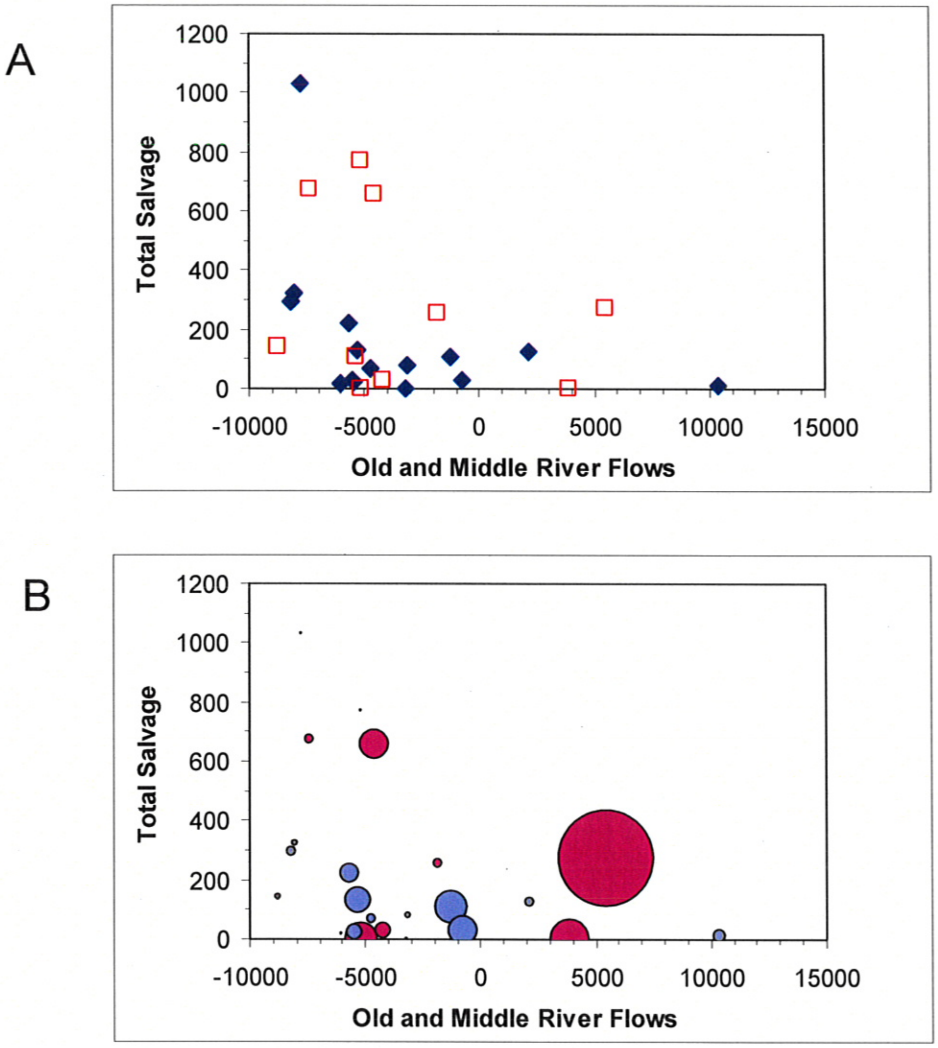

Figure 10. (A) Total salvage of longfin smelt (December through March SWP+CVP) as a function of average Old and Middle River flows during the same period for water years 1982-1992 (squares) and 1993-2007 (diamonds). OMR estimates for 1982-1992 were based on calculations conducted by Lenny Grimaldo; those from 1993-2007 were based on measured flows from USGS. A single point of salvage at 20,962 and OMR at -7744 is not depicted. (B) same data as (A) with bubble size scaled by the previous Fall Midwater Trawl abundance index (red for 1982-1992, blue for 1993-2007).

Table 2. Annual entrainment and loss by water year of longfin smelt juveniles (20 - < 80mm) and adult (≥80 mm) calculated by scaling number salvaged by estimates of prescreen and within facility mortality for other similar species (see Fujimura 2009). Survival of salvaged fish through the salvage, handling, trucking and return phases was also estimated and used to calculate loss from entrainment as (entrainment-survival =loss).

By Water Year

State Water Project

	ENTRAINMENT		*LOSS*		*TOTAL SALVAGE*		*SURVIVAL*	
YEAR	JUVENILES	ADULTS	JUVENILES	ADULTS	JUVENILES	ADULTS	JUVENILES	ADULTS
1993	10,608	17	10,353	16	510	1	255	1
1994	69,964	541	68,282	515	3,364	32	1,682	26
1995	707	1,318	690	1,256	34	78	17	62
1996	1,934	744	1,888	708	93	44	47	35
1997	15,309	0	14,941	0	736	0	368	0
1998	13,187	0	12,870	0	634	0	317	0
1999	13,998	0	13,662	0	673	0	337	0
2000	28,829	304	28,136	290	1,386	18	693	14
2001	45,802	406	44,701	386	2,202	24	1,101	19
2002	1,133,870	1,369	1,106,614	1,304	54,513	81	27,257	65
2003	10,504	3,600	10,252	3,429	505	213	253	170
2004	4,211	2,206	4,110	2,102	202	131	101	104
2005	3,682	101	3,593	97	177	6	89	5
2006	0	0	0	0	0	0	0	0
2007	1,248	0	1,218	0	60	0	30	0
2008	22,578	448	22,036	427	1,086	27	543	21
Total	***1,376,432***	***11,054***	***1,343,345***	***10,530***	***66,175***	***654***	***33,087***	***523***

Central Valley Project

	ENTRAINMENT		*LOSS*		*TOTAL SALVAGE*		*SURVIVAL*	
YEAR	JUVENILES	ADULTS	JUVENILES	ADULTS	JUVENILES	ADULTS	JUVENILES	ADULTS
1993	517	0	441	0	132	0	77	0
1994	11,819	0	10,070	0	3,015	0	1,749	0
1995	0	0	0	0	0	0	0	0
1996	517	105	441	86	132	24	77	19
1997	1,505	52	1,283	43	384	12	223	9
1998	329	105	281	86	84	24	49	19
1999	469	52	399	43	120	12	69	9
2000	1,929	52	1,643	43	492	12	285	9
2001	17,076	262	14,549	215	4,356	60	2,526	47
2002	168,403	419	143,486	344	42,960	96	24,917	75
2003	18,024	0	15,357	0	4,598	0	2,667	0
2004	2,540	0	2,164	0	648	0	376	0
2005	47	105	40	86	12	24	7	19
2006	0	0	0	0	0	0	0	0
2007	141	0	120	0	36	0	21	0
2008	1,290	174	1,099	143	329	40	191	31
Total	***224,606***	***1,325***	***191,374***	***1,088***	***57,298***	***304***	***33,233***	***237***

Winter salvage limit for adult longfin smelt. We continue to have concern that unusual winter salvage circumstances could have a negative effect on longfin smelt. Specifically, when combined SWP and CVP cumulative winter salvage surpasses 5 times the immediate previous Fall Midwater Trawl longfin smelt abundance index, a review of juvenile and adult distribution should take place and should include an assessment of whether to change OMR flows for the protection of longfin smelt.

