The Effects of Delta Hydrodynamic Conditions on San Joaquin River Juvenile Salmon

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Dave Vogel
Natural Resource Scientists, Inc.
P.O. Box 1210
Red Bluff, CA 96080

Introduction

Field tests on salmon survival for the Vernalis Adaptive Management Program (VAMP) have been conducted from 2000 through 2004. These tests were intended to evaluate salmon survival through the lower San Joaquin River and Delta under a range of flows at Vernalis and export pumping in the south Delta during a 30-day period in April and May. Specifically, the experiments were designed to evaluate how San Joaquin River flows (7,000 cfs or less) and exports with a barrier at the head of Old River affect juvenile salmon survival through the Delta (SJRGA 2004). Using the five years of data from the VAMP experiments, a statistically significant relationship between flow and exports has not yet emerged and has prompted the recommendation for more years of tests with a wider range of flow and exports (SJRGA 2005). Part of the lack of statistical significance in study results is attributable to low recoveries of marked/tagged salmon in the experiments from the release locations at Mossdale/Durham Ferry in the San Joaquin River to the recapture locations at Antioch and Chipps Island (Figure 1).

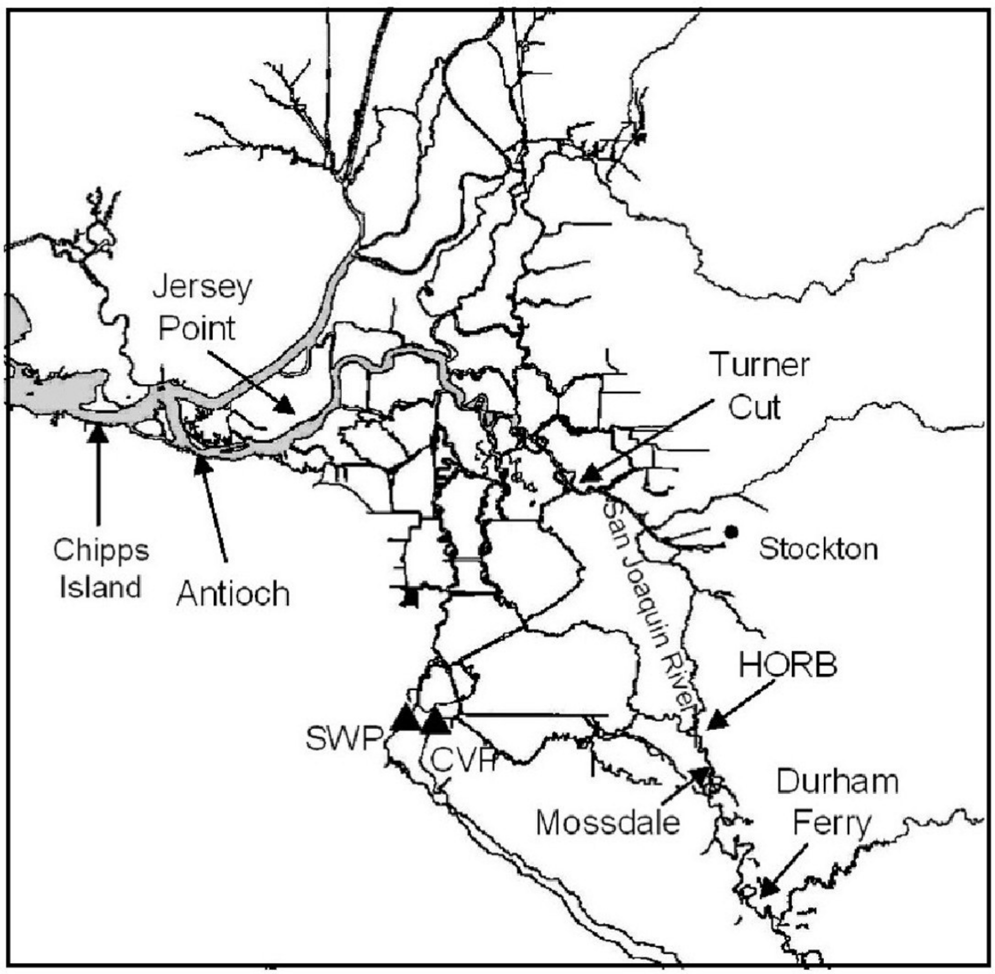

Figure 1. The Sacramento – San Joaquin Delta showing landmarks relevant to the Vernalis Adaptive Management Program (e.g., HORB = head of Old River barrier, SWP = State Water Project export facilities, CVP = Central Valley Project export facilities)

For example, during the 2004 VAMP studies, extremely low or no recoveries of tagged salmon were noted. Releases of 92,264 tagged salmon at Durham Ferry resulted in only two fish recovered at Antioch and three fish at Chipps Island; releases of 73,709 tagged salmon at Mossdale resulted in only one fish recovered at Antioch and three fish at Chipps Island (Table 1). Despite five years of studies, the reasons for the low recoveries and low estimated survival remain unknown, although some possible contributing causes have been suggested (e.g., HORB culvert operations, fish diseases, flow and exports, water temperatures).

Table 1. Recovery information for coded-wire tagged Chinook salmon released during the 2004 VAMP study (SJRGA 2005).

Release Site in the San Joaquin River	Number of Tagged Salmon Released	Number of Tagged Salmon Recovered at Antioch	Number of Tagged Salmon Recovered at Chipps Island
Durham Ferry	23,440	1	0
Durham Ferry	21,714	1	1
Durham Ferry	23,327	0	1
Durham Ferry	23,783	0	1
Mossdale	25,320	1	0
Mossdale	23,586	0	1
Mossdale	24,803	0	2

Additionally, and importantly, when apparent survival differences between groups of salmon released at different times during the VAMP experiments have occurred, causal factors for those differences have not yet been determined. For example, during the 2001 VAMP studies, groups of salmon released just a week apart showed apparent differences in survival, but SJRGA (2002) stated:

> "*Why survival was so much lower for the second group (releases at Durham Ferry, Mossdale, and Jersey Point), relative to the first group is unknown. Flow and export conditions were similar for both groups*."

This paper provides some additional ideas that may partially explain juvenile salmon mortality in the Delta and recommendations to provide more focus on site-specific hydrodynamic conditions in the Delta to better understand causal mechanisms affecting salmon survival. This information has relevance to both the 30-day VAMP period (April 15 – May 15), and pre- and post-VAMP periods because of potential opportunities to improve conditions for wild fish migrations.

The Magnitude of Tidal Effects

It is suggested here that the overwhelming effects of tidal flows and site-specific conditions at critical channel junctions in the central Delta are likely masking any relationships with San Joaquin salmon survival based solely on Vernalis flow or exports levels. The magnitude of the twice daily ebb and flood tides in the mainstem San Joaquin River are enormous compared to Vernalis flows. For example, it has been estimated that, in theory, a slightly buoyant object (e.g., an orange) placed in the San Joaquin at Jersey Point under conditions of a ***net*** flow of 3,000 cfs would move back and forth (seiche) many miles in a downstream and upstream direction with the respective twice daily ebb and flood tides, but would have only moved less than ½ of a mile downstream by the end of the complete tide cycle (approximately 25 hours) (personal communication, Rick Oltman, USGS, September 14, 2000). An example of the difference in the magnitude of tidal flows compared to net flow is illustrated in Figure 2.

