Appendix D
Juvenile Salmonid Migration Rate and Route Selection

January 2017

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D.1 INTRODUCTION

This appendix summarizes our understanding of how select gates, barriers, and hydrodynamic factors in the Delta, particularly those that may be affected by water project operations (Appendix B), affect juvenile salmonid outmigration behavior in terms of migration rates and route selection. This focus on hydrodynamic drivers in the South Delta is not intended to dismiss other factors as potentially important drivers of salmonid behavior. Other reports that review a broader range of environmental cues include Quinn (2005), Williams (2006), Williams (2010), Williams (2012), and Monismith et al. (2014).

State Water Project (SWP) and Central Valley Project (CVP) exports, Old and Middle rivers (OMR) flows, and the San Joaquin River imports to exports ratio (I:E) are metrics currently used to manage CVP and SWP operations with the intent of providing protection to Endangered Species Act (ESA)-listed salmonids (NMFS 2009); the State Water Resources Control Board (SWRCB) also has requirements in the Delta for fish and wildlife purposes under D-1641 (SWRCB 2000). Different metrics are used at different times of year, or in response to different triggering mechanisms. These measures include SWP and CVP South Delta exports that affect hydrodynamics and are thought to affect the migration rate or migration route (behavior) of out-migrating salmonids. The discussion below describes our current understanding of how flow and velocity conditions in the Delta may influence salmonid migration behavior. Installation and operation of gates and temporary barriers as part of water project operations also affect juvenile salmonid migration behavior. There is considerable information on routing at some junctions in the Delta (e.g., Delta Cross Channel [DCC] and head of Old River); however, studies of fish routing, which integrate hydrodynamics and fish behavior within channels or at interior junctions in the southern Delta, are limited.

D.2 CONCEPTUAL MODEL

The Drivers, Linkages, and Outcomes (DLOs) considered for this analysis of salmonid migration behavior are shown in Table D.2-1. Within the larger set of DLOs shown in Table D.2-1, the Salmon Scoping Team (SST) focused on three specific drivers:

- Effects of flow and velocity at junctions on migration route
- Effects of flow and velocity in channels on migration rate
- Effects of water quality on migration

The factors not reviewed in this document (in red italics in Table D.2-1) could also be potentially important drivers of salmonid behavior.

Table D.2-1. Migration Behavior DLO Components for Analysis

Drivers	Linkages	Outcomes
• Flow/velocity (channels) • Flow/velocity (junctions) • Water quality (e.g., temperature, dissolved oxygen, salinity, turbidity, contaminants) • *Hydraulic residence time* • *Spatial/temporal heterogeneity of hydrodynamic/water quality drivers* • *Small-scale hydrodynamics as affected by structures/bathymetry*	• Physiological and behavioral responses to hydrodynamic or water quality conditions, gradients, or variability, such as: – *Rearing* – Active swimming – Passive displacement – Diel movements – *Energy expenditure* – *Selective tidal stream transport*	• Individual outcomes: – Migration rate – Migration route – *Migration timing* – *Timing of Delta entry* – *Delta residence time* – *Rearing location* • *Population outcomes:* – *Population scale outcomes depend on the spatial/temporal heterogeneity of individual outcomes*

Notes: Black text indicates DLOs that were analyzed. Red italicized text indicates DLOs that were not analyzed.

Figure D.2-1 depicts a conceptual model where flow and velocity are local hydrodynamic drivers that are mechanistically linked to salmonid migration rate. In this conceptual model, behavioral responses to flow or velocity might differ in riverine conditions compared to tidal conditions. Because the extent of riverine conditions is determined by the interaction of river flow into the Delta with spring and neap tidal cycles, inflow might affect salmonid migration behavior both via effects on migration rate within a riverine reach and effects on the spatial extent of riverine conditions in the Delta. This conceptual model is just one of the many potential DLOs shown in Table D.2-1.

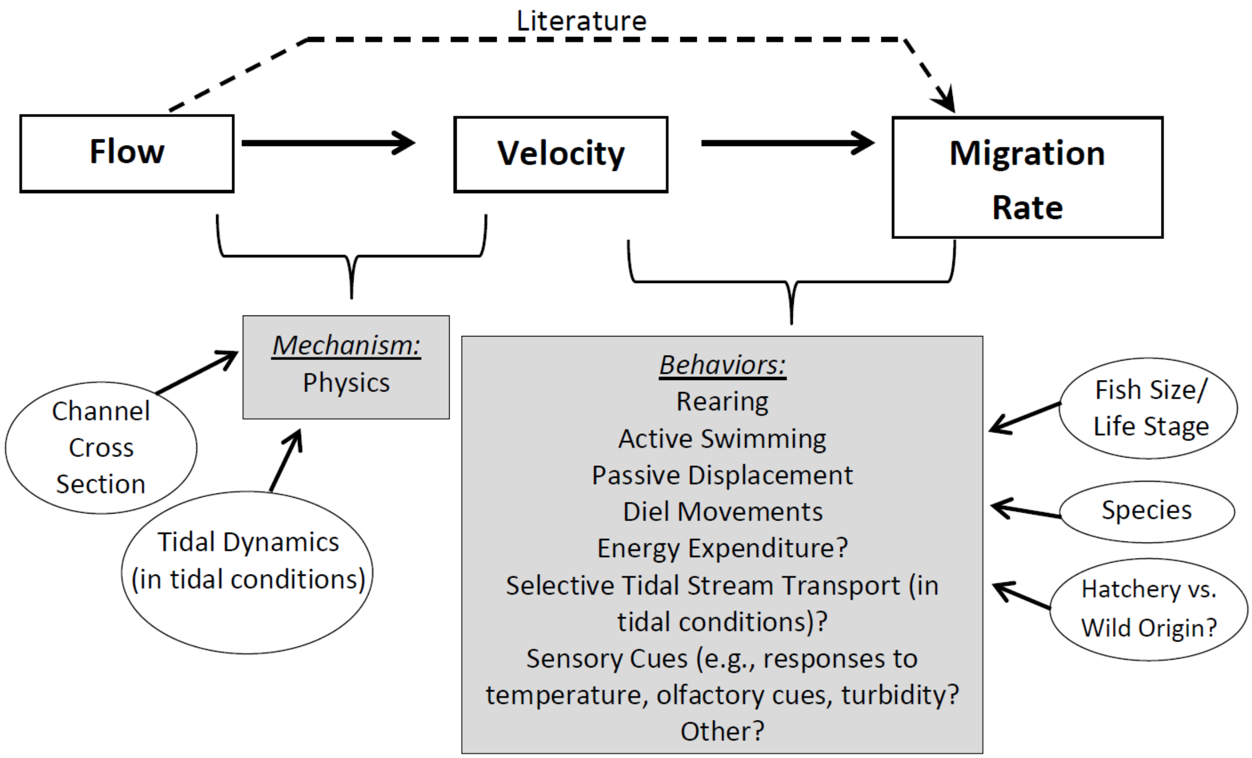

Figure D.2-1. Conceptual Model of the Effects of Channel Velocity on Juvenile Salmonid Migration Rate

Notes: Solid arrows show the mechanistic relationship between drivers and outcomes (white boxes) and dashed arrows show what the majority of literature correlate. Gray boxes summarize the known mechanism or behaviors, and factors that interact with behaviors are shown in ovals.

Evidence indicates that numerous factors affect juvenile salmonid migration rate (i.e., kilometers [km] per day) in the Delta. These covariates may include, but are not limited to, riverine channel velocity, the life stage and size of fish, the species of fish (data are generally for Chinook salmon or steelhead), bi-directional tidal velocity, time of day, and water quality. Route selection in the Delta is also influenced by several factors including flow splits and velocities at channel junctures, water quality, and the presence of gates and barriers. Specific factors affecting migration rates and route selection in the Delta are described in the following sections, particularly as they relate to flows and velocities. For each section, conceptual model predictions are provided followed by an analysis of relevant information and a summary of findings, including whether the available information supports the conceptual model predictions or not.

D.3 RIVERINE CHANNEL VELOCITY AND MIGRATION RATE

D.3.1 CONCEPTUAL MODEL PREDICTION

The conceptual model predicts that riverine channel velocity, defined as having unidirectional downstream flow, is positively correlated with migration rate through the channel.

D.3.2 ANALYSIS

Several studies have shown a positive relationship between velocity (or flow) and migration rate, as summarized below.

- Raymond (1979) observed a decrease in migration rate of juvenile Chinook salmon and steelhead with decreasing flows associated with dams in the Snake River.
- Zabel et al. (1998) found a strong positive relationship between flow and migration rate of juvenile Chinook salmon on a seasonal basis in the Snake River.
- Smith et al. (2002) found a strong and consistent negative relationship between flow and travel time through reaches in the Snake River for both Chinook salmon and steelhead.
- Williams (2006) characterized flow as a proximate factor that influences migration rate of juvenile Chinook salmon through the Delta.
- Hankin et al. (2010) conclude that the Vernalis Adaptive Management Plan (VAMP) study results support the idea that "increased inflows to estuaries and increased down-estuary net current velocities decrease juvenile salmon travel time through the system and increase survival." Note that the VAMP results are based on travel times that include both riverine and tidal reaches.
- Michel et al. (2013) found that water velocity and river flow were positively correlated to movement rate for juvenile late-fall-run Chinook salmon released in January, and that the fastest movement rates were observed in the upper reaches of the Sacramento River where riverine conditions were dominant. Migration rates slowed substantially as fish migrated into the bi-directional tidally dominated regions of the estuary.