Larva Entrainment SWP (~January through April)

The fates of particles were most influenced by injection site location proximity to export pumps or Chipps Island and Montezuma Slough, export levels as they influenced OMR flows and river flows (Sacramento River at Rio Vista or Qwest). Mean percentage of particles entrained in combined SWP and CVP exports was consistently higher for surface oriented particles than for neutrally buoyant particles: Sacramento River (surface oriented = 5.5% and neutral = 3.5%) and San Joaquin River stations (surface oriented = 45.6% and neutral = 43.4%). Significantly more surface oriented than neutrally buoyant particles from Sacramento River locations were entrained by SWP and CVP exports (Pooled Variance t = -2.340; 124 df; *p* = 0.021). The relationship for San Joaquin River injected particles was more complex and varied across stations (Figure 11). For stations immediately north and east of Old River (815 and 906), particle behavior did not appear to affect risk of entrainment, entrainment was high (median ≥ 50%), variable and approximately equal for both surface oriented and neutrally buoyant particles (Figure 11).

Mean residence time -- the average number of days to reach 50% of particle fate following injection -- was lower for surface oriented particles than for neutrally buoyant particles in the Sacramento River (buoyant = 18.1 and neutral = 20.1) and San Joaquin River (buoyant = 19.3 and neutral = 22.0). There was no significant difference in average residence time between surface oriented and neutral particles in the Sacramento River (Pooled variance t = 0.726, 124 df, *p* = 0.469), but there was for particles in San Joaquin River (Pooled variance t = 1.975, 166 df, *p* = 0.050).

Since particle behavior affected entrainment risk and residence time, most of our remaining PTM analyses focus on surface oriented particle analyses.

Particle Fate Analyses

Particle fate was strongly influenced by hydrologic variables, which varied considerably across the study years (Figure 12). In 1992, total exports tracked Rio Vista flow early in the year until Sacramento River flow increased in mid-February; a much smaller increase occurred in the San Joaquin River and corresponded to a strong positive Qwest pulse during the late February period (Figure 12). These flows led to a substantial drop in SWP entrainment for particles injected in mid-January through mid-February, which was otherwise relatively high for the San Joaquin River stations (Figure 13). In 2002, a high outflow event occurred in early January (Figure 12) and resulted in a brief substantial decline in SWP particle entrainment for those injected in

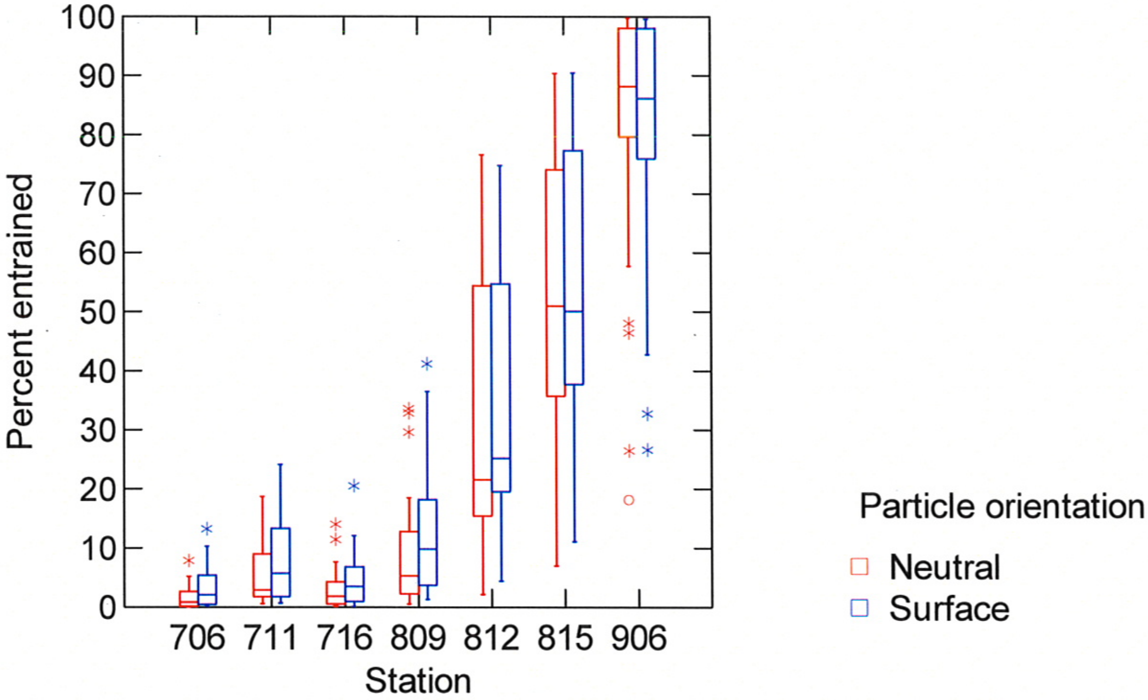

Figure 11. Box plot of percent entrainment at SWP and CVP by injection location (station) with all injection dates and years combined. The box plots show median values with lower and upper quartiles and whiskers showing the smallest and largest observations.

early January. SWP particle entrainment slowly declined again starting in mid-February or March when exports declined and Qwest and OMR flows became more positive (Figure 14). SWP particle entrainment from the San Joaquin River stations was relatively high for mid-January and early February 2002 injection dates as was entrainment Sacramento River stations. Later in spring 2002, exports declined with river flows, so entrainment dropped slowly across injection dates (Figure 14). In 2008, Sacramento River flows increased modestly in January, February and early March, yet exports only briefly in mid-January and late-February became a sizable fraction of the inflow (Figure 12). In particular, Qwest was often positive or near zero in 2008; positive Qwest occurred only sporadically after early January 2002 and before VAMP in mid-April (Figure 12). Positive Qwest and less negative OMR in 2008 led to a much reduced level of SWP particle entrainment (Figure 15). From late March through early June 2008, outflows and OMR flows were reduced to very low levels, which resulted in increasing fractions of injected particles remaining within the Delta after 90 days (i.e., fate unresolved), particularly for upper San Joaquin River stations 815 and 906 (Figure 15). Such a circumstance could have lead to increased salvage late in June as OMR became more negative (Figure 12). Further, the size range of historically salvaged juvenile (age-0) fish (20-60 mm; Figure 7) suggests a protracted