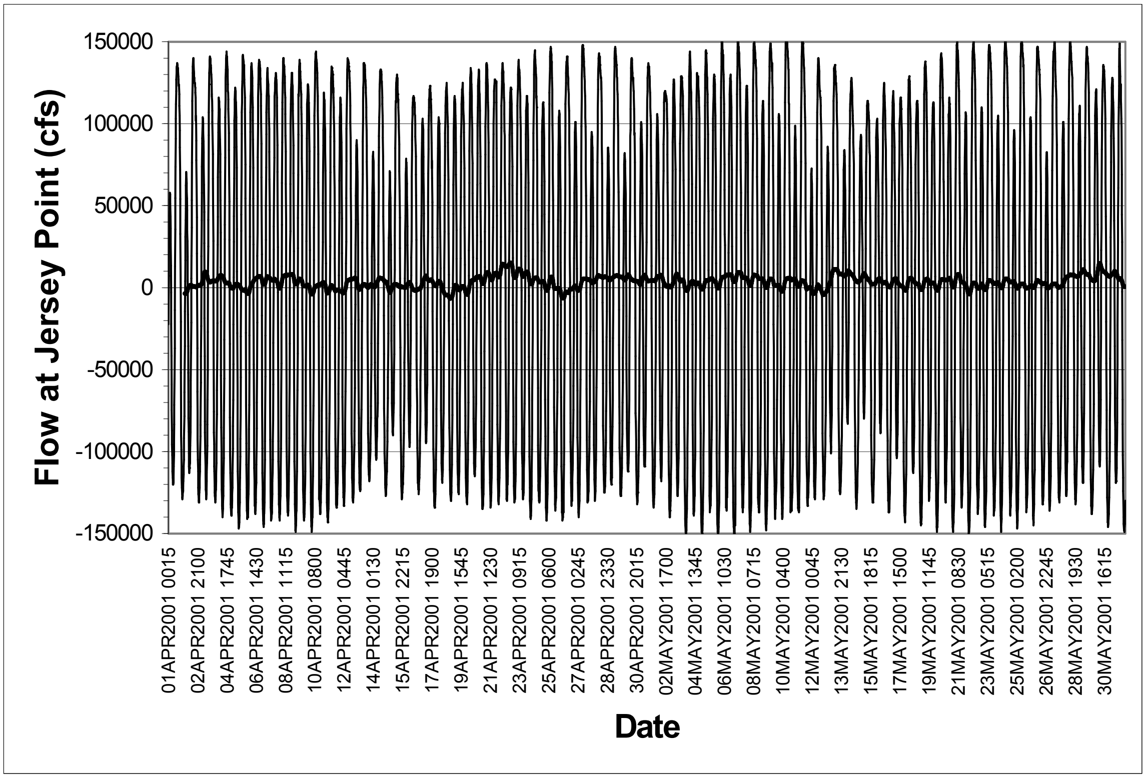

Figure 2. Comparisons of the magnitude of tidal and net flows (dark line) in the San Joaquin River at Jersey Point. Net flows are estimated by computing the approximate 25-hour tide cycle running mean.

In the example time period of April - May 2001, the magnitude of the ebb and flood tide was in the range of about 140,000 cfs to – (minus)140,000 cfs, respectively. However, the approximated net flow was in the range of considerably less than 10,000 cfs. As discussed later in this paper, these enormous tidal flows have a profound effect on salmon movements in the Delta.

Radio-Telemetry Studies of Juvenile Salmon Migration in the Delta

Recent research has provided insights into migratory behavior and migration pathways used by young Chinook salmon in the Delta. The study findings are relevant to understanding how hydrodynamic conditions in the Delta may affect San Joaquin salmon and in interpreting the VAMP study results to date. Some of the telemetry results are summarized as follows:

"From 1996 to 2004, 10 separate studies were conducted by Natural Resource Scientists, Inc. in the Sacramento – San Joaquin Delta on behalf of the U.S. Fish and Wildlife Service, CALFED, and a municipality to monitor the movements of Chinook salmon (Oncorhynchus tshawytscha) smolts using telemetry methods. The monitoring projects were performed in the northern, eastern, central, and southern Delta to better understand the specific mechanisms affecting salmon smolt migration through the region and evaluate the potential effects of water operations on salmon. Smolts fitted with miniature radio transmitters were released and monitored in each of these regions to determine fish movements under a variety of hydrodynamic conditions. Over 800 radio-tagged fish were tracked throughout hundreds of miles of Delta channels using mobile telemetry receivers. I employed a recently-developed U.S. Geological Survey (USGS) time-series, vector- and particle-path animation model to integrate extensive Delta hydrodynamic data for interpreting fish migration behavior. Those data included USGS empirical tidal flow data and estimated channel velocities obtained from the California Department of Water Resources DSM2 model. Telemetered fish movements corresponded well with the magnitude, direction, and duration of water velocity vectors in Delta channels. Based on these results, specific behavior patterns emerged suggesting the primary mechanisms influencing salmon smolt movements on a macro- and micro-scale through the Delta: 1) Telemetered smolts moved large distances (e.g., miles) back and forth with ebb and flood tides; 2) fish behavior and migration pathways were greatly affected by site-specific tidal prism effects in different regions of the Delta; 3) fish position in the channel and localized flow conditions at channel flow splits were primary factors affecting fish migration routes; 4) specific habitats of the Delta where predation appeared higher than other habitats were evident; and 5) numerous other ancillary findings. Field techniques developed as a result of these studies and advances in telemetry equipment will enhance future monitoring of salmon smolt migration through the Delta." (Vogel 2004)

Central Delta Telemetry Studies

In the spring of 2002 and 2003, experiments (funded by CALFED) were conducted by releasing radio-tagged juvenile salmon in the lower San Joaquin River and monitoring their migratory behavior and migration pathways in the central Delta (Vogel 2004). In each of those years, small groups of salmon with miniature (1-gram), individually identifiable radio transmitters of different frequencies were released in the San Joaquin River near Fourteen-Mile Slough and monitored for approximately three to four days after release. The experiments were conducted just prior to VAMP and during VAMP study periods. Figure 3 shows the telemetered locations for fish detections in a portion of the Delta during both years.

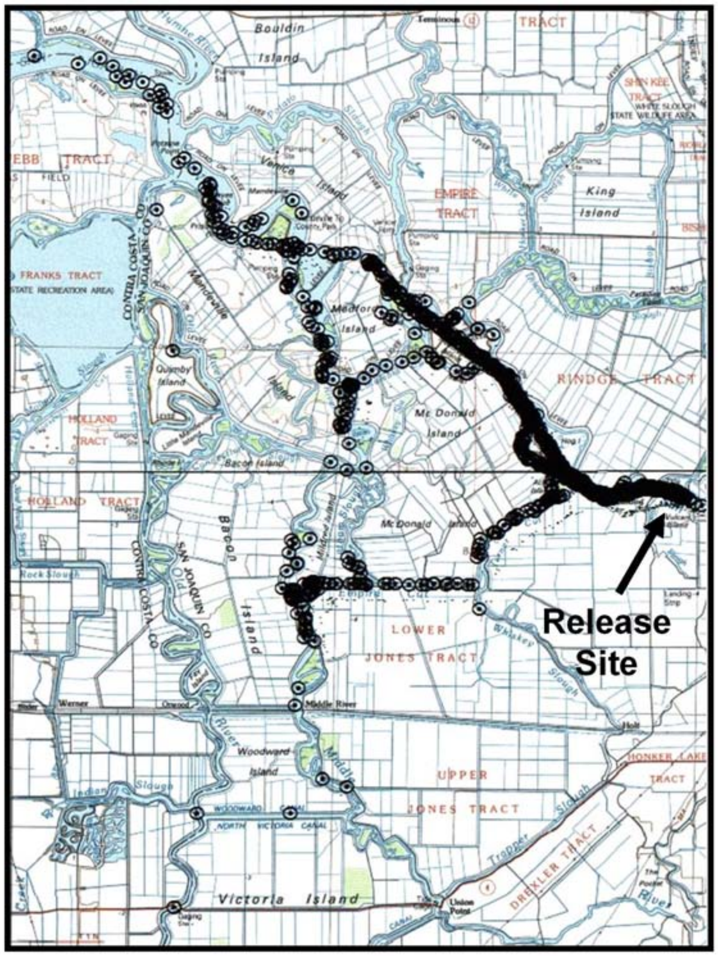

Figure 3. Telemetered locations of radio-tagged juvenile salmon in a portion of the Delta during studies conducted in the spring of 2002 and 2003 (Adapted from Vogel 2004). Additional fish locations outside the map perimeter of Figure 3 (west) are not shown.

Although the studies were more qualitative than quantitative in design[1], a particularly interesting result was the high proportion of radio-tagged fish that moved off the San Joaquin River into south-Delta channels. In particular, Turner Cut appeared to serve as a principal route into the south Delta. Prior to the study, it was assumed that very few fish would enter Turner Cut because only a small portion of the flow enters that channel as compared to the flow in the mainstem (Figure 4). Similar to smolt telemetry studies conducted in the north Delta at the Georgiana Slough bifurcation with the Sacramento River (D. Vogel, unpublished data), a higher proportion of fish moved into the Turner Cut channel than could be explained by flow volume alone (i.e., the proportion of fish diverted was higher than the proportion of flow diverted). For example, in four of the eight separate releases of radio-tagged salmon just downstream of Stockton, half or more of the fish were last detected in channels south of the mainstem San Joaquin River. Fish movements into Turner Cut appeared to be a principal route for fish entry into areas south of the San Joaquin River and to a lesser extent, Columbia Cut or Middle River (Vogel

[1] Study caveats are described in Vogel (2004).