D.3.3 SUMMARY OF FINDINGS

Our basis of knowledge regarding the relationship between riverine channel velocity and migration rate is high. Multiple studies in the Delta and out of basin provide support for the positive correlation between channel velocity and migration rate, confirming the prediction based on our conceptual model. The consequences of migration rate on survival are discussed in Appendix E.

In the past, the use of coded wire tag (CWT) salmon limited the analysis of migration rate as a function of flow and velocity to only a gross estimate of the time between release and time to recapture. The advent of acoustic tag (AT) technology now provides the opportunity to measure reach-specific migration rates for specific routes and exposure to specific flow and velocity conditions including tidal conditions. There is an opportunity to further analyze the AT data summarized in Appendix E to test the relationship between observed migration rates to route-specific measures of flow or velocity.

D.4 LIFE STAGE, FISH SIZE, AND MIGRATION RATE

D.4.1 CONCEPTUAL MODEL PREDICTION

The conceptual model predicts that the migration behavior of juvenile salmonids depends on life stage and the size of fish.

D.4.2 ANALYSIS

Several studies have examined the relationship between water velocity and migration rates, both for actively swimming smolts, and passively displaced fry. These studies are summarized below.

- Peake and McKinley (1998) studied swimming ability of Atlantic salmon parr and smolts in a laboratory setting and found that smolts were able to hold position by swimming, but only up to a certain velocity. On the other hand, parr quickly fatigued when forced to swim in order to maintain position, thus were passively displaced.
- Amado (2012) found that, as flow acceleration increased, fish exhibited positive rheotaxis (facing upstream) to hold position in a current. When fish were no longer able to hold position, they exhibited negative rheotaxis (facing downstream) and swam with the current.
- Kemp et al. (2012) contended that smolts exhibit behavioral responses to stimuli associated with currents. Similar to Amado (2012), Kemp et al. (2012) found that smolts that are actively migrating downstream will exhibit negative rheotaxis, but may exhibit positive rheotaxis when they encounter hydraulic gradients, such as eddies.

Studies have shown that fry and parr swimming ability and downstream displacement is related to fish size and water velocity. These studies are summarized below.

- Greenland and Thomas (1972) found in a laboratory study that smaller fry exhibited weaker swimming ability against an increase in current velocity and, as a result, were more likely to be impinged on a screen at the back of the tank.
- Giorgi et al. (1997) found that the combination of fish length and flow explained most of the variation in migration rate of age-0 Chinook salmon better than any other combination of variables.

- Williams (2006) described that fry simply get swept downstream during very high flows.

Results of research has also shown that larger smolts typically have a faster rate of migration and may exhibit more active swimming. These studies are summarized below.

- Kjelson et al. (1982) found that smolts, defined in the study as fish longer than 70-millimeter (mm) fork length (FL), migrated though the Delta at a rate of 10 to 18 km per day, or approximately 10 to 17 days.
- Baker and Morhardt (2001) observed shorter through-Delta travel times of San Joaquin basin Chinook salmon with increasing smolt size.
- Giorgi et al. (1997) found that migration rate of age-0 Chinook salmon increased with size; however, for yearling Chinook salmon, average migration rate was independent of size and for hatchery and wild steelhead, migration rate decreased with size.

D.4.3 Summary of Findings

Our basis of knowledge is high that the behavioral response to water velocity depends on life stage and size. Multiple studies in the Delta and out of basin provide support for the size or life-stage dependency of fish responses to hydrodynamics, confirming the prediction based on our conceptual model. Larger smolts generally have a greater ability to hold and not be passively displaced compared to smaller fry; this ability could support behaviors such as selective tidal stream transport (STST). Larger smolts typically have a faster rate of migration and may exhibit more active swimming. A knowledge gap is that little is known about whether or how *rearing* fry or parr (as opposed to *migrating* fry or parr) respond to hydrodynamic factors such as water velocity.

D.5 SALMONID SPECIES, AND HATCHERY-PRODUCED VS. NATURALLY PRODUCED SALMONIDS

D.5.1 Conceptual Model Prediction

The majority of scientific literature on the effects of channel velocities or flows on migration rate focuses on Chinook salmon. Our conceptual model prediction is that the influence of channel velocity on migration rate of steelhead smolts may differ from Chinook salmon (Giorgi et al. 1997; Zajanc et al. 2013; Delaney et al. 2014).

D.5.2 Analysis

Studies relevant to the above prediction are summarized below.

- Giorgi et al. (1997) found a positive association between migration rate of juvenile steelhead and flow in the Snake River.

- Zajanc et al. (2013) found that the probability of holding decreased with increasing flow, for both Chinook salmon and steelhead migrating in the Sacramento River.
- Delaney et al. (2014) estimated travel times for acoustic-tagged steelhead smolts in the Delta, from Buckley Cove on the mainstem of the San Joaquin River (just downstream of the mouth of the Calaveras River) to Chipps Island. Travel times ranged from approximately 4 to 7 days depending on the route taken.
- Buchanan (2013) estimated travel times for acoustic-tagged steelhead smolts (average FL = 276.7 mm) in the Delta, from Durham Ferry on the mainstem of the San Joaquin River (upstream of the head of Old River) to Chipps Island in 2011. Average travel time for steelhead releases in 2011 was 11.08 days (SE = 0.12 days). Average travel times for acoustic-tagged fall-run Chinook salmon (average FL = 110.8 mm) through this same reach in 2011 was 3.02 days (SE = 0.27 days; R. Buchanan, personal communication).
- Buchanan (2014) estimated travel times for acoustic-tagged steelhead smolts (average FL = 233.6 mm) in the Delta, from Durham Ferry on the mainstem of the San Joaquin River (upstream of the head of Old River) to Chipps Island in 2012. Average travel time for steelhead releases in 2012 was 9.41 days (SE = 0.25 days). Buchanan et al. (2015) estimated travel times for acoustic-tagged fall-run Chinook salmon (average FL = 112.8 mm) through this same reach for Chinook salmon releases in 2012 was 5.75 days (SE = 0.41 days).
- Appendix E summarizes travel rate, in day/km, for both acoustic-tagged fall-run Chinook salmon and steelhead by reach (Appendix E, Figure E.5-1). For reaches that have estimates of travel rate for both Chinook salmon and steelhead, there is considerable overlap in average travel rate between species.
- Hatchery steelhead are more likely to residualize or move upstream after release than hatchery Chinook salmon (R. Buchanan, personal communication).

It has also been suggested that hatchery-produced Chinook salmon smolts may exhibit different migration rates than naturally spawned smolts (Monzyk et al. 2009; Williams 2010), but information regarding how channel velocity may affect hatchery and naturally spawned smolt migration rates differently within the Delta is uncertain. Relevant studies are summarized below.

- Monzyk et al. (2009) found that travel times for natural Chinook salmon smolts differed from hatchery smolts, depending on reaches within the Snake River.
- Williams (2010) surmised that the migratory behavior of hatchery and naturally produced fish may differ.

D.5.3 SUMMARY OF FINDINGS

Our basis of knowledge is low that migration rate differs between Chinook salmon and steelhead. Although multiple directed studies in the Delta have collected data to evaluate this relationship, the results of these studies have only been examined in Appendices D and E, not in agency reports or peer-reviewed literature, and results are not consistent. Some recent AT data indicate that average through-Delta travel rates for Chinook salmon smolts overlap with travel time of juvenile steelhead (Appendix E, Figure E.5-1), suggesting that steelhead may not differ strongly from Chinook salmon in through-Delta migration rate. In contrast, results of AT monitoring data for juvenile Chinook salmon and steelhead released into the lower San Joaquin River in 2011 and 2012, showed a pattern of salmon travel times through the Delta that were approximately twice as fast as those for larger yearling steelhead. There are limited data with which to assess the prediction that migration rates of hatchery versus wild salmonids will differ; size differences between hatchery fish (likely larger) and wild fish migrating at any given time may confound the hatchery versus wild comparison.

D.6 BI-DIRECTIONAL TIDAL VELOCITY AND MIGRATION RATE

D.6.1 CONCEPTUAL MODEL PREDICTION

The conceptual model predicts that migration rate slows in areas with bi-directional tidal velocity compared to areas with unidirectional flows. Two examples of mechanisms that would support this prediction, which are not mutually exclusive, are: (1) instantaneous movement rates respond similarly in riverine and tidal reaches but the net displacement (and thus over-ground migration rate) is less when bi-directional velocities are present; or (2) for at least part of the day or tidal cycle, instantaneous movement rates respond differently in tidal reaches than in riverine reaches. One possible behavior that may influence migration in the tidal Delta is STST, wherein a fish holds during the flood tide and migrates seaward during the ebb tide. The specific zones in the Delta where bi-directional tidal velocity has a strong presence can vary significantly depending on riverine inflows (Cavallo et al. 2013), geographic location, channel size and configuration, and water project operations (Appendix B).

