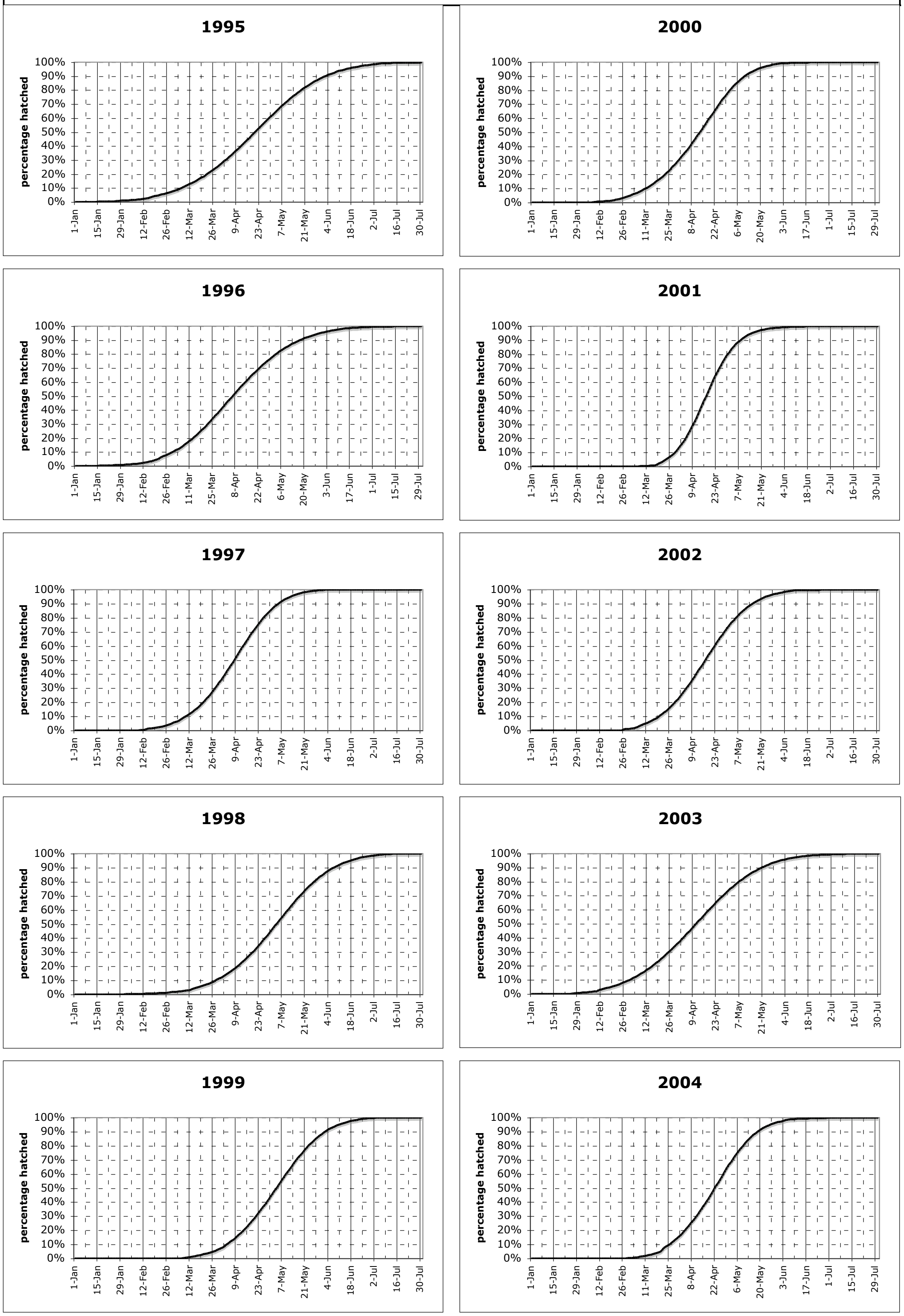

Table 1 delta smelt larval-juvenile entrainment	
year	% larval-juvenile population entrained
1995	0%
1996	0%
1997	31%
1998	0%
1999	5%
2000	13%
2001	8%
2002	24%
2003	25%
2004	4%