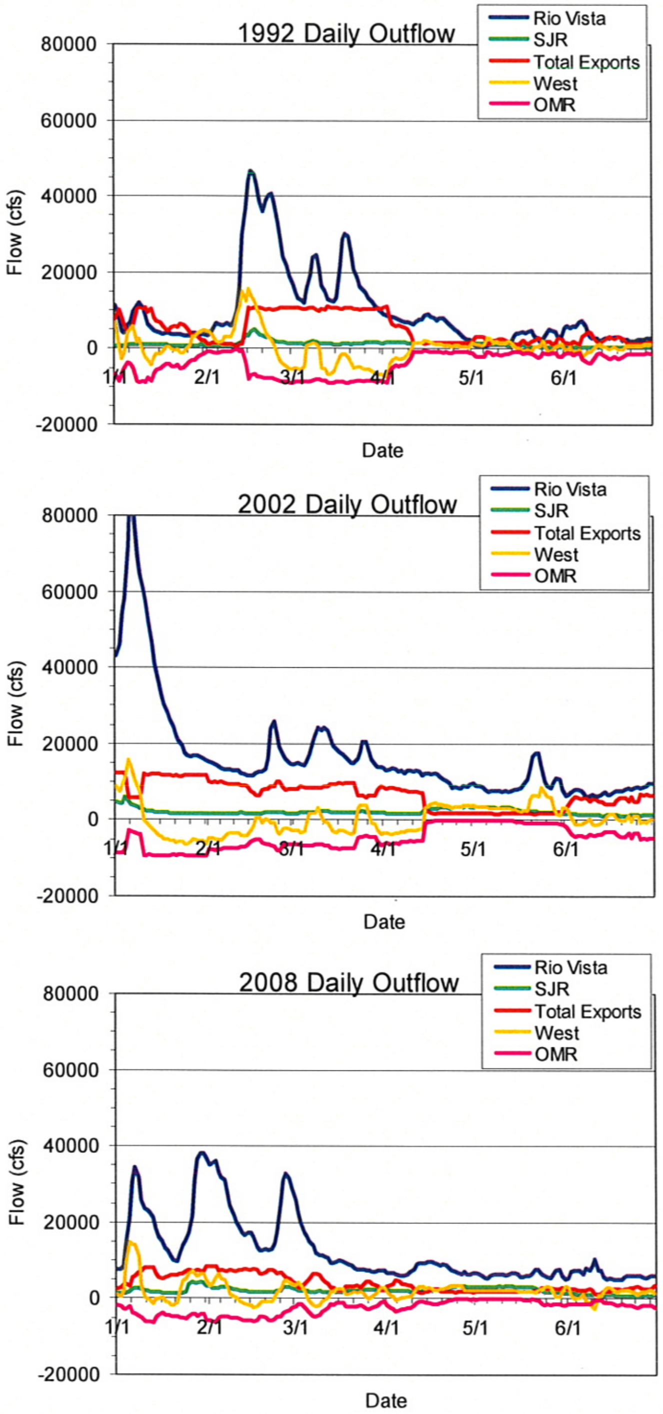

Figure 12. Average daily flow in cubic-feet-per-second (cfs) for the Sacramento River past Rio Vista, the San Joaquin River at Vernalis, total exports at SWP and CVP, flow in the San Joaquin River past Jersey Point (QWEST) and measured (2002) or modeled flow (1992, 2008) in Old and Middle rivers (OMR) for the first 6 months of 1992, 2002 and 2008.

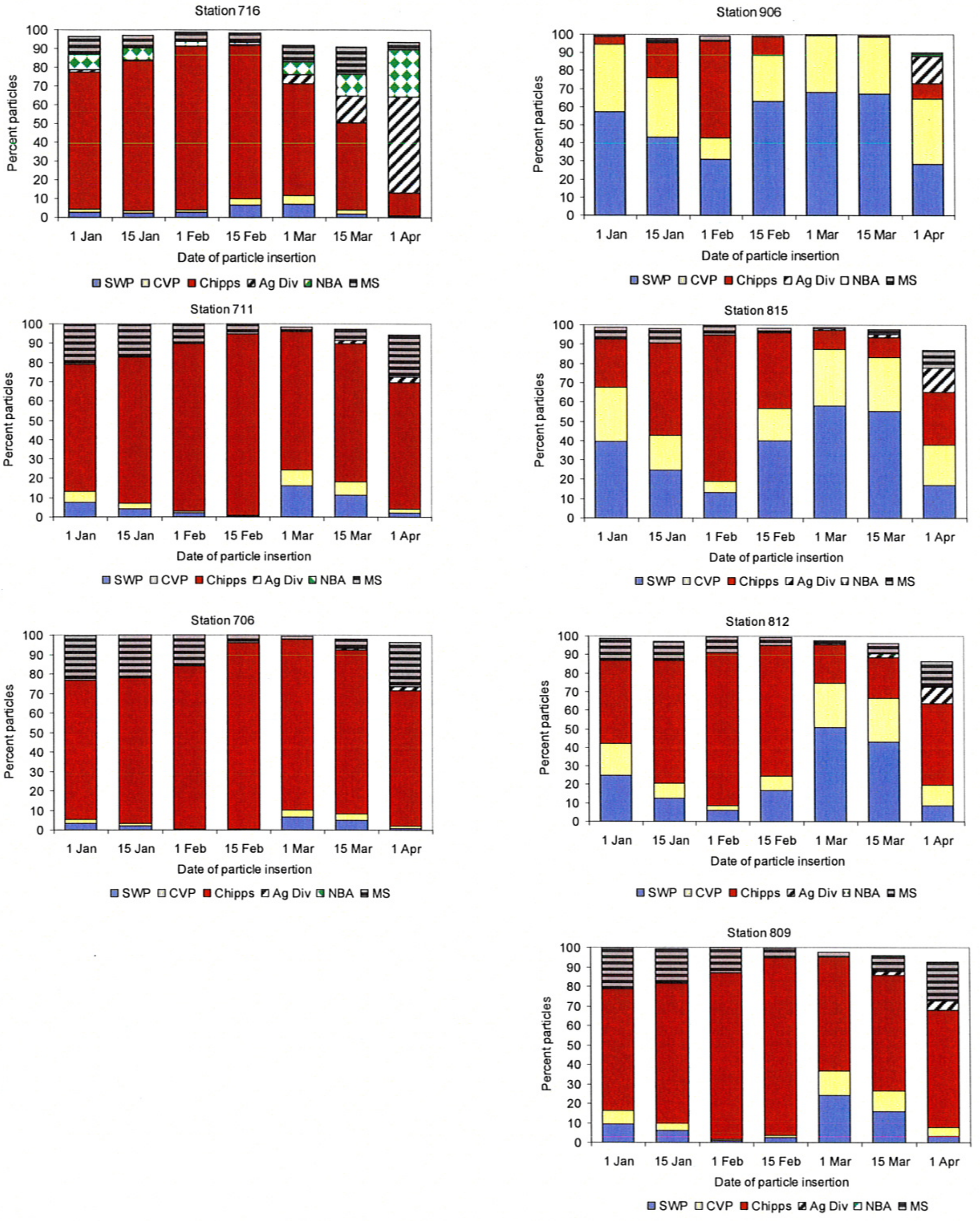

Figure 13. Percentages of surface-oriented particles entrained at the SWP, CVP, Agricultural diversions, North Bay Aqueduct or past Chipps Island after 90 days by station in 1992. Sacramento River stations oriented from upstream to downstream in the left column and San Joaquin stations similarly in the right column.