D.6.2 ANALYSIS

Relevant studies are summarized below.

Flow and Migration Rates

- Baker and Morhardt (2001) did not find an association between Delta inflows and smolt travel time between Vernalis on the San Joaquin River and Chipps Island, and deduced that tidal velocities most likely swamp the effects of riverine inflows.
- Vogel (2005) found that tidal velocities strongly influence the migration of Chinook salmon through the Delta.

- Hankin et al. (2010) concur that the migration rate of Chinook salmon smolts is influenced by the tidal velocities in the Delta; however, the mechanism of how tidal velocities affect migration rate is unclear.
- Williams (2010) looked at Sherwood Harbor and Chipps Island trawl catch of CWT fall-run Chinook salmon released from Coleman National Fish Hatchery and reported a median travel time of 8 days to cover 365 km from the hatchery to Sherwood Harbor (45.6 km per day), and an additional 5 days to cover the additional 80 km to Chipps Island (16 km per day). Williams (2010) suggested that “the change from riverine flow to bi-directional tidal flow may account for the change in pace.”
- Patterns in the recovery of CWT juvenile salmon in the Chipps Island trawl vary among years. Fish and modeled water particle arrival patterns overlap more in years with higher inflow (Figure D.6-1) than in years with low inflow (Figure D.6-2).
- Michel et al. (2013) found that region-specific movement rates of yearling late-fall-run Chinook salmon were fastest through the upper regions of the Sacramento River, and slowest in the Delta (Figure D.6-3). Migration rates in several of the years of study increased between the Delta and estuarine regions of the system.

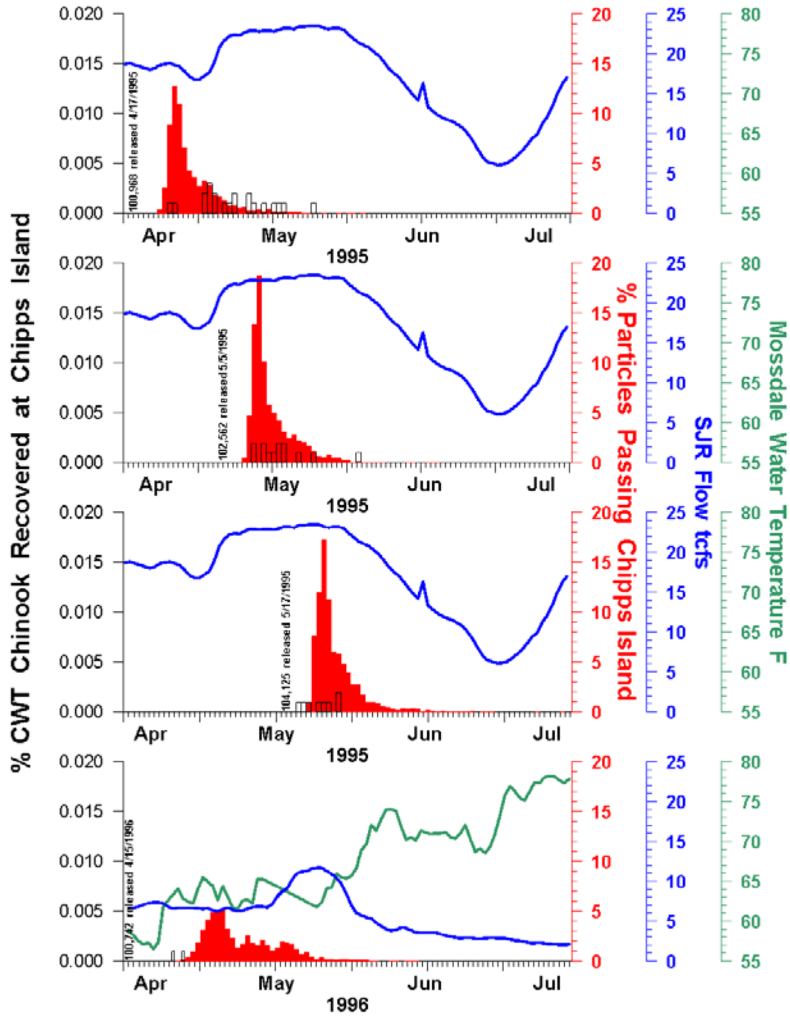

Figure D.6-1. Proportion of CWT-tagged Fish (hollow bars) Released into the San Joaquin River (SJR) During Two Relatively High-flow Years and Recovered in the Chipps Island Trawl, in Relation to Modeled Water Particle Travel Time (red bars), and SJR Flow (blue line) and Water Temperature (green line)

Source: DWR (2009)

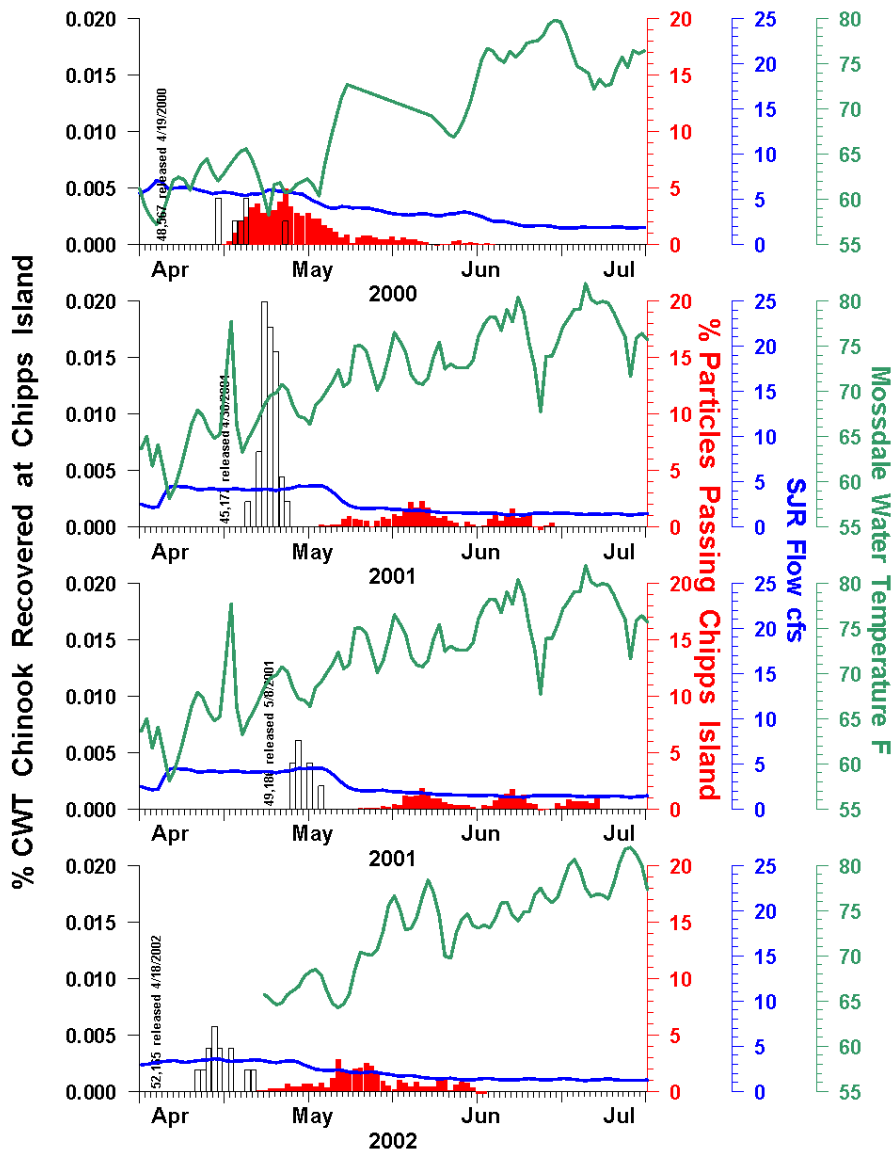

Figure D.6-2. Proportion of CWT-tagged Fish (hollow bars) Released into the San Joaquin River (SJR) During Three Low-flow Years and Recovered in the Chipps Island Trawl, in Relation to Modeled Water Particle Travel Time (red bars), and SJR Flow (blue line) and Water Temperature (green line)

Source: DWR (2009)