2004). Apparently, there are not-yet-understood site-specific conditions that cause this phenomenon but appear to be a combination of tidal effects, spring versus neap tides[2], local channel velocities[3], channel geometry, flows, and fish behavior (among other variables).

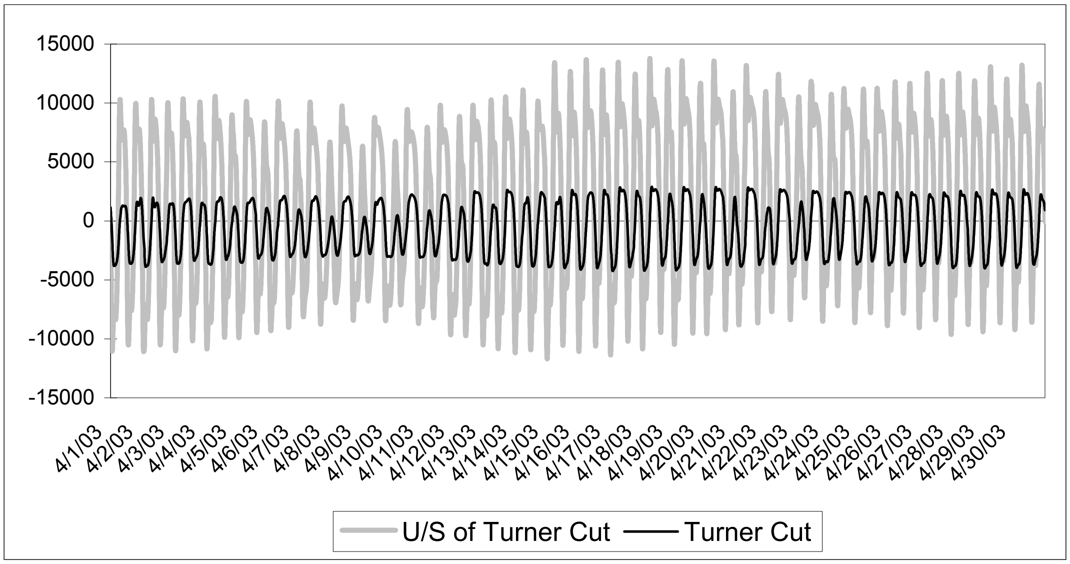

Figure 4. Flows (cfs) at Turner Cut and the mainstem San Joaquin River just upstream of Turner Cut, April 2003. Fifteen-minute flow increments were estimated from DSMII model outputs.

The second interesting finding from these studies was the fact that most fish, once they left the San Joaquin River, did not get back to the mainstem. This finding was unexpected at the time because it was assumed that fish moving into the south Delta channels for reasons solely attributable to the tidal effects (e.g., during a flood tide) would move back out into the San Joaquin River during the change in tidal phase (e.g., an ebb tide). Empirical data were collected that demonstrated some of those fish kept moving in a southerly direction toward the export facilities. Some of the fish entering channels south of the San Joaquin River were tracked several miles into those channels. It was particularly evident that net southerly movement was rapid. Within a period of just several days, some fish were located far south in Middle River and Old River (Vogel 2004). For example, about 20 percent of the fish were documented to have moved from the San Joaquin River into Turner Cut, migrated westerly in Empire Cut past the southern part of flooded Mildred Island, and into Middle River (Figure 3). The total numbers were estimated to be much higher but were not directly observed.[4] One radio-tagged smolt last detected on the mainstem San Joaquin River near Columbia Cut on April 11, 2003 was

[2] "When the principal semidiurnal and diurnal tides are in phase, the partial tides reinforce each other and the tidal ranges are at their maximum. The tides in this period are known as the spring tides. Similarly, when the partial tides are out of phase, their effects tend to cancel each other and the tidal ranges become relatively small. Tides in this period are known as neap tides. The beating frequency of the principal semidiurnal and diurnal partial tides gives rise to the spring-neap tidal cycle variations in a fortnightly period." (Cheng and Gartner 1984).

[3] Complex water currents in a 3-dimensional perspective.

[4] Telemetry reconnaissance did not occur during nighttime hours and many fish likely moved into channels south of the mainstem beyond mobile scanning range.

caught 7 days later at the CVP Tracy fish salvage facilities (a distance of over 20 miles).[5] Although these studies were not designed to track fish all the way to the south Delta, it was evident that many of the fish "disappeared" from the San Joaquin River based on extensive telemetry coverage of the mainstem.

During the studies, strong ebb and flood tidal flows were evident in Turner Cut (Figures 5 and 6). However, estimated net flows were negative, or reverse, which probably explains why many of the fish, once entering Turner Cut, did not return to the mainstem San Joaquin River. It was also evident that the lowest "entrainment" of fish off the mainstem occurred when the net reverse flows and SWP and CVP exports were lowest (Figures 5 and 6).

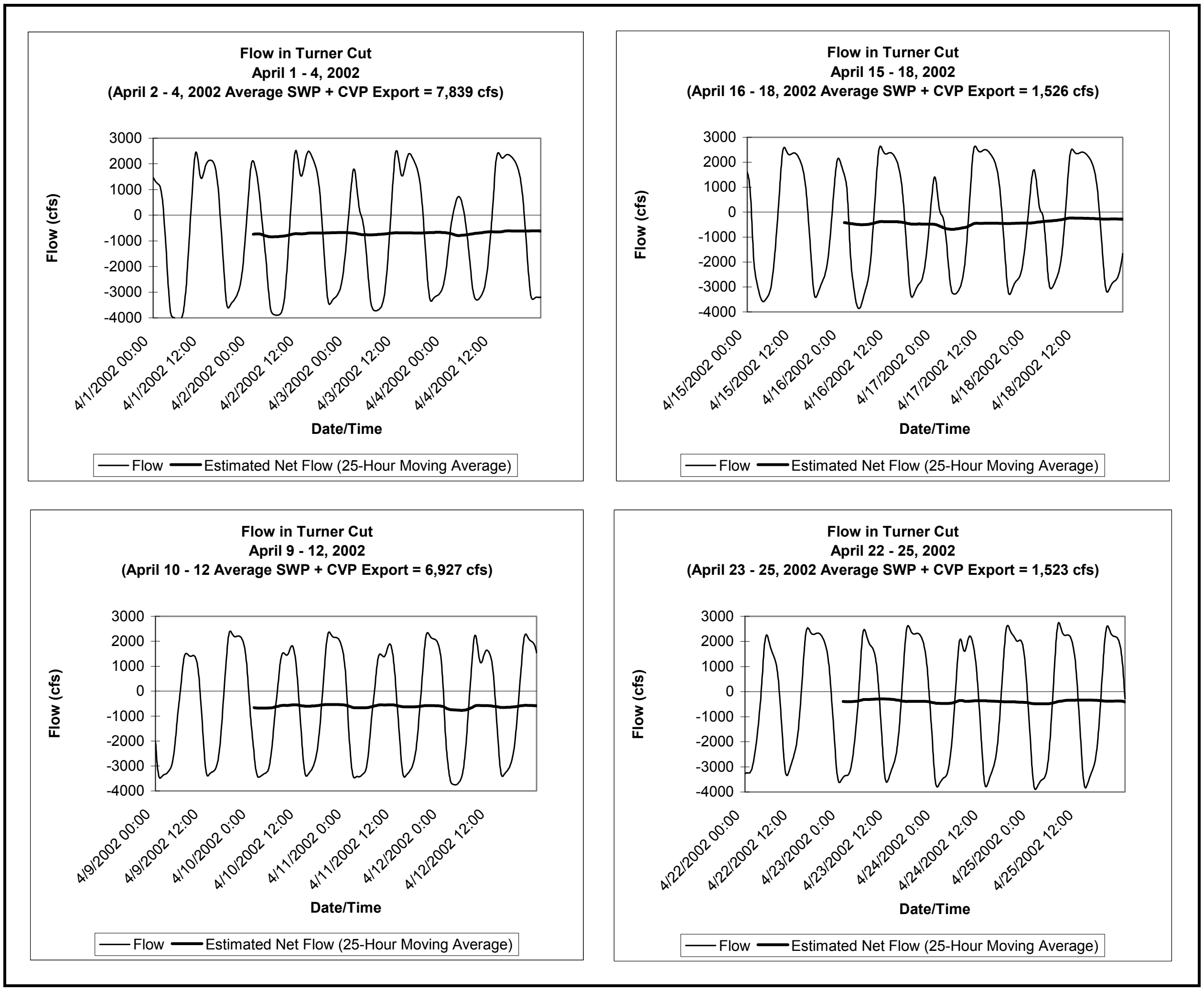

Figure 5. Flow in Turner Cut during the juvenile salmon radio-tag telemetry studies in April 2002.