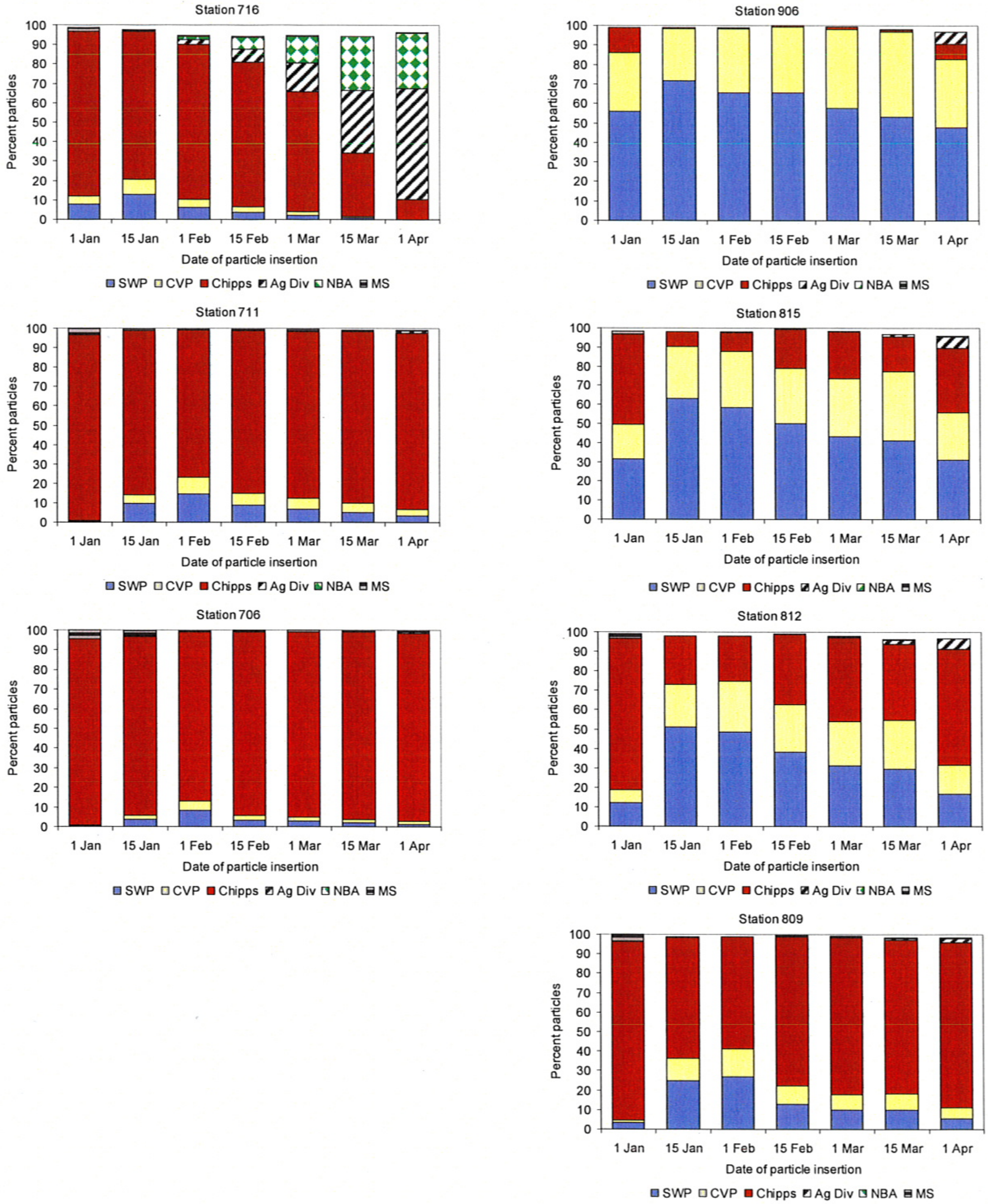

Figure 14. Percentages of surface-oriented particles entrained at the SWP, CVP, Agricultural diversions, North Bay Aqueduct or past Chipps Island after 90 days by station in 2002. Sacramento River stations oriented from upstream to downstream in the left column and San Joaquin stations similarly in the right column.

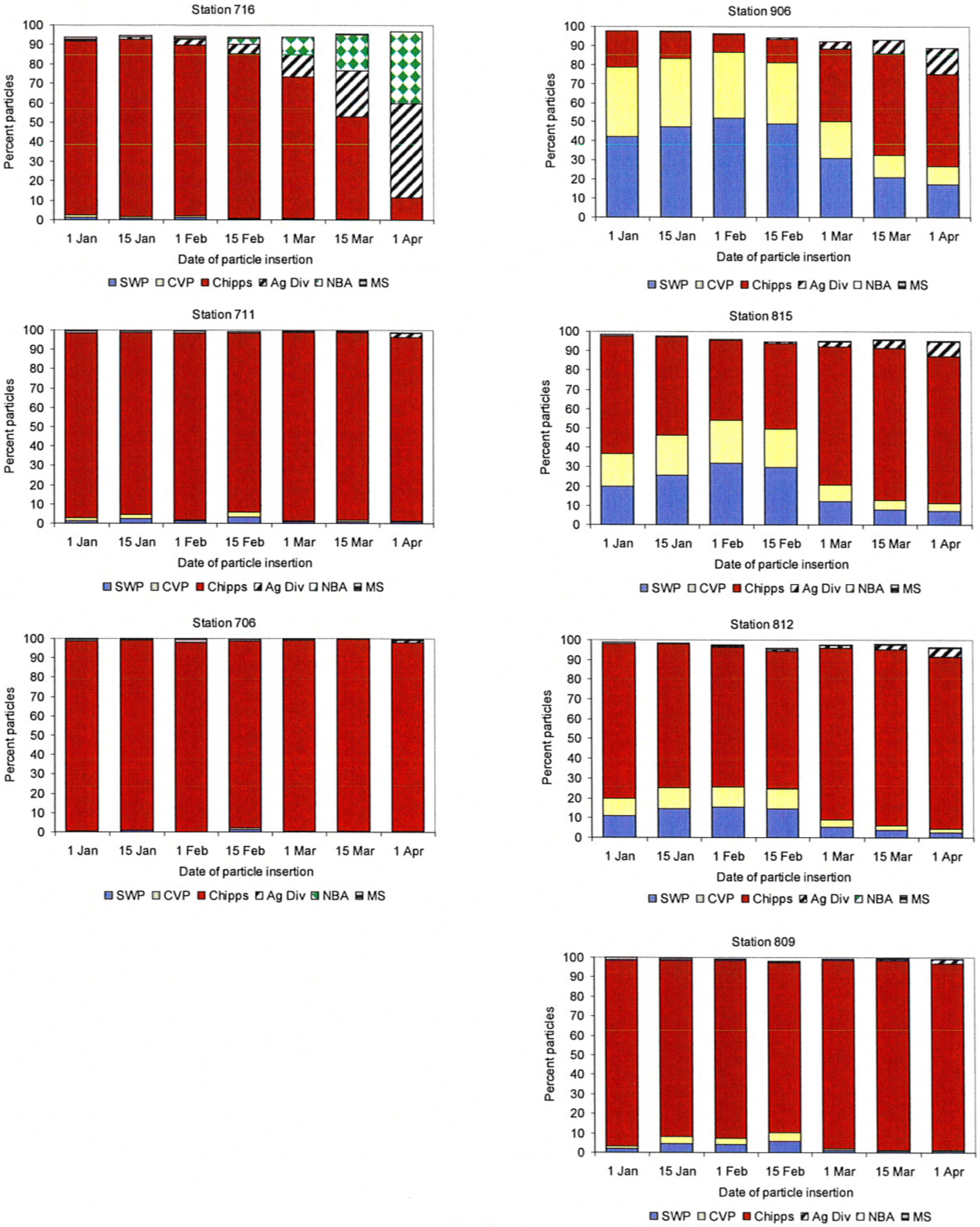

Figure 15. Percentages of surface-oriented particles entrained at the SWP, CVP, Agricultural diversions, North Bay Aqueduct or past Chipps Island after 90 days by station in 2008. Sacramento River stations oriented from upstream to downstream in the left column and San Joaquin stations similarly in the right column.