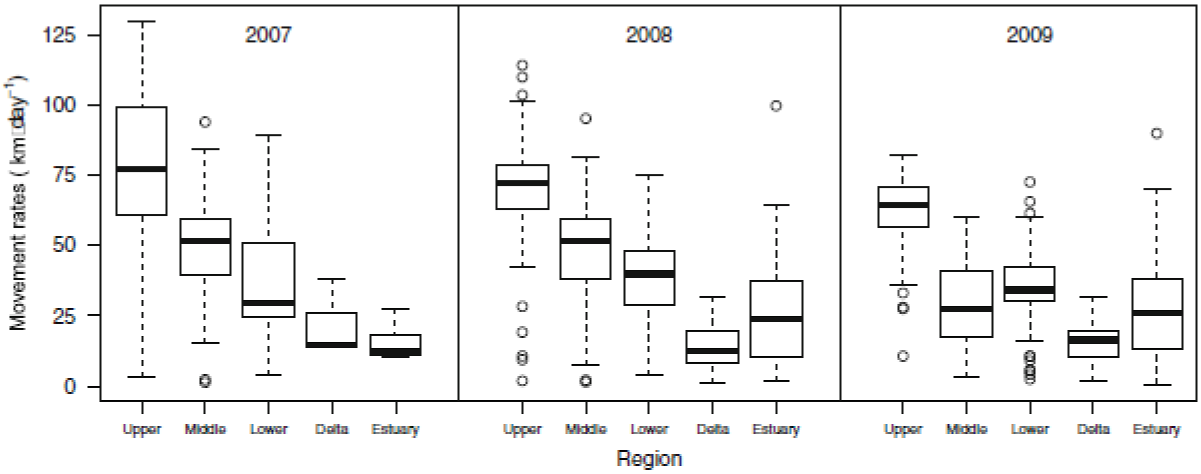

Figure D.6-3. Decreasing Migration Rates for Chinook Salmon in the Delta Compared to Migration Rates in Reaches Upstream of the Delta

Source: Michel et al. (2013)

Selective Tidal System Transport (STST)

- Martin et al. (2009) observed movements of tagged Atlantic salmon smolts in a Canadian estuary that was suggestive of STST.
- Clements et al. (2012) also observed movements of tagged steelhead smolts in an estuary in Oregon that was suggestive of STST.
- Zajanc et al. (2013) cited unpublished data from Phil Sandstrom about steelhead exhibiting STST in the Delta.
- Delaney et al. (2014) observed movements of tagged steelhead smolts in the Delta that were suggestive of STST. This behavior was concluded for one reach in the Delta, which was not identified in the report. Delaney et al. (2014) suggested that further research is needed to determine if STST behavior is exhibited in channels with significantly different cross sections throughout the Delta.
- Monismith et al. (2014) concur that it is not known if Chinook salmon exhibit selective tidal transport; however, it may be an efficient behavior for juvenile salmonids migrating through the Delta.
- Vogel (2002) found that radio-tagged juvenile late-fall-run Chinook salmon "seiched" with bi-directional tidal velocities in the North Delta and South Delta.

D.6.3 SUMMARY OF FINDINGS

Our basis of knowledge regarding slower migration rates through bi-directional tidal reaches is high. Two studies in San Francisco Bay and the Delta demonstrated slower travel times through tidal reaches compared to riverine reaches, and additional peer-reviewed literature from other systems support salmonid behavior suggesting STST. These study results generally confirm the conceptual model prediction that migration rate slows in areas with bi-directional tidal velocity compared to areas with unidirectional flows, though uncertainty remains as to the specific behavioral mechanisms underlying that pattern.

D.7 DIEL MOVEMENTS

D.7.1 CONCEPTUAL MODEL PREDICTION

The conceptual model predicts that juvenile salmon may exhibit diel patterns of movement. Diel movements can influence the rate of migration of Chinook salmon and steelhead smolts (Chapman et al. 2012).

D.7.2 ANALYSIS

Relevant studies are summarized below.

- Williams (2006) concludes that "there is good evidence for diurnal patterns in migratory behavior, but [these patterns] also vary," and provides several examples of diurnal patterns observed in monitoring data within California's Central Valley.
- Chapman et al. (2012) found that movements of late-fall-run tagged Chinook salmon yearlings in the Sacramento-San Joaquin watershed exhibited significantly more nocturnal movements in the upper Sacramento River watershed (as far upstream as Redding, California) than in the Delta. By the time they reached the "estuary" region (roughly, west of Sherman Island to the Golden Gate Bridge), the timing of movement was more equalized between day and night (Chapman et al. 2012). Steelhead smolts on the other hand, generally exhibited more equalized levels of nocturnal and daytime movements in all regions studied (Chapman et al. 2012).
- Diel movement of both Chinook salmon and steelhead smolts was influenced by discharge (Chapman et al. 2012); an increase in discharge resulted in smolts being more likely detected during the day. This was attributed to increased turbidity associated with increased discharge, which decreases a predator's ability to see their prey. Water temperature was also shown to have an influence on diel movements of both Chinook salmon and steelhead smolts, although not necessarily independent of other covariates (Chapman et al. 2012).
- Evidence from AT monitoring suggests Chinook salmon migrate in the South Delta more during the day than at night (R. Buchanan, personal communication).

D.7.3 SUMMARY OF FINDINGS

Our basis of knowledge is medium regarding diel movement patterns in juvenile salmonids in the Central Valley. The literature supports the conceptual model prediction that juvenile salmonids exhibit diel patterns of movement; the specifics of those patterns may differ between Chinook salmon and steelhead, by geographic location, and in response to factors such as temperature and turbidity. Understanding diel patterns can be relevant for management. For example, this information is needed to adjust DCC gate operations to minimize fish entrainment into the DCC based on predicted diel exposure of fish moving past the DCC.

D.8 CHANNEL JUNCTIONS AND MIGRATION ROUTE

The Delta is a complex interconnected network of channels representing the estuarine transition between the upstream tributary rivers and the downstream bays and coastal waters. As a result of this network of channels, juvenile salmonids migrating downstream into and through the Delta encounter a number of channel junctions that, depending on behavioral selection, determine the migratory pathway through the Delta. A number of factors are thought to affect the behavioral response of juvenile salmonids at a junction including:

- Magnitude of river flow
- Channel velocity
- Influence of tidal action on both flow direction and velocity
- Configuration of the channel junction
- Location of the juvenile salmonids in the channel cross section with respect to the channel junction
- Physical barriers such as the Head of Old River Barrier (HORB)

It has been hypothesized that habitat conditions, the length of each pathway, and, hence, the potential duration of juvenile residence in the channels vary, and the potential exposure of juveniles to sources of mortality vary among pathways. Flow patterns, including water velocities and flow splits at these channel junctions, are among the factors that potentially affect route selection.

D.8.1 CONCEPTUAL MODEL PREDICTIONS

The conceptual model predicts that route selection at channel junctions is proportional to flow splits, which are a function of tidal velocity, flow direction, and junction geometry. Route selection at channel junctions varies geographically within the Delta in response to effects of tides, Delta inflow, exports, and barrier operations that affect channel velocities and flow splits. Route selection is expected to be affected by exports proportionally to the incremental effect of exports on water velocity and flow within a channel or at a channel junction. Export effects on route selection are expected to be greatest in the immediate vicinity of the export facilities and diminish as a function of distance away from the facilities.

D.8.2 ANALYSIS

Cavallo et al. (2015) compiled data on juvenile Chinook salmon migration behavior from AT studies at six junctions in the Delta including the head of Old River, Georgiana Slough, DCC, Sutter Slough, Steamboat Slough, and Turner Cut. Flow estimates (river inflow, export rates, the proportion of flow entering the distributary, the ratio of velocities in the main channel to that in the distributary, and proportion of time over a day that flow was entering the distributary) over a 24-hour period corresponding to the day of arrival of tagged salmon at each junction were estimated using the one-dimensional (1-D) DSM2 hydrodynamic model. The proportion of juvenile salmon (both fall-run and late-fall-run Chinook salmon) migrating into each junction channel from 41 release groups was used as the basis for route selection. A best-fit linear model was used to describe the relationship between hydrodynamic metrics and route selection. The proportion of flow entering a distributary was selected as the best model predictor accounting for 70% of the observed variance in route selection ($R^2 = 0.70$; $P < 0.001$). The regression model was then used to predict route selection at nine junctions over a range of river inflow and export conditions represented in the hydrodynamic simulations.

Results of the model analysis showed that more fish entered junctions with strong riverine influence like head of Old River and Georgiana Slough where tidal flow reversals were diminished and flow entered the distributary throughout the day. There were fewer fish entering the single distributary monitored in the tidally dominated regions of the Delta (i.e., Turner Cut) where both inflow and diversions had only small effects on predicted route selection. The hydrodynamics at tidally dominated distributaries were dominated by tidal flow resulting in substantial periods each day when flows were not entering the distributary. Geometry of the junction and channels and tidal conditions at the time the fish enters the junction were identified as factors affecting route selection, but the data used to develop the model had very little information derived from tidal junctions (only Turner Cut in some instances). Exports affected the predicted proportion of fish routing by up to 7%. The effect of exports was greatest at the junction directly connected to channels leading to the export facilities (i.e., head of Old River) and diminished with distance from the export facilities.

D.8.3 Summary of Findings

Results of these analyses were generally consistent with the qualitative predictions from the conceptual model and prior studies (Kemp et al. 2005; Perry 2010) that route selection is proportional to the flow split at channel junctions and that the effect of exports on flows and velocities, and subsequently on route selection, diminishes with distance away from the facilities. Perry (2010) also showed a higher proportion of fish entering Georgiana Slough junction under low flows and greater tidal reversal.