[5] After capture at the Tracy facilities, the radio-tagged salmon was subsequently kept alive for a week in an aquarium. The incision on the fish resulting from the surgical implant of the miniature radio transmitter was completely healed with no evident fungus or disease (Lloyd Hess, USBR, personal communication).

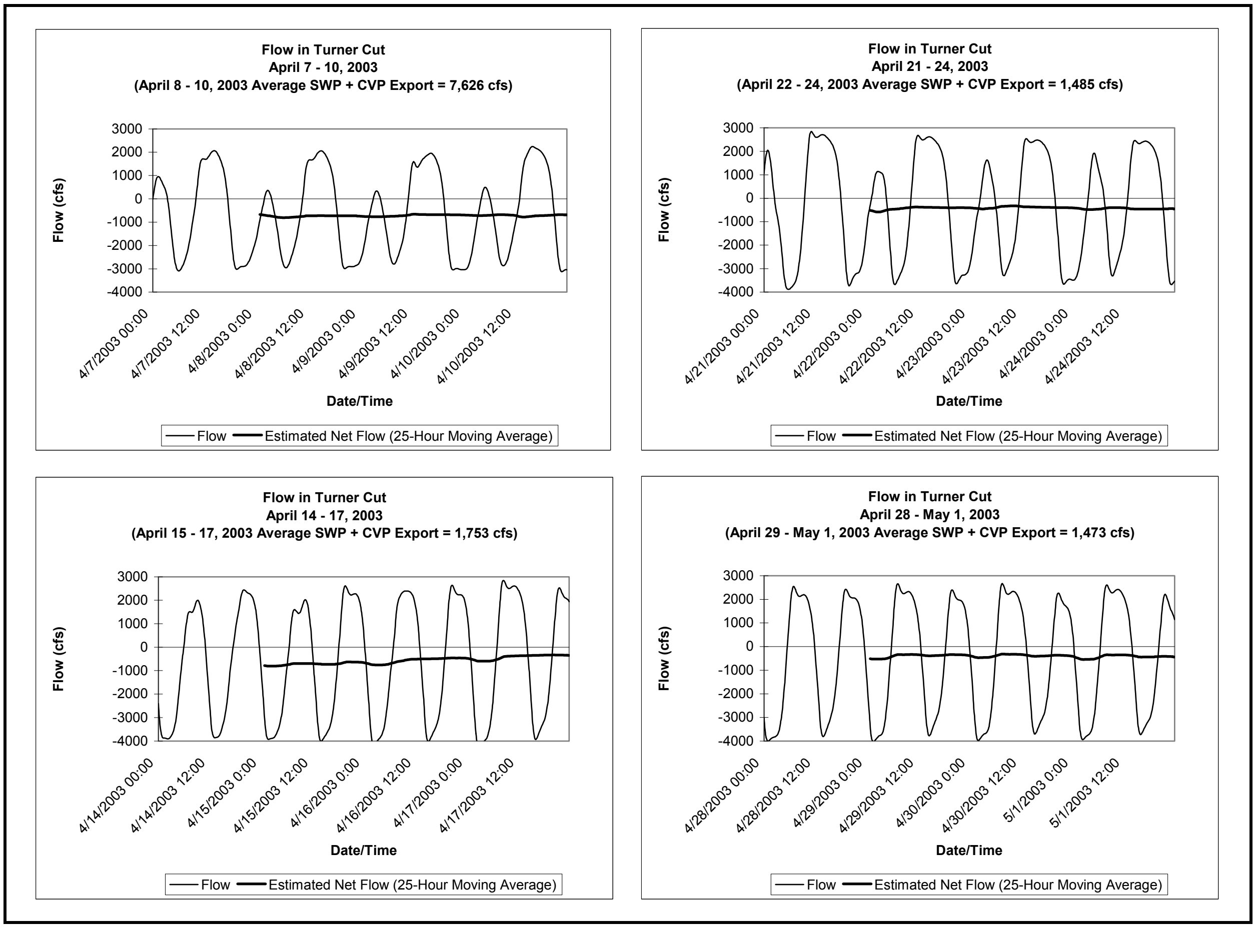

Figure 6. Flow in Turner Cut during the juvenile salmon radio-tag telemetry studies in April - May 2003.

South Delta Telemetry Study

Additional insights into potential causal mechanisms affecting juvenile salmon migration and survival in the Delta may be derived from a radio-telemetry study of juvenile salmon migration in the south Delta within closer proximity to the export facilities. This study, funded by the U.S. Fish and Wildlife Service, examined the migration behavior and pathways of salmon smolts released in Old River nine miles north of the Delta export facilities during the winter of 2000. This study focused on salmon smolt movements in Old River during relatively low and medium south Delta export conditions[6].

When radio-tagged smolts were released in Old River nine miles north of Clifton Court (CC) during combined exports in the range of 8,000 – 11,000 cfs, it was estimated that about two-thirds of the fish were entrained into the export facilities during the study period. Generally, the fish exhibited a rapid, southerly migration pattern in concert with the high southerly flow direction caused by medium export levels damping out or eliminating northerly or downstream flows in Old River (Vogel 2002). In contrast, during combined exports of about 2,000 – 3,000 cfs, telemetered fish movements showed

[6] "Low" was approximately 2,000 – 3,000 cfs combined exports; "medium" was approximately 8,000 – 11,000 cfs combined exports (Vogel 2002).

strong north and south movements in response to the ebb and flood tides and remained in Old River longer than fish during medium exports; less than one-third of the fish were estimated to have been entrained into the export facilities during the study. Figures 7 and 8 show comparisons of how the combined effects of CC gate operations and CVP pumping affect flows in Old River at the USGS flow monitoring site.