Table 2
Percentage of hatched larval-juvenile smelt entrained from one 20 mm survey to the next

survey mid-date	survey #	% hatched smelt entrained	survey mid-date	survey #	% hatched smelt entrained
26-Apr-95	1	0%	22-Mar-00	1	2%
10-May-95	2	0%	5-Apr-00	2	3%
24-May-95	3	0%	19-Apr-00	3	16%
7-Jun-95	4	0%	3-May-00	4	1%
21-Jun-95	5	0%	17-May-00	5	1%
6-Jul-95	6	0%	31-May-00	6	1%
20-Jul-95	7	0%	14-Jun-00	7	0%
4-Aug-95	8	0%	28-Jun-00	8	1%
13-Apr-96	1	1%	21-Mar-01	1	0%
27-Apr-96	2	0%	4-Apr-01	2	6%
11-May-96	3	0%	18-Apr-01	3	10%
25-May-96	4	1%	3-May-01	4	2%
11-Jun-96	5	1%	16-May-01	5	0%
26-Jun-96	6	0%	1-Jun-01	6	0%
10-Jul-96	7	0%	13-Jun-01	7	1%
24-Jul-96	8	1%	27-Jun-01	8	0%
2-Apr-97	1	37%	20-Mar-02	1	no survey
16-Apr-97	2	27%	4-Apr-02	2	66%
30-Apr-97	3	3%	17-Apr-02	3	11%
14-May-97	4	0%	1-May-02	4	1%
29-May-97	5	1%	15-May-02	5	0%
11-Jun-97	6	2%	30-May-02	6	2%
26-Jun-97	7	3%	12-Jun-02	7	1%
10-Jul-97	8	1%	26-Jun-02	8	2%
8-Apr-98	1	0%	26-Mar-03	1	10%
23-Apr-98	2	0%	9-Apr-03	2	32%
6-May-98	3	0%	23-Apr-03	3	13%
20-May-98	4	0%	7-May-03	4	1%
3-Jun-98	5	0%	21-May-03	5	3%
17-Jun-98	6	0%	4-Jun-03	6	4%
30-Jun-98	7	0%	18-Jun-03	7	5%
15-Jul-98	8	0%	1-Jul-03	8	8%
14-Apr-99	1	16%	31-Mar-04	1	14%
28-Apr-99	2	0%	14-Apr-04	2	3%
12-May-99	3	3%	28-Apr-04	3	1%
25-May-99	4	3%	12-May-04	4	0%
9-Jun-99	5	1%	26-May-04	5	0%
23-Jun-99	6	1%	9-Jun-04	6	0%
8-Jul-99	7	1%	23-Jun-04	7	0%
21-Jul-99	8	1%	8-Jul-04	8	0%