Numerous study plans, data, and results have been prepared, collected, and evaluated regarding the HORB's effect on salmonid migration route. The SST has not identified a specific gap in information about how the physical HORB affects fish routing at the junction. The SST suggests that there are some conditions when a non-physical barrier may be deployed, which have not been evaluated, and thus gaps in our knowledge about how salmonid migration rate and route are affected under these flows remain. In addition, the incremental contribution of guidance provided by the non-physical barrier in improving overall salmonid survival to Chipps Island has not been quantified.

D.9 EFFECTS OF OLD AND MIDDLE RIVER FLOWS ON MIGRATION ROUTE

SWP and CVP exports may, depending on other Delta hydrologic conditions such as inflow from the San Joaquin River, result in reverse flows occurring in OMR. Although flow in OMR may reverse naturally in response to flood tide conditions, the addition of SWP and CVP export effects results in a greater magnitude and longer duration of reverse flow conditions than would occur in response to tidal conditions only. OMR reverse flows have been identified as one of the water project management conditions in the *Biological and Conference Opinion for the Long-Term Operations of the Central Valley Project and State Water Project* (NMFS 2009) during the winter and spring period of juvenile salmonid migration through the Delta.

D.9.1 CONCEPTUAL MODEL PREDICTIONS

The conceptual model predicts that increased negative OMR flow draws fish from the Sacramento River or lower San Joaquin River into the Interior Delta and toward the export facilities, and prevents fish that have entered the Interior Delta from navigating northward through Delta channels to the Delta exit. For San Joaquin River fish that have already entered the Interior Delta at the head of Old River, increased OMR reverse flows may result in faster entry to salvage facilities at the CVP and SWP, and so may be associated with higher survival from the head of Old River to Chipps Island via the CVP salvage route (Buchanan et al. 2013; Appendix E).

D.9.2 ANALYSIS

In 2012, a steelhead study was designed and implemented in an effort to learn more about the effects of OMR reverse flows on route selection and survival through the Delta (Delaney et al. 2014). Yearling steelhead from the Mokelumne River hatchery were implanted with ATs and released into the San Joaquin River in the vicinity of Stockton. Tag detectors were deployed in various channels and channel junctions located throughout the central and southern Delta. Unfortunately, tag detectors were not deployed in such a configuration that the probability of detection at all individual receivers could be estimated. Thus, although results of AT monitoring show that juvenile steelhead migrate downstream through a variety of pathways and exhibit a wide range of behavioral responses to channel junctions under various export and hydrodynamic conditions, no specific information on route choice for most junctions was developed (Delaney et al. 2014). The study showed that a higher probability of steelhead tags, located at the west end of Railroad Cut in Old River (about

10 miles from the export facilities), moved south towards the export facilities as OMR reverse flow became more negative (Delaney et al. 2014).

Results of the Delaney et al. (2014) study may apply to Sacramento River origin salmonids that reach the San Joaquin River mainstem and South Delta, but studies to assess how OMR reverse flows affect Sacramento River salmonid migration rate and route selection in the region north of the San Joaquin River mainstem have not been done. The SST feels there is a gap in our understanding of how OMR reverse flows impact the migration rate and routing and survival of juvenile salmonids in the Delta. However, the SST did not specifically address effects of OMR reverse flows on survival (Appendix E). The effect of OMR reverse flows on migration and survival in the Delta is a knowledge gap that should be addressed.

D.9.3 SUMMARY OF FINDINGS

Our basis of knowledge regarding the influence of OMR reverse flows on migration routing is low. The relationship between hydrodynamic conditions in OMR and the mechanisms underlying route selection by juvenile Chinook salmon and steelhead are poorly understood. The majority of information on the effects of OMR reverse flows on salmonid behavior has been derived from relationships between salmonid salvage at the SWP and CVP and the magnitude of reverse flows occurring when these fish were migrating through the Delta. Planning, implementation, and analysis of AT survival and migration studies have not focused on the mechanisms and interactions between local water velocities and flows and the resulting salmonid route selection in the OMR channels. Results of the one study explicitly designed and conducted to assess potential interactions and relationships between OMR reverse flow as a function of export rates, and juvenile steelhead migration behavior and susceptibility to migration into the Interior Delta in response to OMR reverse flows (Delaney et al. 2014) was inconclusive. The mechanisms affecting salmonid migration behavior in South Delta channels in response to OMR reverse flows are complex and poorly understood.

Studies to assess how OMR reverse flows affect Sacramento River fish migration rate and route selection in the region north of the San Joaquin River mainstem have not been done. Uncertainties exist regarding how OMR reverse flows impact the migration rate and routing of Sacramento River origin juvenile salmonids in the Delta. Because of the regulatory importance of OMR reverse flows and their hypothesized effect on salmonid migration and ultimately survival, further analysis of refined hydrodynamic simulation modeling coupled with field measurements of water velocities, flows, and migration patterns to assess entrainment risk and survival (at both a reach-specific and regional scale) is needed. Information collected as part of both North Delta salmonid AT studies and those from the South Delta (e.g., VAMP, six-year steelhead study and associated juvenile salmon studies) is available and can be used as part of the technical basis for evaluating in greater detail South Delta export operations and how they affect juvenile salmonids migrating through the Delta.

D.10 EFFECTS OF WATER QUALITY GRADIENTS ON MIGRATION RATE AND MIGRATION ROUTE

D.10.1 CONCEPTUAL MODEL PREDICTION

The conceptual model predicts that water quality conditions or gradients (such as salinity, water temperature, dissolved oxygen concentrations, and turbidity gradients) affect salmonid migration rate or migration routing. Due to time constraints and, for some water quality constituents, less well-known linkages to water project operations, only a very cursory review is provided here.

D.10.2 ANALYSIS

Relevant available information is summarized below.

- Salmonids may use olfactory cues and potentially other water quality gradients to help guide migration throughout their lifecycle (Hasler and Wisby 1951; Dittman and Quinn 1996).
- Hallock et al. (1970) conducted the first AT study in the Delta that examined the effects of water temperature and dissolved oxygen concentrations in the lower San Joaquin River during the fall adult upstream migration period. The study found that route selection in sonic-tagged adult Chinook salmon was influenced by dissolved oxygen and, to a lesser extent, temperature. Adult salmon avoided water with less than 5 parts per million (ppm) dissolved oxygen by staying farther downstream (Hallock et al. 1970). Temperatures higher than 66°F had a similar, but less sharply defined effect (Hallock et al. 1970).
- Water temperature may affect the migration of juveniles by influencing growth, smolt transformation, saltwater survival, and disease (Adams et al. 1975; Holt et al. 1975; Wurtsbaugh and Davis 1977; Hughes et al. 1978; Boles 1988; Cech and Myrick 1999; McCullough 1999; Benjamin et al. 2013). Chinook salmon can smolt at temperatures ranging from 6 to 20°C; however, salmon that smolt at higher temperatures (greater than 16°C) tend to display impaired smoltification patterns and reduced saltwater survival, while juvenile salmon that rear in the 10 to 17.5°C temperature range are optimally prepared for saltwater survival (Myrick and Cech 2005). Steelhead successfully undergo parr-smolt transformation at temperatures between 6.5 and 11.3°C, and show little seawater adaptation at temperatures above 15°C (Adams et al. 1975). Cooler temperatures (less than 10°C) tend to increase their seawater adaptation. Cooler temperatures also reduce their risk of predation and disease, both of which are increased at higher temperatures (Myrick and Cech 2005), which could affect migration rates.

D.10.3 Summary of Findings

Only a cursory review of water quality cues and salmonid behavior was done; therefore, no basis of knowledge statement is provided. Also, additional information is needed on how project operations affect water quality gradients and how these might influence juvenile salmonid migration behavior. Gaps in knowledge exists regarding the effects of water project operations on water quality gradients and associated juvenile migration cues.

D.11 EFFECTS OF TEMPORARY BARRIERS ON MIGRATION RATE AND ROUTE

During the spring and summer months, the California Department of Water Resources (DWR) installed a series of temporary riprap barriers at strategic locations in the South Delta (Appendix A) for the purpose of stabilizing and increasing water surface elevations in South Delta channels to facilitate agricultural irrigation and to mitigate for effects of SWP export operations on water levels. In addition, a temporary barrier has occasionally been installed at the head of Old River during the spring to reduce the movement of juvenile salmonids into Old River in an effort to reduce exposure to the SWP and CVP export facilities and improve survival.

D.11.1 Conceptual Model Predictions

The conceptual model predicts that survival of juvenile salmonids to Chipps Island is higher in routes that avoid the Interior Delta; thus, overall survival to Chipps Island is anticipated to be higher in the presence of barriers that block access to the Interior Delta routes (e.g., at the head of Old River). However, installation of other temporary barriers in the South Delta results in local changes in flows and water velocities that can affect salmonid route selection and migration rates. Survival through regions of the Delta where temporary barriers are installed is expected to be lower when the barriers are in than when they are not installed because of the attraction of predators to the barrier sites. Barriers that result in changes in migration behavior that cause delays in migration out of the Delta are expected to result in reduced survival.