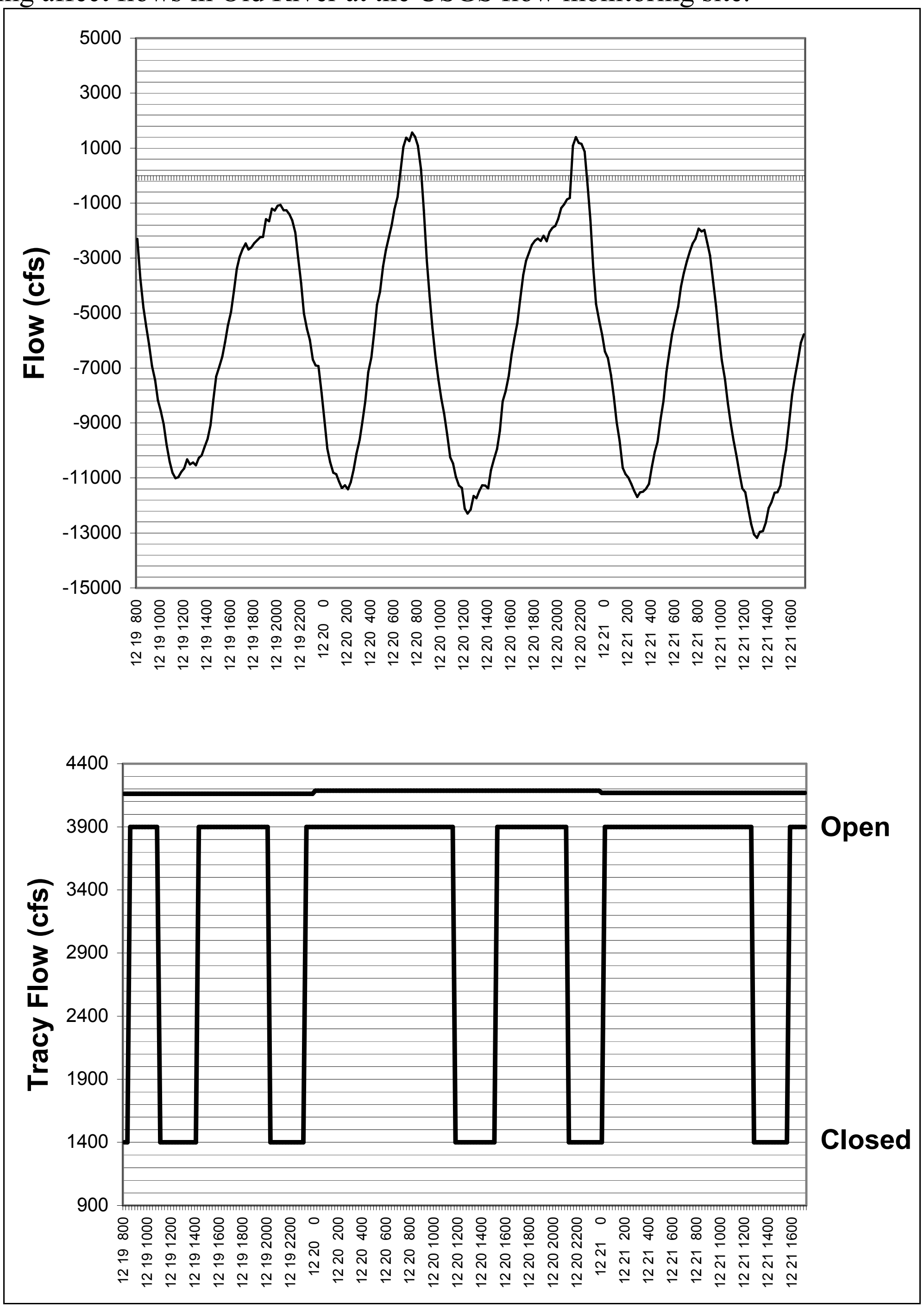

Figure 7. Old River flow (cfs) (top graph) measured at Highway 4 bridge and CVP pump flow (cfs) at Tracy and Clifton Court gate operations (bottom graph) (from Vogel 2002).

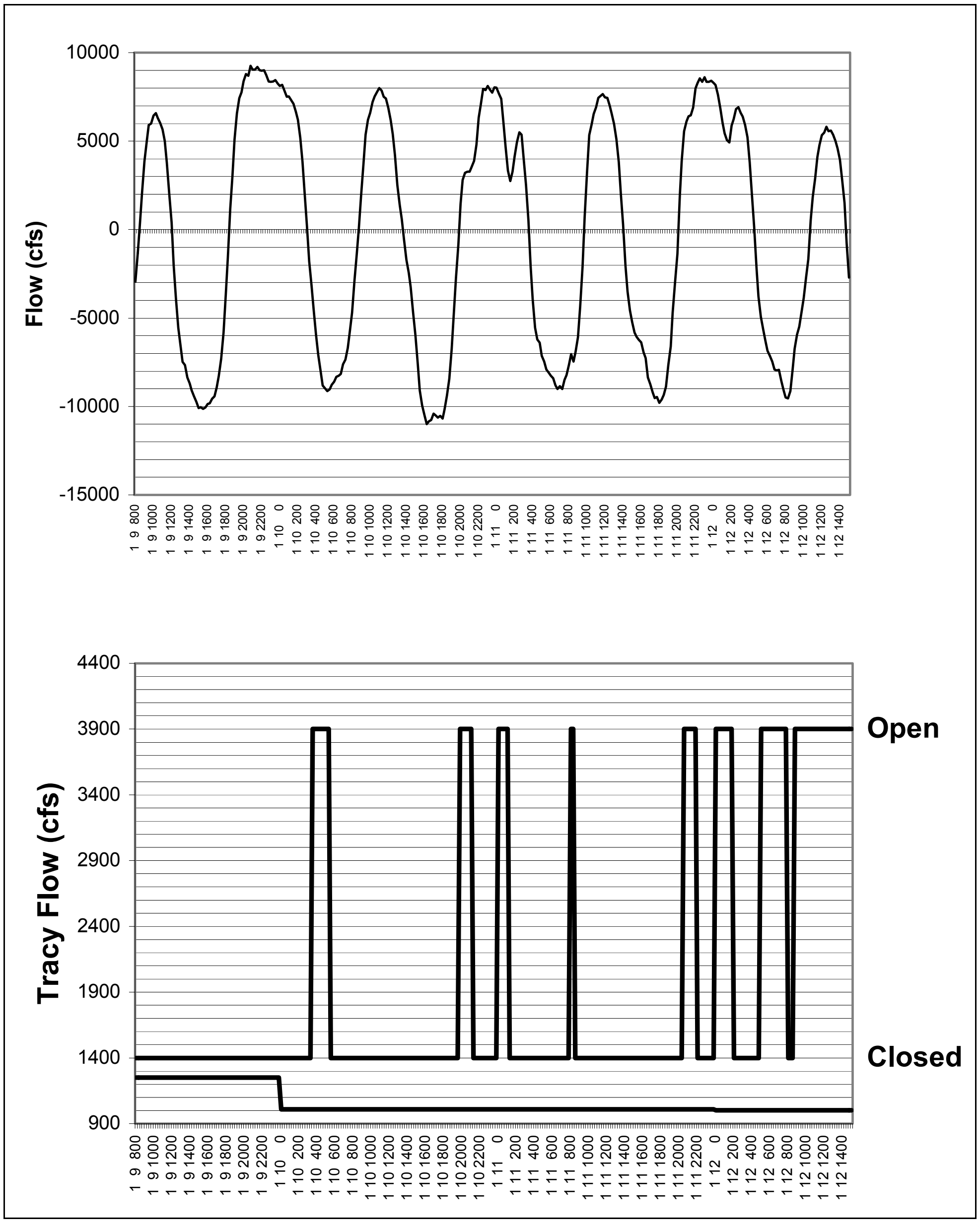

Figure 8. Old River flow (cfs) (top graph) measured at Highway 4 bridge and CVP pump flow (cfs) at Tracy and Clifton Court gate operations (bottom graph) (from Vogel 2002).

As can be seen from empirical data obtained from the USGS flow station at Old River, the combined operation of the CC forebay gates and CVP pumping, under certain conditions, can reverse the direction of an ebb tide in Old River. Under some conditions, opening the gates and CVP pumping can cause an otherwise northerly ebb flow in Old River to change to a southerly flow direction. Figure 7 shows that the combined effect of the two facilities can result in nearly continuous negative (southerly) flow in Old River even during periods of relatively low south Delta exports. The specific operation of the CC gates is probably a more relevant variable affecting salmon smolts than SWP pumping levels because of the lag time between gate operation and pumping (Vogel

2002). For example, the estimated maximum flow through the CC gates is 12,000 cfs[7] which likely has a significant effect on smolt movements within the narrow, south Delta channels and the tidal prism in that region is less as compared to the mainstem San Joaquin in the central Delta. Even with low export levels, net reverse flow of lesser magnitude than medium export levels was still evident which explains why some of the fish were still entrained during periods of low export (Figure 9) (Vogel 2002).

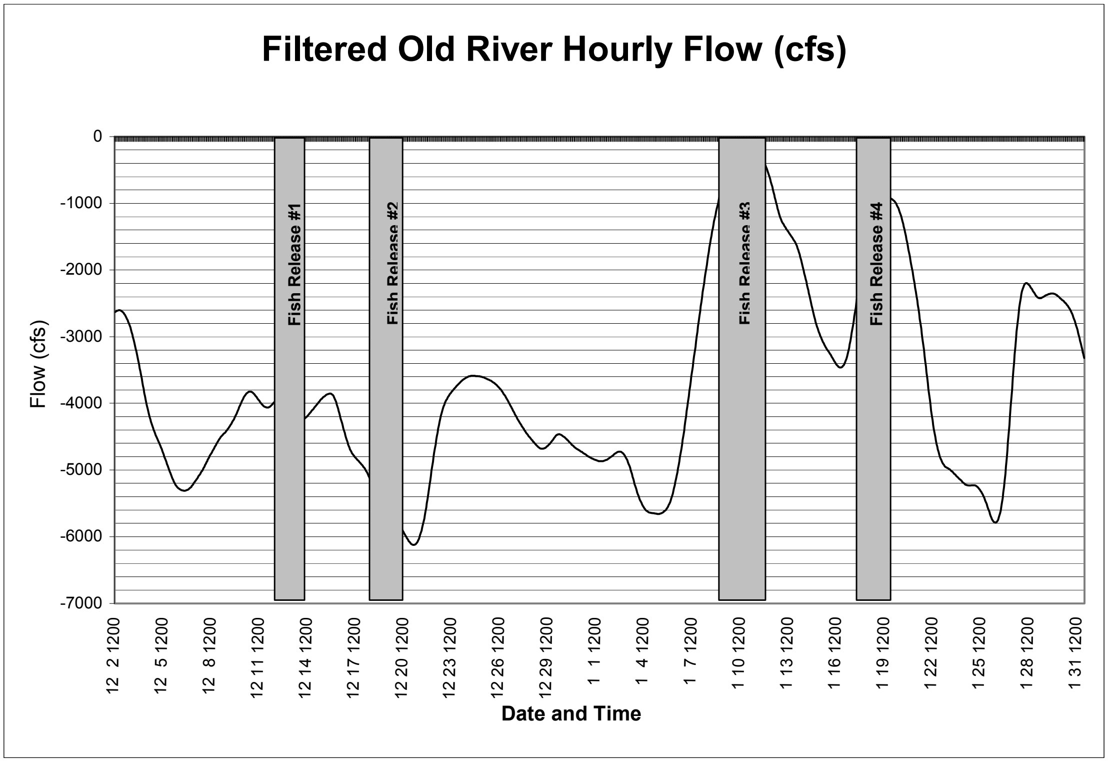

Figure 9. Magnitude and direction of net flow direction in Old River measured at the Highway 4 bridge, December 2000 – January 2001 (from Vogel 2002).