Delta residence time for some individuals or long travel times from some upstream spawning locations.

The effects of OMR and Qwest flows on particle entrainment appear to be antagonistic to one another. Increasingly negative OMR starting from -1000 cfs rapidly increases percent particle entrainment, whereas increasing Qwest tends to dampen the percent entrainment response (Figure 16). Limiting OMR flows to -2000 to -4000 while maintaining a positive Qwest substantially reduced entrainment for every injection period (Figure 16). In particular, during periods of positive Qwest, particles injected at stations 906 and 815 would flux into the south Delta via Old River (mostly) or Middle River, then flux out again via False River.

Mean residence time in the Delta generally decreased with more negative OMR flows (Figure 17). Conversely, when negative OMR flows ranged between -1000 and -2000 cfs mean residence time could substantially exceed 30 days, and in a few cases exceeded 50 days. Mean residence time was also lower for injection locations (706 and 809) in close proximity to Delta boundary locations of Chipps Island and Montezuma Slough than those farther upstream. In general most particles resolved their fates well within the 90 day larva development period; however, when OMR ranged between about -1000 to -3000 and Qwest was positive, mean residence times substantially exceeded 30 days for upstream injection locations.

Annual Entrainment and Effects

Total annual entrainment of surface-oriented particles was calculated to emulate loss of longfin smelt larvae over the January through June time period modeled for each year. Similar calculations for neutrally buoyant particles were provided for comparison. In each case we initially based calculations on larva hatching density estimates from a series of mostly dry years (1991-1994), during which larva densities were much higher at Sacramento River stations than at San Joaquin River stations. Based on higher Sacramento River hatch densities, annual total particle entrainment at the SWP was highest for surface-oriented relative to neutrally buoyant particles in every year and reached a peak under 2002 hydrology at just over 9% (Table 3). In 2008, with Wanger export restrictions in place and the resulting favorable hydrology described previously, percent entrainment at the SWP declined to about 2.2% for surface oriented particles (Table 3). For comparison, we repeated calculations with densities in the Sacramento and San Joaquin rivers about equal, as occurred in 2005 larvae sampling. The annual proportion of particles entrained in the SWP during 2008 increased by about 1% to 3.1% of the total particles (Table 4). Similar SWP entrainment increases of about 1% occurred in 1992 and 2002 when Sacramento River and San Joaquin River hatching densities approached equality, and a greater proportion of the particles "hatched" closer to the export pumps. Combined CVP and SWP entrainment was even more substantial, suggesting peak entrainment in the range of 15-17% (2002 in Tables 3 and 4).

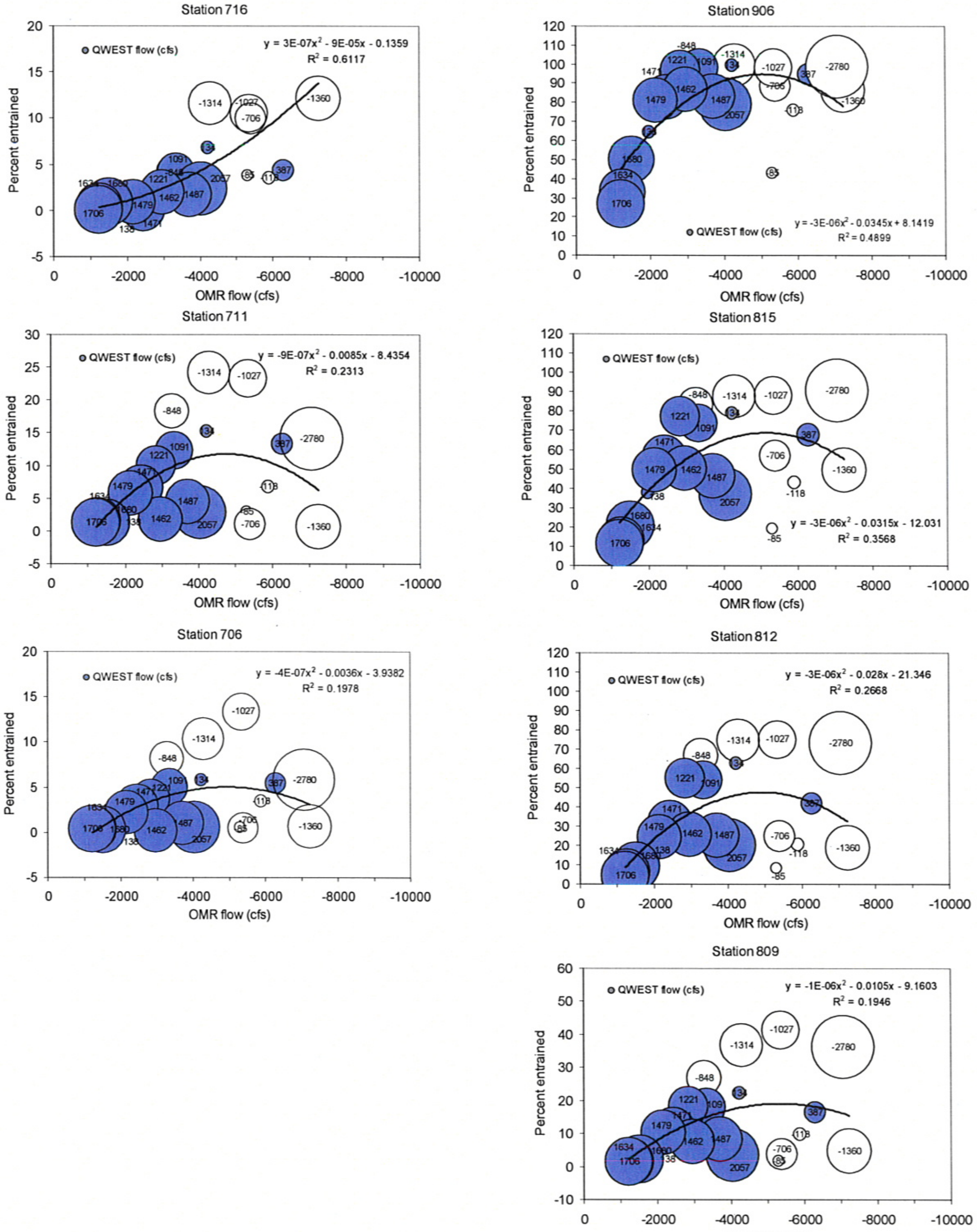

Figure 16. Relationships between Old and Middle River flows and percent of surface-oriented particles entrained at the SWP and CVP exports combined for 1992, 2002 and 2008 by station. The bubble sizes are scaled to and labeled with average Qwest flows for the same 90 day periods as OMR flows.