D.11.2 Analysis

Temporary barriers affect flows and velocities in specific Delta channels, which may affect salmonid migration rates. Barriers may also affect migration routing via changed flows and velocities and/or physical blockage or guidance effects. As part of SWP and CVP operations, both temporary rock barriers (e.g., agricultural barriers in the South Delta, the HORB) and operable barriers (DCC and Clifton Court Forebay [CCF] radial gates) are used to regulate and manage water flows through Delta channels and reduce the effects of export operations on water surface elevations in South Delta channels (Appendix A).

The effect of the temporary agricultural barriers in Old River near Tracy, Middle River, and Grant Line Canal (Appendix A) on juvenile salmon migration rate was evaluated in 2011 (SJRGA 2013). Travel times through the Delta were compared before and after the initiation of barrier installation. However, because of temporal changes in conditions through the study season, effects of barriers on travel time were confounded by other temporally varying conditions (e.g., flow, exports, water temperature)—in particular, installation of all three barriers began near the time of increases in combined export rates (approximately June 1) from less than 4,000 cubic feet per second (cfs) to greater than 8,000 cfs. Travel time to CCF was also shorter after installation of the OMR barriers began (SJRGA 2013).

The only effect observed at the Grant Line Canal barrier was on route selection at the head of Middle River. More fish selected Old River at that junction after barrier installation began and fewer Chinook salmon successfully passed the immediate vicinity of the barrier after installation began (passage success = 0.9972 before versus 0.9732 after, $P = 0.04$; SJRGA 2013). From this single year of study, the effect of the temporary agricultural barriers was limited and somewhat paradoxical (e.g., shorter travel time through the Old River route after barrier installation). In interpreting these findings, it is important to note that factors other than barrier installation changed between passage of treatment groups (in particular, increasing exports). Also, comparisons were made relative to the initiation of barrier installation, which lasted one to four weeks, depending on the barrier. Fish had relatively unimpeded passage during early parts of installation. Most tagged fish had passed through the region before the barriers were installed.

As part of the South Delta Temporary Barrier Project evaluation (DWR 2011a, 2011b), the 1-D DSM2 open channel, unsteady flow, hydrologic simulation model was used to estimate changes in average daily flow in various Delta channels with and without the temporary barriers, extending over a network from the I Street bridge in Sacramento to Vernalis on the San Joaquin River and west to Martinez. The model is used each year to represent actual hydrologic boundary conditions during the period that the barriers are installed. The validation of model predictions for the temporary barrier evaluation (DWR 2011a, 2011b) reflects a spatial and temporal scale that was considered to be appropriate for evaluation of the effects of the temporary barriers on flow and stage in various Delta channels (e.g., average daily conditions).

Results of the DSM2 simulation model evaluation showed that installation of the temporary barriers significantly altered stage and flows in the South Delta (DWR 2011a, 2011b). The effects of barrier installation were typically localized to the channels in the immediate vicinity of each barrier and diminished with distance upstream and downstream. For example, installation of the Middle River barrier in 2008 raised water elevation at the barrier approximately 0.5 feet, but the effect was limited, spatially, to the Middle River channel. Installation of the Grant Line Canal barrier was found in 2008 to raise water levels in the canal by approximately 1.5 feet, as well as raising water levels in Middle River by approximately 1 foot and levels in Old River by approximately 0.5 feet (DWR 2011a). The barriers were also found to diminish tidal variation in flows with the effect most pronounced in OMR when the Grant Line barrier was installed. Model analyses of the effects of the temporary barriers on hydrodynamics in the South Delta in 2009 are presented in DWR (2011b).

Although the SST did not conduct a comprehensive review of the existing study plans and data on the effect of various agricultural barriers on migration rate and route, the SST feels there are gaps in our knowledge of how fish behavior is affected by the barriers. The SST notes that, because these barriers are usually constructed in mid-April or later, the presence of the barriers overlaps with the migration timing of Central Valley steelhead (from either basin, but particularly the San Joaquin basin for both geographic and migration-timing reasons) and spring-run Chinook salmon that enter the South Delta. In years when the HORB is not installed or water levels are less of a concern, construction of these barriers may not occur until late May or later, by which time most listed salmonids have exited the Delta. The incremental contribution of the South Delta barriers to salmonid migration rate and route selection over a range of hydrologic conditions remains unknown.

The HORB is used to reduce the proportion of juvenile salmon and steelhead migrating into Old River in the spring. Results of DSM2 simulation modeling show that installation of the HORB significantly reduces the flow of water that enters Old River and Grant Line Canal from the lower San Joaquin River (DWR 2011a, 2011b). The HORB increases flows in the mainstem of the San Joaquin River, decreases flow in Old River between the head and Grant Line Canal, and decreases minimum velocity in Middle River between the head and Tracy Boulevard. The HORB creates a physical barrier to juvenile salmonids migrating from the San Joaquin River into Old River, although culverts through the barrier provide limited opportunities for salmonid migration through the barrier.

Results of early CWT studies generally show a pattern of increased juvenile survival when fish do not migrate into Old River; however, results of more recent AT studies using both juvenile Chinook salmon and steelhead have not shown a consistent pattern of increased survival for those fish that remain in the San Joaquin River mainstem (Appendix E, Section E.4).

Results of the non-physical HORB studies conducted by Bowen et al. (2009) provided information on the potential behavioral response of migrating juvenile salmonids to hydrodynamic conditions occurring adjacent to the head of Old River; however, detailed information on actual water velocities and flow direction were not included as part of the analysis of the behavioral response to hydrodynamic conditions occurring at the channel split between Old River and the San Joaquin River. Results of these studies did, however, suggest substantial predation mortality on juvenile Chinook salmon in the vicinity of the head of Old River and within the scour hole located immediately downstream of the confluence. The effect of export operations on the behavior of juvenile salmonids encountering the head of Old River was not experimentally investigated as part of these studies.

The magnitude of predation on acoustically tagged juvenile salmonids increases the uncertainty of the interpretation of AT study results, since effective sample sizes of tagged salmonids will diminish as tagged fish move downstream, split at various channels, and experience mortality (Johnston and Kumagai 2012; Vogel 2010, 2007), thereby reducing certainty in migration and survival estimates. Predation on tagged fish by migratory predators makes it difficult to identify when the subsequent behavior of a tag reflects a predator rather than a downstream-migrating salmonid (DWR 2012; Bowen et al. 2009; Bowen and Bark 2012). A summary of juvenile salmonid routing, barrier effectiveness, and predation at the head of Old River is provided in DWR (2015a).

D.11.3 SUMMARY OF FINDINGS

Our basis of knowledge regarding the effect of temporary barriers on fish movement and routing is medium as it is supported by multiple non-peer-reviewed agency reports. Key findings from the available literature can be summarized as follows:

- Installation of temporary barriers in the South Delta directly affects local hydrodynamic patterns of water velocities, flows, and tidal changes.
- Temporary rock barriers create physical barriers blocking juvenile salmonid migration into specific channels.
- Changes in migration behavior of juvenile salmonids in combination with the hydrodynamic and physical structure of the barriers can affect vulnerability to predation mortality.
- The incremental contribution of the installation of temporary barriers during the late winter and spring on migration rate and survival to Chipps Island for juvenile salmon and steelhead over a wide range of hydrologic conditions remains uncertain.

D.12 DELTA CROSS CHANNEL AND GEORGIANA SLOUGH MIGRATION ROUTE

The DCC radial gates are located on the Sacramento River upstream of Walnut Grove (Appendix A) and regulate the movement of water from the Sacramento River through a constructed channel into the Interior Delta and subsequently into the South Delta where it can be exported at the SWP and CVP facilities. Under SWRCB D-1641, the DCC is required to be closed during the late winter and spring to avoid the movement of juvenile salmonids through the DCC into the Interior Delta where survival studies have shown mortality is increased. Georgiana Slough is a natural channel located immediately downstream of Walnut Grove (Appendix A) that also provides a pathway for juvenile salmonids to migrate into the Interior Delta.

D.12.1 Conceptual Model Predictions

The conceptual model predicts that salmonids that enter the Interior Delta through the DCC or Georgiana Slough have lower survival when compared to salmonids migrating in the Sacramento River mainstem. The probability of juvenile salmonids migrating into the DCC or Georgiana Slough varies in response to local hydrodynamic conditions. Understanding the linkage between local hydrodynamics at the DCC and Georgiana Slough and salmonid migratory behavior can be applied to studies on migration route selection in the South Delta.

D.12.2 Analysis

The DCC was built by the CVP to facilitate the movement of Sacramento River water to the South Delta pumping plant. When the DCC gates are open, they allow migration of fish from the Sacramento River into the Interior Delta. Georgiana Slough is a natural channel that conveys water from the Sacramento River into the Interior Delta. Flow in the Sacramento River in the vicinity of these two junctions is unidirectional (downstream during periods of high river flow) and bi-directional (flowing both upstream and downstream) in response to tidal conditions when river flow is reduced.