The "zone of influence" delineating exactly where in the central or south Delta that exports have an overriding influence on salmon "entrainment" into the south Delta is presently unknown and would vary depending on export levels. The smolt telemetry study conducted in December 2000 – January 2001 provided empirical evidence that the zone of influence extends at least as far north as the northwestern tip of Woodward Island, a distance of approximately nine river miles north from the CC gates. The two smolt telemetry studies conducted in the mainstem San Joaquin River suggest that the zone of influence is probably much further north (e.g., Turner Cut and Columbia Cut) but the unknown specific regions would depend on many complex and interrelated hydrodynamic variables (e.g., exports, river flow, tides, tidal prisms, localized channel velocities, channel geometry, etc.) combined with fish behavior. The existing VAMP studies presently do not have any elements to identify that important zone of influence on salmon.

[7] Joint Operations Center, California Department of Water Resources

Results of the VAMP Fish Survival Experiments

In evaluating potential effects of Delta hydrodynamic conditions on salmon, it is important to recognize the fact that juvenile salmon dispersal from upstream areas attenuates in a downstream (seaward) direction. Juvenile salmon do not readily school together during outmigration. Additionally, the previously-described enormous effect of ebb and flood tides and widely varying, site-specific conditions in the interior Delta greatly redistributes the fish over a wide geographic area. This phenomenon is evidenced by results of the telemetry studies and the protracted recaptures of tagged fish at Chipps Island during the VAMP studies.

I examined data collected during the first two years of the VAMP experiments (i.e., 2000 and 2001) because they provided the most robust database for fish recaptures at Chipps Island and the ocean fisheries, and because of apparent differences in survival rates between release groups. Results for the 2002, 2003, and 2004 VAMP experiments resulted in very low fish recaptures at Chipps Island, and ocean fisheries data are not yet available. Table 2 and Figures 10 and 11 provide a summary of the 2000 and 2001 VAMP fish survival experiments.

Table 2. Summary of 2000 and 2001 VAMP fish survival experiments.

Release Location	Release Date	Number of Days to Median Recapture	Average Vernalis Flow (cfs) during the Days to Median Recapture	Average SWP + CVP Exports during the Days to Median Recapture	Estimated Survival Based on Chipps Island Trawl	Estimated Survival Based on Ocean Catch
2000 VAMP Study						
Durham Ferry	April 17, 2000	10	6,180	2,345	0.31	**0.36**
Mossdale	April 18, 2000	7	6,256	2,367	0.31	**0.31**
Durham Ferry	April 28, 2000	9	5,693	2,108	0.19	**0.18**
2001 VAMP Study						
Durham Ferry	April 30, 2001	8	4,423	1,480	0.34	**0.25**
Mossdale	May 1, 2001	8	4,432	1,499	0.31	**0.27**
Durham Ferry	May 7, 2001	6	4,334	1,520	0.13	**0.11**
Mossdale	May 8, 2001	6	4,322	1,525	0.19	**0.10**

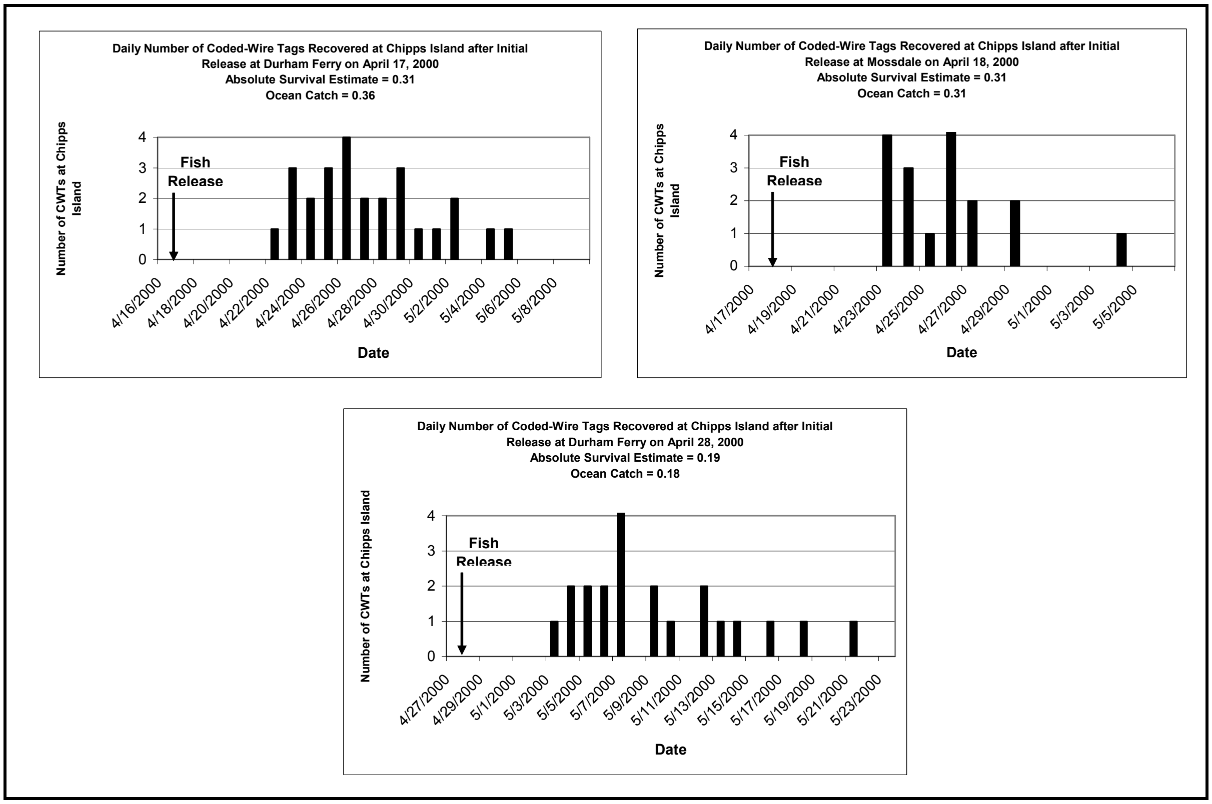

Figure 10. Recaptures of coded-wire tagged salmon at Chipps Island during the 2000 VAMP study.