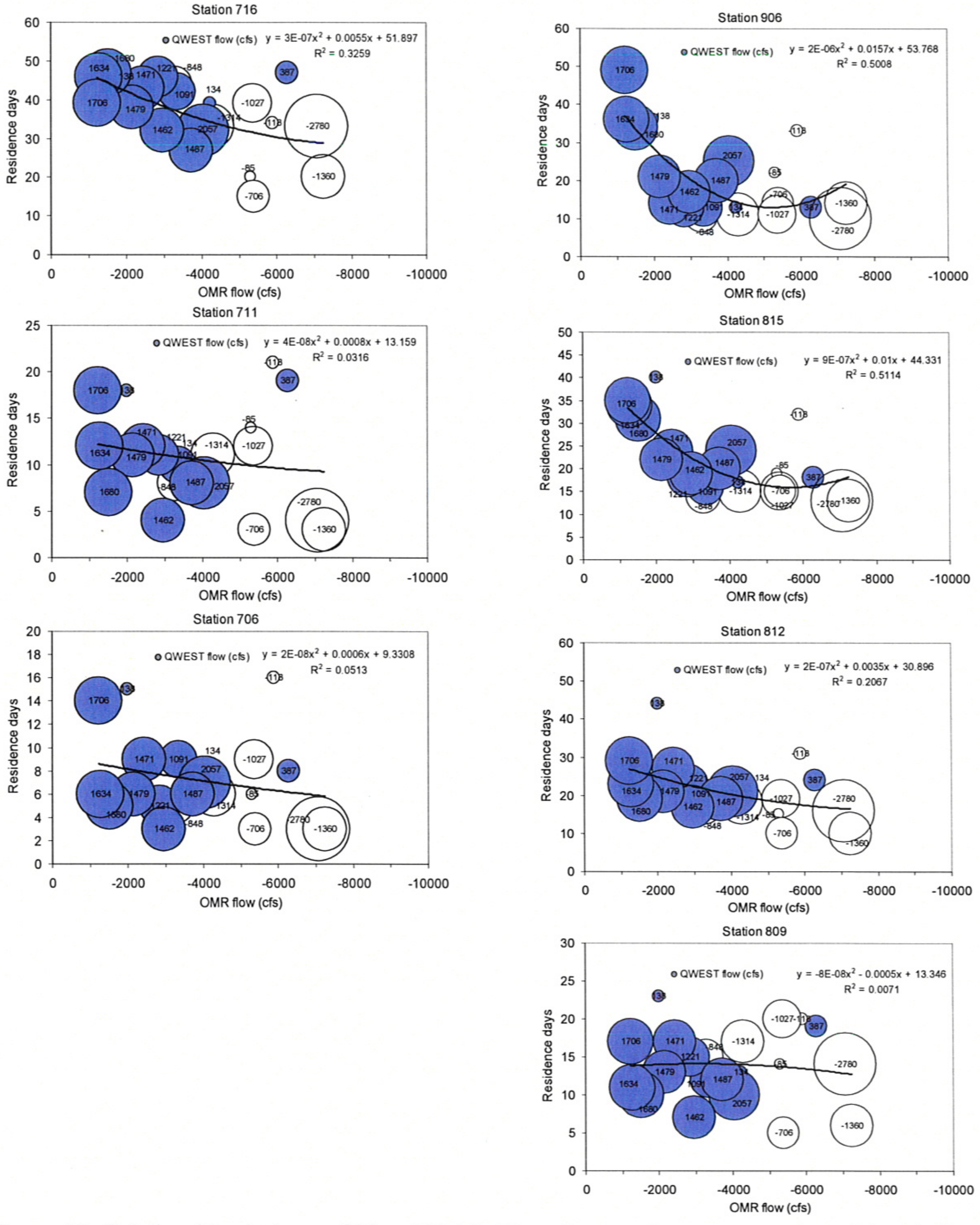

Figure 17. Relationships between Old and Middle River flows and average number of days to the fate of 50% of the particles entrained at the SWP+CVP exports, NBA, and Ag diversions, past Chipps, or into Montezuma Slough by station. The bubble sizes are scaled to and labeled with the average Qwest flows (cfs) for the same 90 day periods as the OMR flows.

Table 3. Annual particle fate (% of total resolved) by location from 90-day scaled PTM results using relative larva densities from 1991-1994 where Sacramento River station larva densities were much higher than those of San Joaquin River stations. Table does not include the fates of a small number of particles unresolved after the 90-day runs.

Year	Behavior	CVP%	Montezuma%	Chipps%	AgDiv%	NBA%	SWP%	CVP+SWP%
1992	neutral	2.06	10.96	82.02	0.74	0.74	3.49	5.55
1992	surface	2.91	11.33	79.43	0.71	0.71	4.91	7.82
2002	neutral	4.44	1.27	85.19	1.21	0.77	7.11	11.56
2002	surface	5.72	0.94	82.15	1.19	0.82	9.18	14.90
2008	neutral	1.10	1.10	94.52	1.11	0.60	1.56	2.66
2008	surface	1.54	0.96	93.69	1.04	0.59	2.17	3.71

Table 4. Annual particle fate (% of total resolved) by location from 90-day scaled PTM results using relative densities similar to 2005 where Sacramento River station larva densities were only slightly higher than those of San Joaquin River stations. Table does not include the fates of a small number of particles unresolved after the 90-day runs.

Year	Behavior	CVP%	Montezuma %	Chipps%	AgDiv%	NBA%	SWP%	CVP+SWP%
1992	neutral	2.59	10.98	80.39	0.73	0.73	4.58	7.16
1992	surface	3.36	11.33	78.07	0.70	0.71	5.83	9.20
2002	neutral	5.12	1.33	83.11	1.21	0.77	8.47	13.59
2002	surface	6.30	0.97	80.34	1.19	0.82	10.39	16.69
2008	neutral	1.73	1.09	92.88	1.16	0.60	2.54	4.27
2008	surface	2.18	0.96	92.09	1.07	0.59	3.10	5.29

To the extent that our data approximated actual hatching densities and PTM modeling with surface-oriented particles roughly emulated the movements of longfin smelt larvae within the Delta, our results suggest that larva entrainment at the SWP might be substantial (2-10% of total; Tables 3 and 4) under the relatively low outflow conditions modeled. Such high entrainment percentages would only be expected during periods of low downstream transport flows during which Qwest was generally negative. Conversely, when river flow surpassed about 40,000 cfs, SWP particle entrainment dropped substantially (c.f. Figures 12-15) and was generally low when river flow surpassed 55,000 cfs (c.f. Figures 12 and 14 for January 1 injections) even with exceptional high exports and negative OMR (Figure 12). If such a high river flow circumstances occurred throughout the principal hatching period of January through March, SWP expected larvae entrainment would be less than one percent of total, given the assumed relative San Joaquin River spawning densities. Also, we interpret these results as additive to subsequent salvage of juveniles described in the next section. Unfortunately, we have yet to devise absolute abundance estimates for juveniles to derive a complete estimate of entrainment.

The current OCAP and delta smelt BO could trigger export restrictions in December, January or February, based on a turbidity increase or adult delta smelt salvage, but neither trigger is guaranteed. Further, substantial OMR restrictions would not come into effect until a spent delta smelt adult or a larvae was detected or Delta water temperatures surpassed 12°C; occurrence of these conditions was unlikely until late

February or more likely mid-March. Thus, some protections for longfin smelt larvae are needed, particularly in January and February, independent of those for delta smelt, even if these longfin smelt protections are uncommonly enacted.