The use of radio tags and ATs over the past 15 years has provided an opportunity to monitor route entrainment of juvenile Chinook salmon and steelhead in the Delta. In 2009, studies were conducted using ATs to investigate how survival through the Delta varied with DCC gate operations (Perry and Skalski 2009). These studies documented route selection and reach-specific survival for tagged late-fall-run salmon migrating from Sacramento to Chipps Island and migrating through three main migration routes: Sutter and Steamboat sloughs, the Sacramento River mainstem, and Georgiana Slough (Perry 2010; Perry et al. 2010, 2014). Results of these studies showed that DCC gate closures can decrease the number of fish entering the Interior Delta through the DCC, but under low Sacramento River flows, and bi-directional tidal flow, similar proportions of tagged fish entered the Interior Delta through Georgiana Slough alone. Under low flows and bi-directional tidal flow in the Sacramento River near the entrance of Georgiana Slough, the number of fish entering Georgiana Slough increased and many tagged fish moved upstream into Georgiana Slough on flood tides.

Results of these studies provided estimates of reach-specific migration rates and route selection over a range of Sacramento River flow conditions with the DCC gates open and closed. The studies also provided information on the relationship between water velocities and changes in flow direction in response to tidal conditions as factors affecting migration route selection (Perry 2010; Perry et al. 2014).

Studies in the early 1990s were conducted to assess the potential effectiveness of a non-physical barrier (sound) for reducing the proportion of juvenile Chinook salmon entering Georgiana Slough using spray-dyed Chinook salmon that were released at various locations in the Sacramento River and Georgiana Slough in an effort to assess migration route selection (Hanson and SLDMWA 1996). Juvenile Chinook salmon that were released into the Sacramento River downstream of the confluence with Georgiana Slough were subsequently collected in Georgiana Slough demonstrating that these juveniles had been routed on the flood tide into Georgiana Slough. Results of the analysis showed evidence that, in general, the proportion of juvenile downstream migrating Chinook salmon that enter Georgiana Slough was in proportion to the flow split between the Sacramento River and Georgiana Slough. Although these studies did not provide detailed information on the behavioral response or route selection between the Sacramento River and Georgiana Slough, they did provide foundational information on the relative proportion of juvenile salmonids following flow cues and subsequently migrating from the Sacramento River into Georgiana Slough. No information was collected on water velocities, or on the specific location within the Sacramento River channel cross section where the juvenile Chinook salmon were migrating.

The use of radio tags and ATs in conducting juvenile Chinook salmon survival studies in the 2000s provided the first significant opportunity to monitor the behavioral response of juvenile Chinook salmon and steelhead encountering channel junctions. Using the AT technology, a series of studies were conducted to investigate the behavioral response of juvenile Chinook salmon to hydrodynamic conditions occurring within the Sacramento River when the DCC gates were open and closed (Perry and Skalski 2009). These additional studies also investigated route selection, behavioral response to channel junctions, and reach-specific survival in the North Delta, including migration selection through Sutter and Steamboat sloughs, the Sacramento River mainstem, and Georgiana Slough (Perry 2010; Perry et al. 2010, 2014). Results of these studies provided important information on the behavioral response of juvenile Chinook salmon to channel junctions. For example, these AT studies found that the DCC gate closures could increase the number of fish entering Georgiana Slough, and that many tagged fish moved into Georgiana Slough on flood tides. Both acoustic and CWT studies demonstrated that survival rates for juvenile Chinook salmon that migrated from the Sacramento River into the Interior Delta through Georgiana Slough were lower than corresponding survival rates for those juvenile Chinook salmon that remain in the Sacramento River during their downstream migration (Brandes and McLain 2001; Newman 2008; Newman and Brandes 2010; Perry 2010; Perry et al. 2010, 2014). The Perry and Skalski (2009) and Perry (2010) DCC AT studies were conducted using an acoustic detection array that could not determine the location of the tagged fish within the water column or details of the individual behavioral responses of salmonids when encountering channel junctions. Results of the studies, which were conducted over several years, provided estimates of reach-specific migration rates, route selection, and survival over a range of Sacramento River flow conditions with the DCC gates open and closed. The studies provided information on the relationship between water velocities and changes in flow direction in response to tidal conditions as factors affecting migration behavior (Perry 2010). A limitation of ATs is that predators that eat tagged salmon and migrate past a receiver will bias survival estimates. Some AT studies have developed a predator filter to address this concern, while others have not.

During 2010 and 2011, detailed fine-grained 3-D acoustic tagging and monitoring was conducted using late-fall-run Chinook salmon in the Sacramento River as part of the Georgiana Slough non-physical barrier research investigation (DWR 2012). High-resolution 3-D AT detection provided detailed information on the precise location and migratory pathway for each of the ATs, originally placed in salmon, and information on migration behavior through the study reach. In addition, Acoustic Doppler Current Profilers (ADCPs) were deployed within the study reach to continuously measure water velocity profiles in the Sacramento River immediately adjacent to the confluence with Georgiana Slough. Analysis of the fine-grained information on the precise location and migratory pathway of individual salmonids, in combination with detailed information on the velocity fields that they encountered during migration past the confluence with Georgiana Slough, provides insight into the interaction between the location of the fish within the Sacramento River, water velocity and direction, and subsequent behavioral response when encountering the Georgiana Slough junction.

Results of these studies demonstrate that the lateral location of juveniles within the Sacramento River is one of the factors influencing the probability that a fish will subsequently migrate into Georgiana Slough. Hydraulic streaklines suggest that juvenile salmonids migrating on the western side of the Sacramento River (farthest away from the confluence with Georgiana Slough) have a significantly lower probability of migrating into the slough compared to juveniles on the eastern side of the Sacramento River, which is subject to the hydrodynamic influence of the Georgiana Slough confluence. Fish movement into Georgiana Slough was also related to river flow and tidal conditions (Perry et al. 2014).

Fish being diverted into Georgiana Slough was related to river flow and tidal conditions but was not found to be related to SWP or CVP export rates. However, the construction of the DCC is a direct result of water project operations and when open allows the movement of fish into the Interior Delta. The proportion of salmonids moving into the Interior Delta through the DCC or Georgiana Slough was largely unaffected by exports. The detailed 3-D AT juvenile salmonid monitoring and corresponding field measurements and modeling of flows and velocities are the most detailed and intensive studies conducted to date in the Delta on the behavioral response of juvenile salmonids to a channel junction and associated hydrodynamics. Results from these studies provide insights into the migration of tagged late-fall-run juvenile salmon on a diel basis during the winter over a relatively wide range of Sacramento River flow conditions. There is likely considerable variability in fish movement and migration between seasons, races, and size of fish that has not been investigated.

After evaluating results of experimental tests using various alternative non-physical barrier technologies, DWR implemented the Georgiana Slough Non-Physical Barrier Study in 2011 and 2012 to test the effectiveness of using a non-physical barrier, referred to as a behavioral Bio-Acoustic Fish Fence (BAFF). The BAFF combines three stimuli expected to deter juvenile Chinook salmon and steelhead from entering Georgiana Slough: sound, high-intensity modulated light (previously known as stroboscopic light), and a bubble curtain. In 2014 a floating fish fence was tested as a potential method of guiding juvenile salmonids away from Georgiana Slough into an area of the Sacramento River where flows would guide the fish downstream. As part of the studies, hydrodynamics and velocity were measured simultaneously to fine-scale fish movements. ADCPs were deployed along the non-physical barrier to assess velocity and general hydrodynamic conditions, and flow proportions entering Georgiana Slough. Six fixed ACDPs were deployed along the BAFF for the duration of the studies, and drifting ADCPs were deployed at several time periods to interpolate surface velocities between the fixed ADCP locations (Perry et al. 2012; DWR 2012).

The purpose of the velocity studies was to determine the hydrodynamics that potentially affect fish entrainment into Georgiana Slough. The measured hydrodynamic data were used in a model to estimate velocity streamlines and 2-D velocity fields. Velocity fields are complex to assess, and were simplified using the entrainment zone and critical streakline concepts.

Areas within the junction where a large percentage of particles share the same fate are called entrainment zones. The critical streakline is the spatial divide between the entrainment zones. The critical streakline at the Georgiana Slough junction separates the entrainment zone for modeled particles that enter Georgiana Slough and the entrainment zone for particles that remain in the Sacramento River during downstream flow conditions. The streakline position can be related to the discharge ratio (the proportion of flow that enters Georgiana Slough from the Sacramento River) scaled by the channel width. There are potentially six tide conditions that must be considered to correctly compute the discharge ratio in junctions where the tidal currents are reversing:

- Upstream, downstream, and converging flows when water is entering the side channel
- Upstream, downstream, and converging flows when water is leaving the side channel

This is important when considering tidally averaged or longer time scales used in regulatory management actions. The correct calculation of the tidally averaged discharge ratio is the average of the ratio, not the ratio of the average. The ratio should be calculated at the shortest time scale appropriate for the use, and then averaged over the time scale of interest. Calculating the average of the components of the ratio and then the ratio itself is common in the Delta, but often produces incorrect results (DWR 2013).

The approach used to evaluate the interaction of channel hydrodynamics on juvenile salmonid route selection at the Georgina Slough channel junction serves as a model for interdisciplinary collaborative scientific investigations in the South Delta. The Georgiana Slough studies used high-resolution ATs and a fine-grained tag detection network focused on the channel junction to map the location and movement of individual Chinook salmon and steelhead as they migrated downstream in the Sacramento River and responded to hydraulic conditions at the Georgiana Slough junction over a range of flow and tidal conditions. In addition, actual water velocity measurements were made using an array of ADCP and hydrologic modeling to determine the flow and velocity at the time and location of each migrating fish. Similar multivariate monitoring and modeling approaches would be applicable to determining the relationships between SWP and CVP export rates, flow and velocity at specific locations in channel junctions, and migration rate and route selection in the South Delta.