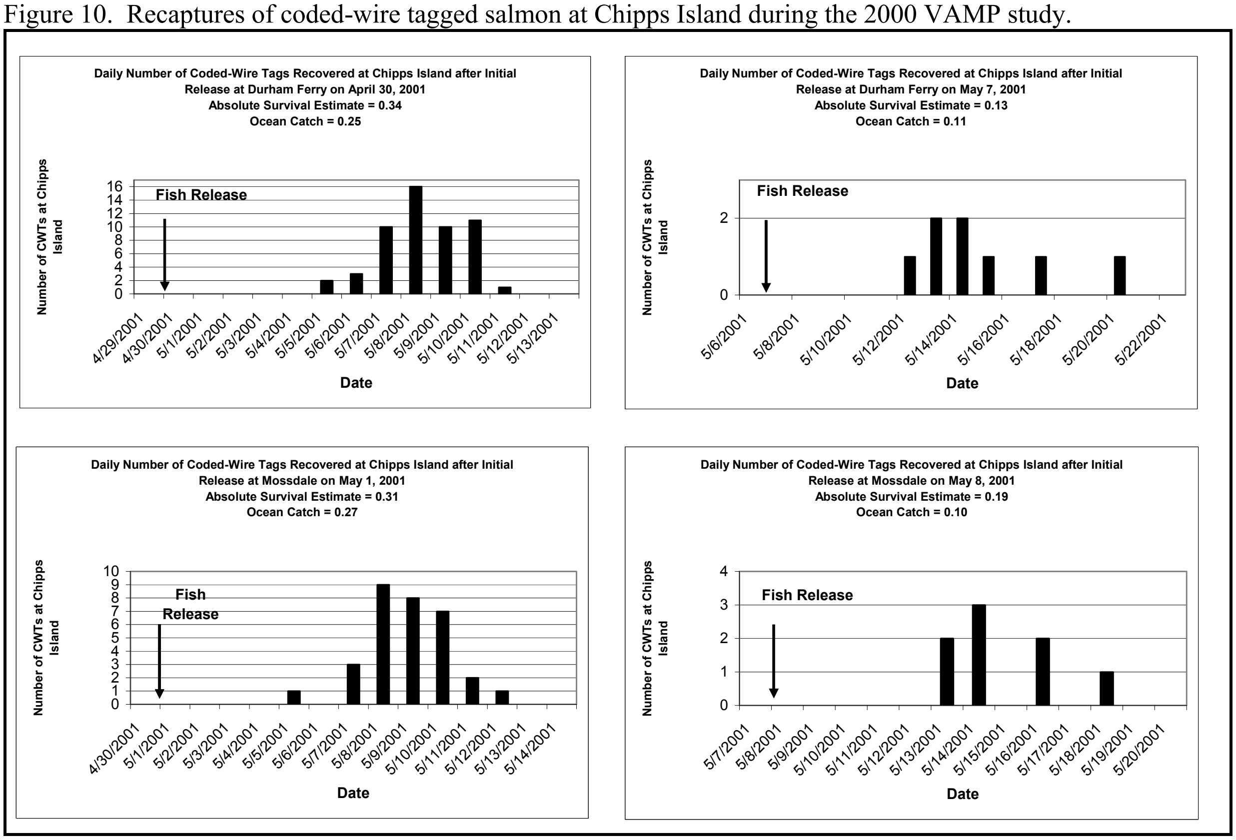

Figure 11. Recaptures of coded-wire tagged salmon at Chipps Island during the 2001 VAMP study.

There was an apparent difference in fish survival between the early and later fish releases during both years, even though Vernalis flows and export levels did not change appreciably within those years. Different groups of fish released only 7-10 days apart during similar conditions of Vernalis flows and export levels showed about a two-fold difference in survival as measured by both Chipps Island recoveries and ocean catch recoveries (Table 2). If these survival differences are real[8], the reasons for the apparent variability are unknown but emphasize the importance of further investigations into potential causative factors.

In a riverine environment, it is generally expected that higher flows will result in faster downstream movement of juvenile salmon. However, in the Delta where tidal flows are dominant and fish migration pathways are complex, the effects of Delta inflows on fish movements are largely unknown. In examining potential relationships, I used the time period between fish release date and date of median recapture of all tagged fish at Chipps Island as an indicator to compare fish migration rates during the 2000 and 2001 VAMP experiments (Table 2). There was a general trend suggesting that higher Vernalis flows resulted in slower migration rates which is counter-intuitive to that expected. However, there was also a trend suggesting that higher export levels also resulted in slower migration rates (Table 2). If such relationships reflect reality, export levels may have a confounding influence on fish migration rates through the Delta (e.g., by causing net reverse flows in specific channels resulting in more complicated fish migration routes). However, the timing of neap and spring tides could also have a significant affect on migration rates and should be evaluated. It's apparent that more information will be needed prior to deriving conclusions on the VAMP experiments, but the data collected to date indicate that factors affecting San Joaquin salmon movements through the Delta are considerably more complex than just Vernalis flows and export levels.

Each of the channel junctions in the Delta has unique site-specific conditions that can affect the resulting migration pathways used by salmon. The relevance of this is that each of the fish during the VAMP experiments encounters different conditions at each of the channel junctions. This occurs because the arrival times are different, and therefore tides and hydrodynamic conditions are different. For example, one fish reaching a particular channel junction may encounter strong downstream flow that would keep the fish in the mainstem San Joaquin River whereas, another fish reaching that junction six hours later may encounter strong reverse flow into the diverging channel and behaviorally move in a direction that would take it off the mainstem and make it more prone to entrainment. Therefore, when examining fish survival data for the VAMP experiments, it is important to recognize the Delta's constantly changing dynamic environment that may be a greater determinate of survival for any fish release group than just Vernalis flows.

For instance, assuming the VAMP fish migrate downstream at approximately one-half miles/hour, the majority of fish would reach the San Joaquin Deep Water Channel one day after release. I assumed that the fish migrate unidirectionally (downstream) between

[8] Because of low recapture rates, some, or all, of the VAMP experiments may not demonstrate statistical significance.

the release sites at Mossdale and Durham Ferry until reaching the Deep Water Channel near Stockton. Hydrodynamic conditions change dramatically where the San Joaquin River enters the dredged shipping channel. Although it is not possible to know the exact hydrodynamic conditions encountered by each of the test fish when reaching Turner or Columbia Cuts, it can be assumed that the majority of the fish reached this Delta region a day after release. When fish encounter the region near Turner Cut and Columbia Cut, the majority of the fish would be expected to seiche back and forth, perhaps several times, past these channel junctions because the environment is greatly dominated by tides, not stream flow. Based on results of the juvenile salmon telemetry studies and VAMP studies to date, it is suggested in this paper that the most prominent factors affecting juvenile salmon migration and survival come into play in this region of the Delta. Because the natural emigration of salmon through the Delta cannot be controlled like the release timing for the VAMP marked hatchery fish, it is important to acquire a better understanding of how site-specific conditions at key channel junctions such as Turner Cut and Columbia Cut affect salmon.

Recommendations

Although the general mortality factors affecting salmon in the Delta are known (e.g., predation, unscreened diversions), many site-specific causal mechanisms are not clearly understood. This circumstance is largely attributable to unknown migration behavior and routes utilized as the juvenile salmonids negotiate numerous Delta channels in a hydraulically complex, tidal environment (Vogel 2004). A popular hypothesis is that a portion of the fish mortality is caused by the net reverse flow in some locations within the Delta channels caused by export operations. Longer and more complicated fish migration routes and navigation problems caused by the hydrological effects of export pumping are believed to be among factors affecting juvenile Chinook salmon (Vogel 2004). Although the VAMP studies are designed to determine the extent of mortality between “points A and B” (Mossdale/Durham Ferry and Jersey Point, respectively), they do not identify where and how that mortality occurs between those points. Additional studies are necessary to answer those questions.

It is suggested here that a significant percentage of San Joaquin salmon mortality occurs because fish are diverted off the mainstem San Joaquin River in high proportions, primarily at Turner Cut and Columbia Cut. Based on recent research monitoring the movements of radio-tagged salmon in the central and south Delta, the probable primary migration pathways that lead juvenile salmon into the interior and south Delta are depicted in Figure 12. The mechanisms explaining how and why salmon smolts can be diverted off the mainstem San Joaquin River into channels south of the Delta remain unknown. Also, it appears that some smolts, once they move into those south channels, do not re-emerge back into the San Joaquin to continue normal migration toward salt water. This latter phenomenon is also not understood. Because of net reverse flows that fish encounter in specific channels south of the San Joaquin River, outmigrating salmon apparently have difficulty re-emerging back into the mainstem. The magnitude of the net reverse flows increases with closer proximity to the south Delta export facilities. Once salmon enter this region of the Delta, the fish likely experience high mortality rates caused by predation and entrainment into unscreened diversions and the export facilities. Some fish are known to survive the migration all the way to the export facilities, are salvaged, and transported out to the western Delta or San Francisco Bay. However, the proportion of total numbers of salmon unsuccessfully navigating these interior Delta channels is unknown.