Table 3

Dates and day of the year when water temperature reached 12 and 20 degrees C

station	year	date of temp, deg C		day of year	
		12	21	12	21
Cache Sl.	1995	19-Feb-95	18-Jun-95	50	169
	1996	28-Jan-96	23-May-96	28	144
	1997	12-Feb-97	28-May-97	43	148
	1998	27-Feb-98	28-Jun-98	58	179
	1999	22-Feb-99	17-Jun-99	53	168
	2000	7-Feb-00	18-May-00	38	139
	2001	6-Mar-01	8-May-01	65	128
	2002	14-Feb-02	28-May-02	45	148
	2003	12-Jan-03	20-May-03	12	140
	2004	19-Feb-04	30-May-04	50	151
	2005	19-Jan-05	22-May-05	19	142
Goodyear Sl.	1995	12-Jan-95	21-Jun-95	12	172
	1996	2-Jan-96	27-Apr-96	2	118
	1997	16-Feb-97	13-May-97	47	133
	1998	15-Feb-98	13-Jun-98	46	164
	1999	23-Feb-99	18-Jun-99	54	169
	2000	25-Jan-00	20-May-00	25	141
	2001	5-Mar-01	8-May-01	64	128
	2002	12-Feb-02	29-May-02	43	149
	2003	14-Jan-03	20-May-03	14	140
	2004	15-Feb-04	25-Apr-04	46	116
	2005	3-Feb-05	14-May-05	34	134
SJR at San Andreas Landing	1995	1-Jan-95	31-May-95	1	151
	1996	4-Feb-96	27-Apr-96	35	118
	1997	20-Feb-97	12-May-97	51	132
	1998	11-Mar-98	14-Jun-98	70	165
	1999	20-Mar-99	16-Jun-99	79	167
	2000	13-Mar-00	23-May-00	73	144
	2001	9-Mar-01	16-May-01	68	136
	2002	22-Feb-02	30-May-02	53	150
	2003	28-Feb-03	29-May-03	59	149
	2004	8-Mar-04	30-May-04	68	151
	2005	17-Feb-05	27-Jun-05	48	178
SJR at Pittsburg	1995	3-Feb-95	26-Jun-95	34	177
	1996	8-Feb-96	5-Jun-96	39	157
	1997	30-Jan-97	24-May-97	30	144
	1998	2-Mar-98	5-Jul-98	61	186
	1999	2-Mar-99	21-Jun-99	61	172
	2000	11-Feb-00	24-May-00	42	145
	2001	6-Mar-01	19-May-01	65	139
	2002	21-Feb-02	4-Jun-02	52	155
	2003	30-Jan-03	2-Jun-03	30	153
	2004	22-Feb-04	14-Jun-04	53	166
	2005	29-Jan-05	30-Jun-05	29	181
Sacramento R. at Rio Vista	1995	1-Feb-95	27-Jul-95	32	208
	1996	6-Feb-96	30-Jun-96	37	182
	1997	10-Mar-97	22-May-97	69	142
	1998	14-Mar-98	7-Jul-98	73	188
	1999	20-Mar-99	20-Jun-99	79	171
	2000	13-Mar-00	24-May-00	73	145
	2001	10-Mar-01	18-May-01	69	138
	2002	23-Feb-02	1-Jun-02	54	152
	2003	7-Mar-03	24-Jun-03	66	175
	2004	7-Mar-04	1-Jun-04	67	153
	2005	20-Feb-05	30-Jun-05	51	181
SJR at Antioch	1995	21-Feb-95	27-Jun-95	52	178
	1996	8-Feb-96	4-Jun-96	39	156
	1997	29-Jan-97	20-May-97	29	140
	1998	28-Feb-98	27-Jun-98	59	178
	1999	28-Feb-99	19-Jun-99	59	170
	2000	8-Feb-00	22-May-00	39	143
	2001	4-Mar-01	18-May-01	63	138
	2002	20-Feb-02	31-May-02	51	151
	2003	22-Feb-03	29-May-03	53	149
	2004	22-Feb-04	20-Jun-04	53	172
	2005	13-Feb-05	2-Jun-05	44	153
Martinez	1995	2-Feb-95	25-Jun-95	33	176
	1996	9-Feb-96	3-Jul-96	40	185
	1997	31-Jan-97	17-May-97	31	137
	1998	28-Feb-98	4-Jul-98	59	185
	1999	19-Mar-99	30-Jun-99	78	181
	2000	13-Feb-00	16-Jun-00	44	168
	2001	7-Mar-01	14-Jun-01	66	165
	2002	20-Feb-02	2-Jul-02	51	183
	2003	28-Jan-03	26-Jun-03	28	177
	2004	16-Feb-04	15-Jul-04	47	197
	2005	12-Feb-05	9-Jul-05	43	190
SJR @ Burns Cutoff	1995	28-Jan-95	23-Jun-95	28	174
	1996	2-Feb-96	1-Jun-96	33	153
	1997	27-Jan-97	22-May-97	27	142
	1998	18-Jan-98	14-Jun-98	18	165
	1999	26-Feb-99	25-May-99	57	145
	2000	25-Jan-00	21-May-00	25	142
	2001	22-Feb-01	8-May-01	53	128
	2002	18-Feb-02	27-May-02	49	147
	2003	31-Jan-03	20-May-03	31	140
	2004	19-Feb-04	29-Apr-04	50	120
	2005	8-Feb-05	13-Jun-05	39	164