NMFS (2009) includes a reasonable and prudent alternative (RPA) requiring DWR and the U.S. Bureau of Reclamation to consider engineering solutions to reduce the diversion of juvenile salmonids from the Sacramento River into the Interior and South Delta (NMFS 2009; Action IV.1.3). In response to this requirement, DWR has prepared an assessment of potential engineering approaches to improving juvenile salmon migration at various channel junctions in the Delta (DWR 2015b). Much of the technical knowledge gained through the investigations conducted on the Sacramento River regarding juvenile salmonid migration associated with the DCC and Georgiana Slough investigations was used in identifying potential alternative engineering technologies that would potentially improve migration and survival of salmonids in the Delta.

D.12.3 SUMMARY OF FINDINGS

Our basis of knowledge regarding the influence of barriers on migration route through the Sacramento River is high. Multiple peer-reviewed studies have demonstrated the effect of these barriers on route selection. Summary findings are as follows:

- The effects of DCC gate closures on overall migration rate and route selection are well understood; however, further investigation is needed to examine alternative radial gate operations such as partial gate openings, opening the gates on a day/night cycle, or operating the gates in accordance with river flows and tides that would allow some water flow into the Interior Delta to benefit water quality and other uses while continuing to provide fish protection.
- Although there have been several non-physical barrier studies, there are conditions that have not been investigated such as low Sacramento River flow and strong tidal flow reversals that represent gaps in our knowledge base).
- The application of high-resolution ATs in combination with detailed site-specific hydrodynamic monitoring (ADCP velocity and flow monitoring) and simulation modeling has proven to be an effective approach to assessing the interaction between

local hydrodynamics and salmonid route selection at Georgiana Slough and the DCC but has not been applied to migration or survival studies in the South Delta.
- A variety of site-specific conditions, including the location of the migrating salmonid within the channel cross section, channel configuration, flow and velocity patterns, and other factors, have been identified as affecting route selection.
- River flow and tidal conditions have been identified as important factors affecting hydrodynamics at the DCC and Georgiana Slough; hydrodynamics in the Sacramento River in the vicinity of the DCC and Georgiana Slough are not affected by SWP and CVP exports.
- The investigations conducted to date have focused on the potential application of non-physical barriers to guide juvenile salmonids away from potentially adverse migration pathways. Further investigation is required to evaluate the potential to use a non-physical barrier or floating fish fence technology as a method for guiding migrating salmonids into potentially beneficial pathways, such as Sutter or Steamboat sloughs.
- Although a great deal of knowledge was gained on the interaction between hydrodynamic conditions at the Sacramento River-Georgiana Slough junction, the ability to effectively transfer this knowledge to channel junctions in the South Delta remains uncertain.
- The incremental benefits of applying a fish guidance technology at a location such as the Georgiana Slough junction on the overall migration and survival of juvenile salmonids out of the Delta (e.g., to Chipps Island) has not been tested over a range of environmental conditions.

D.13 EFFECTS OF CLIFTON COURT FOREBAY OPERATIONS ON MIGRATION RATE AND ROUTE

Operable radial gates are used to control water flow into the SWP CCF (Appendix A). The gates are opened at approximately high tide stage to allow water to flow into CCF and stored temporarily before being exported. When the radial gates are open, velocities entering CCF are high (up to approximately 15 feet per second) and then diminish as CCF fills. When the radial gates are closed, no fish enter CCF. Due to time and resource constraints, the SST did not attempt to synthesize the available science on CCF operations and its relation to salmonid behavior at that location. However, the SST acknowledges the potential importance of this topic on salmonid migration rate and routing through the Delta. The SST is not aware of any studies that have tested the effect of radial gate operations on local hydrodynamics or salmonid response. Additional investigations are needed to better understand: the effects of radial gate operations on hydrodynamic conditions in the OMR region of the Delta; the response of juvenile salmonids to hydrodynamic changes associated with gate operations; quantification of the water velocities and flows entering CCF (this would also be used to improve hydrodynamic simulation model assumptions and relationships); and the relationship between SWP export operations, South Delta hydrodynamics, and juvenile salmonid migration and entrainment risk. A conceptual proposal to assess effects of radial gate operations was included in Appendix G in the South Delta Salmonid Research Collaborative (SDSRC) progress report (SDSRC 2014).

D.14 EFFECTS OF VERNALIS INFLOW:EXPORT RATIO ON MIGRATION RATE AND ROUTE

NMFS (2009) includes an RPA that regulates SWP and CVP exports in April and May based on a ratio of San Joaquin River inflows at Vernalis and combined CVP/SWP exports (the I:E ratio). Management under the I:E ratio targets juvenile steelhead migrating downstream from the San Joaquin River watershed. Currently, only two years of AT information are available from the six-year steelhead study (2011 and 2012) for juvenile steelhead migration through the lower San Joaquin River and Delta (Appendix E); results from the remaining four years are currently being analyzed. The currently available data and analyses focus on survival and are inadequate to assess potential relationships between the I:E ratio and juvenile steelhead migration rates and route selection.

Analyses regarding the I:E ratio have been used to regulate spring water management as part of NMFS (2009) since 2009. Past studies have observed fish migration and routing at a range of I:E ratios, but there could be value in evaluating the effects of additional I:E ratios that would be relevant to management decisions. The SDSRC suggested an approach to achieve better information regarding additional I:E ratios (SDSRC 2014, Appendix G). Further information on migration rate and route at different I:E ratios may also shed light on the corresponding survival results, but not all junctions are monitored in the South Delta. The lack of information and analysis of the potential relationship between I:E and juvenile steelhead migration is an important gap.

D.15 DISCUSSION

Results of fine-resolution acoustic and hydrodynamic monitoring in the Sacramento River demonstrate the ability to predict route selection of juvenile salmonids encountering Georgiana Slough based on the location of the fish in the channel cross section and the hydraulic streakline with a proportion of the river flow entering the slough (DWR 2012; Perry et al. 2010, 2014). Similar studies that integrate salmonid migration behavior and hydrodynamics at channel junctions have not been conducted in the South Delta.

Results of the hydrodynamic simulation modeling show that the proportion of flow splits at channel junctions such as Turner Cut and Columbia Cut are dominated by river inflow and tidal conditions with a substantially lower influence from exports. These results are consistent with those presented by Cavallo et al. (2015) noting that it would be very difficult to influence route selection along the lower San Joaquin River by managing SWP and CVP export rates. As an alternative to trying to affect route selection at junctions along the

San Joaquin River, DWR (2015b) investigated engineering solutions such as the installation of non-physical barriers. However, results of more recent AT studies have not detected a consistent pattern between route selection and juvenile Chinook salmon survival in the South Delta (Appendix E).

Based on the limited numbers of AT studies that have been conducted and analyzed to date, there remains uncertainty in:

- How migration rates and routes vary through specific reaches
- How migration rate and route selection depends on covariates such as temperature, flow, or water velocity that vary within and among years
- The trade-offs between faster migration rates as a possible predator avoidance mechanism within the Delta, and slower migration rate as a growth opportunity that may reduce predation in estuarine and ocean environments

Future studies and analyses to help address these areas of uncertainty are likely to depend on a stronger interdisciplinary team approach to designing experimental studies and associated biological and physical data collection and analysis. For example, refining hydrodynamic simulation models for use in biological applications will require additional modeling and statistical analyses to accurately predict water velocities and flow direction at the specific time and location in the channel when an acoustic-tagged juvenile salmonid encounters a channel junction. This refinement is needed to better understand the mechanisms through which local hydrodynamic conditions affect juvenile salmonid route selection (Appendix B). Hydrodynamic simulation models that have been calibrated and validated against field velocity and flow measurements could be linked to models that predict fish migration behavior and route selection. The fish migration behavior and route selection models could be based on individual fish, or comprise part of a larger lifecycle salmonid model, and used as a decision tool to investigate the effects of export management and other non-export-related actions on juvenile salmonid migrations.

Also, there is currently no broad scientific agreement on flow or velocity thresholds that affect salmon migration rate within a channel or salmon migration behavior at all channel junctions. Outside of the North Delta, it is not currently possible to predict how specific changes in flow and velocity resulting from export operations impact migration rates or route selection. AT studies have not shown strong relationships between exports and route selection under the conditions tested. Exports, velocities, and flows may be linked at some locations such that determining relative effects among these variables will be difficult. Through further refinement of reach-specific results of AT studies, in combination with refinements to the hydrodynamic simulation models and associated juvenile salmonid migration and lifecycle models, new insights are expected into the relationships between changes in channel velocity and flow at a channel junction, the incremental contribution of exports, tides, and river flow on velocities and flows, and the corresponding route selection of juvenile fish in the central and South Delta. Results of these types of analyses will help develop a better understanding of the magnitude of changes to hydrodynamic conditions that subsequently affect route selection.

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