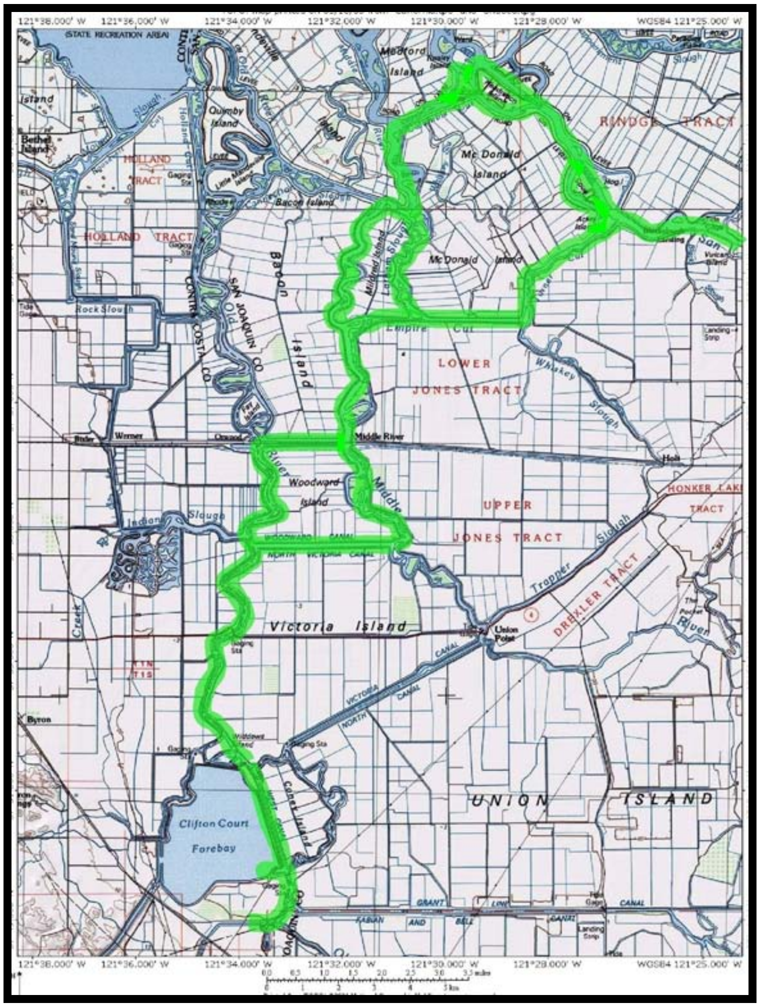

Figure 12. Probable primary migration pathways for juvenile salmon between Turner and Columbia Cuts and the south Delta export facilities.

For the foregoing reasons, it is recommended that more intensive investigations be focused on site-specific conditions San Joaquin River salmon encounter during their outmigration and evaluating distinct migration pathways used by the salmon. One analytical tool for accomplishing these objectives was developed for Columbia River salmon studies and may be applied in the Delta. The technique is to tag juvenile salmon with miniature sonic (acoustic) transmitters and detect their migration throughout the Delta using strategically-placed fixed-station data loggers (Figure 13). The individually-identifiable tags are sufficiently small (0.75 grams) so that the transmitters can be successfully implanted in fish smaller than 100 mm in fork length. The data loggers create a time stamp of when each fish passes the fixed-station sites. Then, using hydrodynamic model outputs (or flow monitoring stations), the flows and velocities at those sites could be estimated to correlate conditions fish experienced which would provide relevant information to understand why certain migration pathways are "chosen". Also, a network of these acoustic stations could help develop reach-specific mortality rates. Data derived from these studies, when used in conjunction with hydrodynamic models of the Delta, would provide valuable information to potentially improve water project operations and fish survival. For example, experiments could be conducted to determine the particular conditions needed to reduce entrainment of salmon off the mainstem San Joaquin River (e.g., potential changes in the timing and magnitude of export operations associated with tidal phase and physical alterations at Turner and Columbia Cuts).

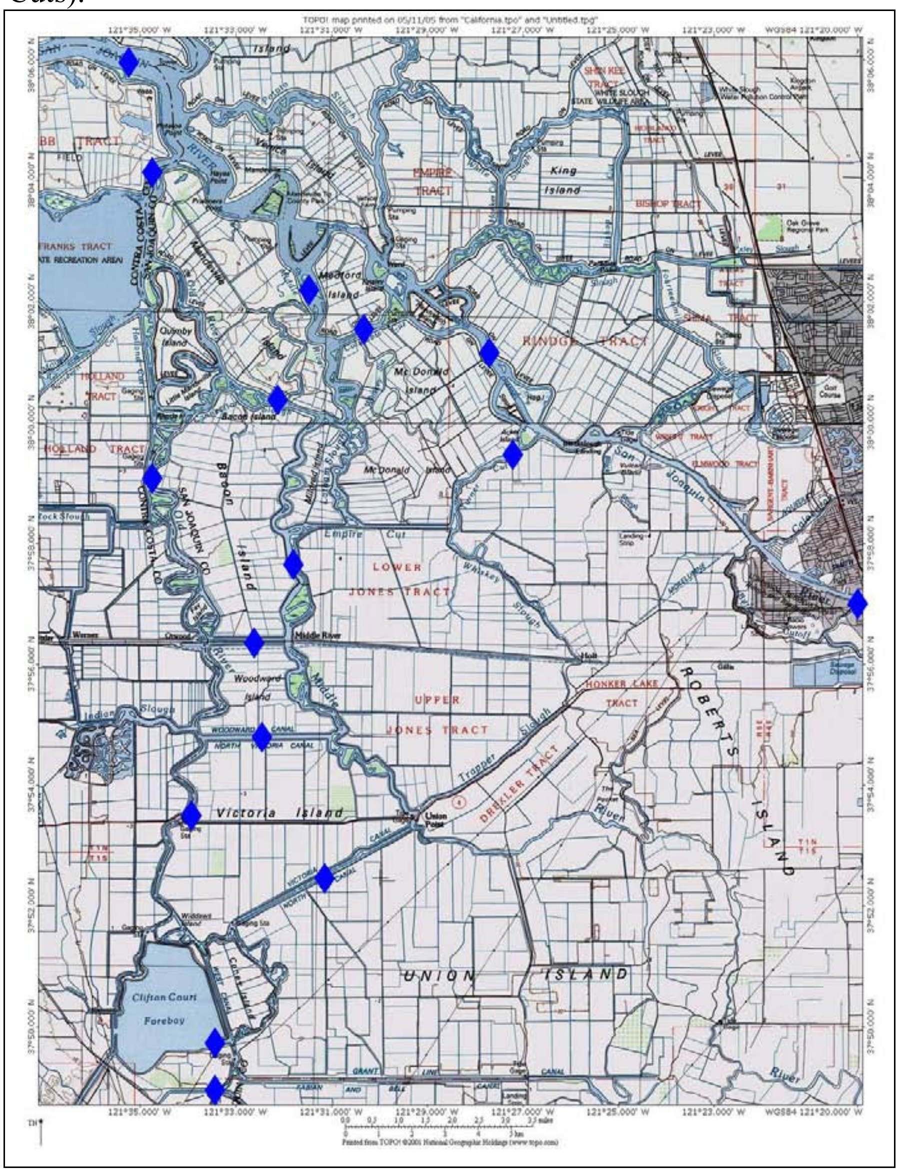

Figure 13. Recommended locations for placement of sonic receivers to detect the presence of acoustic-tagged juvenile salmon released in the San Joaquin River.

References

Cheng, R.T. and J.W. Gartner. 1984. Tides, tidal and residual currents in San Francisco Bay, California – Results of measurements, 1979-1980. U.S. Geological Survey. Water Resources Investigations Report 84-4339. February 1984.

SJRGA. 2005. 2004 Annual Technical Report on Implementation and Monitoring of the San Joaquin River Agreement and the Vernalis Adaptive Management Plan. Prepared for the California Water Resource Control Board in compliance with D-1641. January 2005. 131 p.

Vogel, D. 2005. Monitoring Chinook salmon smolt migration in the Sacramento – San Joaquin Delta using telemetry, 1996 – 2004. Abstract of presentation provided at the California-Nevada American Fisheries Society Conference in Sacramento. March 19, 2005.

Vogel, D.A. 2004. Juvenile Chinook salmon radio-telemetry studies in the northern and central Sacramento-San Joaquin Delta, 2002 – 2003, Final Report. Contract report for CALFED, administered by the National Fish and Wildlife Foundation. Natural Resource Scientists, Inc. January 2004. 188 p.

Vogel, D.A. 2002. Juvenile Chinook salmon radio-telemetry study in the southern Sacramento-San Joaquin Delta, December 2000 – January 2001. Contract report for the U.S. Fish and Wildlife Service. Natural Resource Scientists, Inc. June 2002. 27 p. plus figures and appendices.

Vogel, D.A. 2001. Juvenile Chinook salmon radio-telemetry study in the northern Sacramento-San Joaquin Delta, January – February 2000. Contract report for the U.S. Fish and Wildlife Service. Natural Resource Scientists, Inc. May 2001. 34 p. plus figures and appendices.