Table 4
Percentage of larval-juvenile smelt hatched

survey mid-date	survey #	% hatched	survey mid-date	survey #	% hatched
26-Apr-95	1	56%	22-Mar-00	1	19%
10-May-95	2	72%	5-Apr-00	2	37%
24-May-95	3	84%	19-Apr-00	3	61%
7-Jun-95	4	92%	3-May-00	4	82%
21-Jun-95	5	97%	17-May-00	5	95%
6-Jul-95	6	99%	31-May-00	6	99%
20-Jul-95	7	100%	14-Jun-00	7	100%
4-Aug-95	8	100%	28-Jun-00	8	100%
26-Apr-95	1	56%	21-Mar-01	1	3%
10-May-95	2	72%	4-Apr-01	2	19%
24-May-95	3	84%	18-Apr-01	3	52%
7-Jun-95	4	92%	3-May-01	4	84%
21-Jun-95	5	97%	16-May-01	5	95%
6-Jul-95	6	99%	1-Jun-01	6	99%
20-Jul-95	7	100%	13-Jun-01	7	100%
4-Aug-95	8	100%	27-Jun-01	8	100%
2-Apr-97	1	39%	20-Mar-02	1	10%
16-Apr-97	2	64%	4-Apr-02	2	28%
30-Apr-97	3	85%	17-Apr-02	3	50%
14-May-97	4	96%	1-May-02	4	74%
29-May-97	5	100%	15-May-02	5	90%
11-Jun-97	6	100%	30-May-02	6	97%
26-Jun-97	7	100%	12-Jun-02	7	100%
10-Jul-97	8	100%	26-Jun-02	8	100%
8-Apr-98	1	13%	26-Mar-03	1	31%
23-Apr-98	2	26%	9-Apr-03	2	47%
6-May-98	3	45%	23-Apr-03	3	65%
20-May-98	4	65%	7-May-03	4	80%
3-Jun-98	5	83%	21-May-03	5	90%
17-Jun-98	6	92%	4-Jun-03	6	96%
30-Jun-98	7	98%	18-Jun-03	7	99%
15-Jul-98	8	100%	1-Jul-03	8	99%
14-Apr-99	1	9%	31-Mar-04	1	15%
28-Apr-99	2	23%	14-Apr-04	2	35%
12-May-99	3	44%	28-Apr-04	3	61%
25-May-99	4	67%	12-May-04	4	84%
9-Jun-99	5	86%	26-May-04	5	95%
23-Jun-99	6	95%	9-Jun-04	6	99%
8-Jul-99	7	99%	23-Jun-04	7	100%
21-Jul-99	8	100%	8-Jul-04	8	100%

Table 5
Percentage entrainment of larval-juvenile smelt present at the time of each survey

survey mid-date	survey #	% entrained	survey mid-date	survey #	% entrained
26-Apr-95	1	0%	22-Mar-00	1	0%
10-May-95	2	0%	5-Apr-00	2	1%
24-May-95	3	0%	19-Apr-00	3	10%
7-Jun-95	4	0%	3-May-00	4	1%
21-Jun-95	5	0%	17-May-00	5	1%
6-Jul-95	6	0%	31-May-00	6	0%
20-Jul-95	7	0%	14-Jun-00	7	0%
4-Aug-95	8	0%	28-Jun-00	8	1%
26-Apr-95	1	0%	21-Mar-01	1	0%
10-May-95	2	0%	4-Apr-01	2	1%
24-May-95	3	0%	18-Apr-01	3	5%
7-Jun-95	4	1%	3-May-01	4	2%
21-Jun-95	5	1%	16-May-01	5	0%
6-Jul-95	6	0%	1-Jun-01	6	0%
20-Jul-95	7	0%	13-Jun-01	7	1%
4-Aug-95	8	1%	27-Jun-01	8	0%
2-Apr-97	1	14%	20-Mar-02	1	
16-Apr-97	2	17%	4-Apr-02	2	18%
30-Apr-97	3	2%	17-Apr-02	3	5%
14-May-97	4	0%	1-May-02	4	1%
29-May-97	5	1%	15-May-02	5	0%
11-Jun-97	6	2%	30-May-02	6	2%
26-Jun-97	7	3%	12-Jun-02	7	1%
10-Jul-97	8	1%	26-Jun-02	8	2%
8-Apr-98	1	0%	26-Mar-03	1	3%
23-Apr-98	2	0%	9-Apr-03	2	15%
6-May-98	3	0%	23-Apr-03	3	8%
20-May-98	4	0%	7-May-03	4	1%
3-Jun-98	5	0%	21-May-03	5	3%
17-Jun-98	6	0%	4-Jun-03	6	4%
30-Jun-98	7	0%	18-Jun-03	7	5%
15-Jul-98	8	0%	1-Jul-03	8	8%
14-Apr-99	1	1%	31-Mar-04	1	2%
28-Apr-99	2	0%	14-Apr-04	2	1%
12-May-99	3	1%	28-Apr-04	3	0%
25-May-99	4	2%	12-May-04	4	0%
9-Jun-99	5	1%	26-May-04	5	0%
23-Jun-99	6	0%	9-Jun-04	6	0%
8-Jul-99	7	0%	23-Jun-04	7	0%
21-Jul-99	8	1%	8-Jul-04	8	0%

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