Juvenile Entrainment (~March through June)

Circumstances leading to juvenile entrainment probably began during the spawning and larval stages; that is, spawning took place farther in the Delta and once hatched larvae were drawn into the south Delta during winter and spring, growing along the way -- or possibly within Clifton Court Forebay -- to the 20mm minimum size for identification and were salvaged in spring or early summer. A couple lines of evidence support this latter contention. First, the timing and pattern of age-0 salvage follows the same pattern as that of hatching, but shifted 3 months (90 days) later in the year (i.e., the time necessary to grow to 20mm) (Figure 18). Second, fish at the 20mm minimum size threshold continued to be salvaged in good numbers in June, about 3 months after the last of the strong hatching months, March (Figure 7). The sporadic salvage of 20-40mm longfin smelt in summer months (Figure 7) may have resulted from rare upstream spawning in the Sacramento or San Joaquin Rivers (see CDFG 2009) and later emigration or from portions of the Delta that have under some conditions extremely long residence times, that larvae and juveniles can travel large distances before being entrained or both. Our 90 day PTM runs described in the previous section were designed to capture the entire larval period and encompass a time span sufficient for particle fate to be resolved; however, fates were not always resolved at 90 days, particularly for spring injection dates (Figures 13-15). These findings lead to the conclusion that juvenile salvage and loss (Table 2) is additive to estimated larval loss as described by the PTM runs (Tables 3 and 4).

Juvenile salvage at the SWP was considerable in a few years when outflow was low (e.g., 1988 and 2002) and very low when outflow was high (e.g., 1982-1983, 1995-1996; Figure 19). Fujimura (2009, Appendix B) estimated that loss at the SWP was a multiple of salvage (ca. 16x higher; Table 2). Yet, even in high salvage years like 2002, juvenile (age-0) loss was only likely to add another few percent to the loss calculated for larvae based on the PTM runs. In 2008, juvenile loss may have been more substantial given the very low number of spawners believed present.

Spring hydrodynamics have been highly variable across all measures (Figures 20 and 21). Inflows declined over the period of record and since the late 1990s. Spring exports increased through the late 1980s, declined sharply starting about 1990 during the drought, and though highly variable, the trend remained essentially flat after about 1995 (Figure 20A-C). Spring OMR flows fluctuated over time, but remained generally negative and generally declining (Figure 21). Spring X2 position trended similar to exports, but with a lag (Figure 20B and C). Spring X2 position moved rapidly upstream with low inflows and increasing exports in the mid- to late-1980s, and continued to remain high even after exports dropped as the drought persisted through the early 1990s. With the return of higher outflows in the mid-1990s, X2 trended strongly

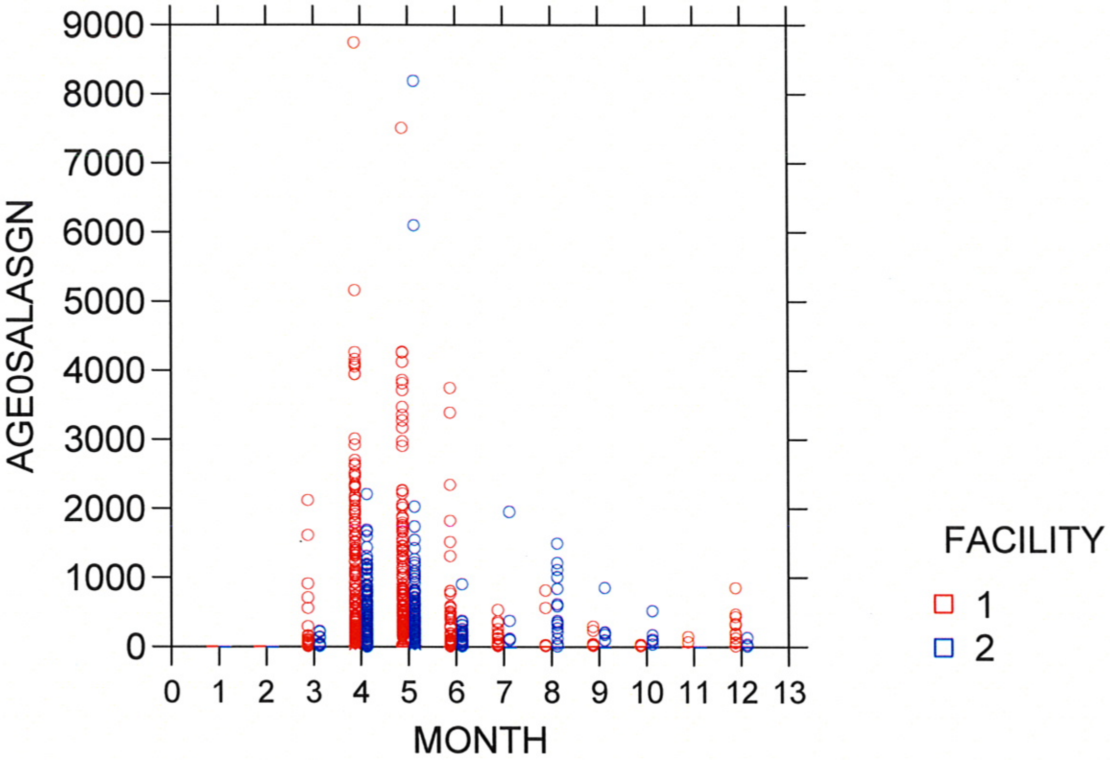

Figure 18. Scatter of juvenile longfin smelt salvage by month 1982 through 2007 for the SWP (red) and CVP (blue).

downward and has only increased slightly through the early 2000s. After an upswing with higher inflows during the mid-1990s, OMR flows declined and were strongly negative from the 2000 to 2004 and less negative in more recent years (Figure 21); the recent years of increased longfin smelt juvenile salvage corresponded with these strongly negative OMR flows (c.f., Figures 19 and 21).

Similar to Grimaldo et al. (accepted), we found a significant negative relationship between spring OMR flows and juvenile longfin smelt salvage ($r^2 = 0.466$, $p < 0.05$, 13 df; Figure 22A). Similar to patterns of particle entrainment in the SWP and CVP, juvenile salvage increased rapidly as OMR flows became more negative than about -2000 cfs (Figure 22A and B).

Conversely, as winter-spring or just spring outflows increased, X2 shifted downstream and salvage of juvenile longfin smelt decreased significantly ($r^2 = 0.656$, $p < 0.002$, 24 df; Figure 23A). This relationship improved when the outflow period was more contemporaneous with salvage in spring (Figure 23B). In these relationships, two mechanisms influenced salvage: 1) when X2 is located downstream of the Delta, substantial spawning may have occurred downstream of the Delta, reducing the proportion of juveniles (and larvae) susceptible to entrainment; and 2) when X2 was

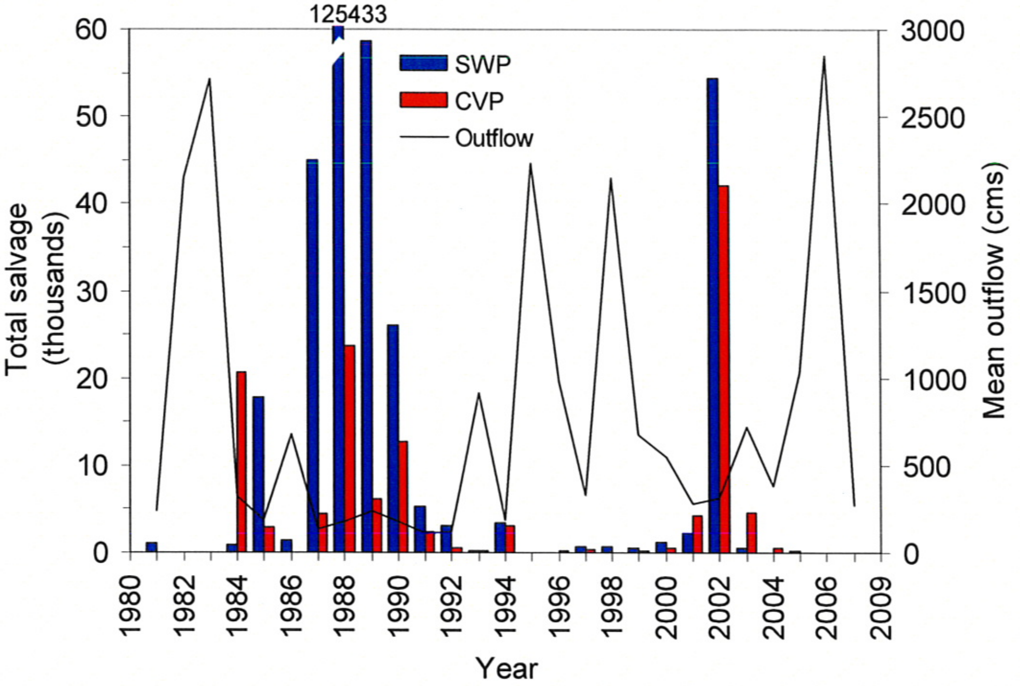

Figure 19. Total spring (Apr-Jun) salvage of longfin smelt at the State Water Project and Central Valley Project for 1981 through 2007 and mean Delta outflow in cubic meters per second for the same period.

located downstream of the Delta, the associated higher outflow would both increase the region of net downstream currents and would transport juveniles (and larvae) more rapidly downstream, reducing their vulnerability to entrainment. Thus, as spring outflow increased the entrainment risk to longfin smelt juveniles dropped rapidly in a manner similar to that detected through particle tracking.

The availability for and presence in salvage of juvenile longfin smelt from 20-60 mm FL (Figure 7) indicates a protracted period of vulnerability during low outflow years. This was suggested by incomplete fate resolution within 90 days for late March and April injected particles (cf. Figures 13-15). Also during spring, OMR flows became less negative during the Vernalis Adaptive Management Program (VAMP; about 15 April through 15 May; http://www.delta.dfg.ca.gov/jfmp/vamp.asp), generally increasing residence time (Figure 17) and allowing for more growth prior to salvage. Moreover, because OMR flows often become more negative in late May and June after VAMP restrictions abate, larvae and juveniles remaining in the Delta face increased risk of entrainment.

The pelagic orientation of larval and juvenile longfin smelt and their similar responses to outflows and OMR flows indicate that similar actions would benefit and should be taken for each. These could include: 1) short, periodic pulse flows through the central Delta January through June to transport larvae and juveniles away from the region of vulnerability; and 2) less negative OMR flows to reduce entrainment into the south

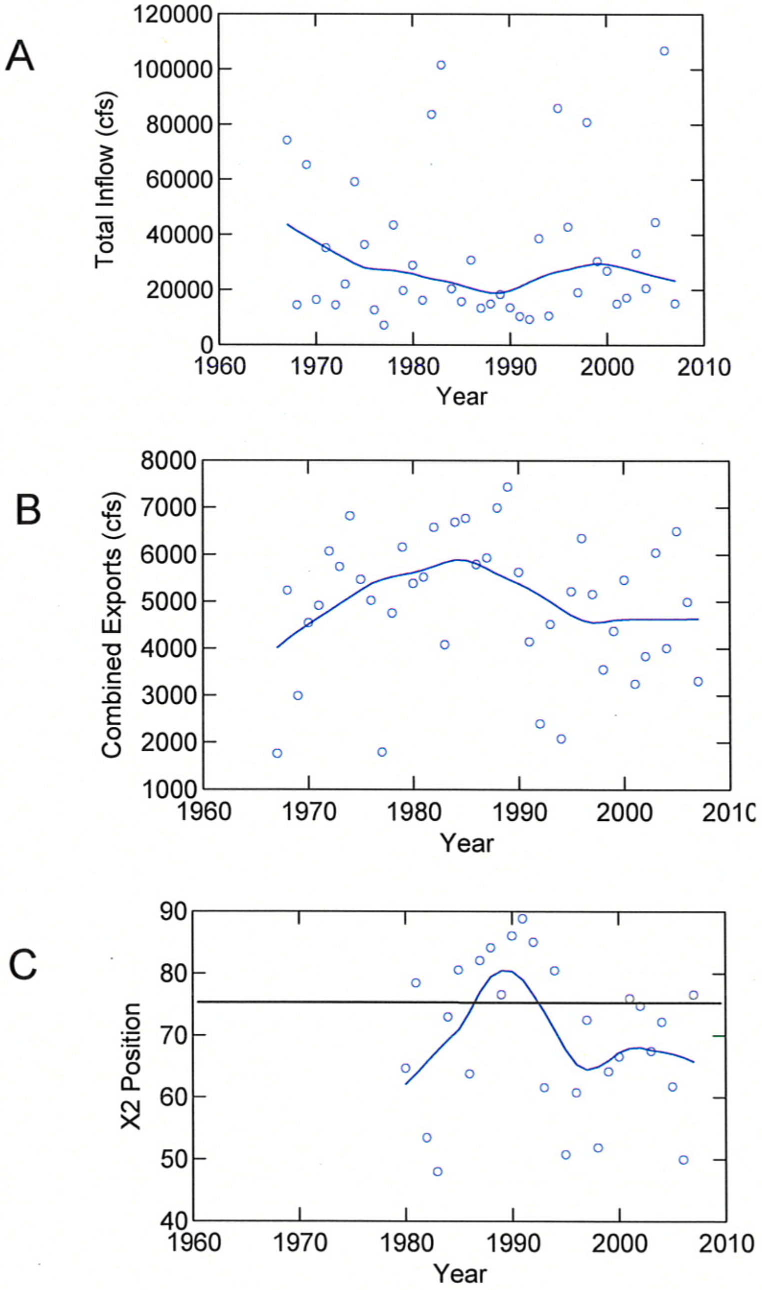

Figure 20. Trends in average spring (Apr-Jun) total delta inflow (A), combined SWP /CVP exports (B), and X2 position (C), 1967-2007, except for (C), which was 1980-2007. A LOWESS line was plotted through points to show general trend. The horizontal line in (C) at 75 km represents the location of Chipps Island.