EFFECTS OF WATER PROJECT OPERATIONS ON JUVENILE SALMONID MIGRATION AND SURVIVAL IN THE SOUTH DELTA

Volume 1: Findings and Recommendations

Prepared for:
Collaborative Adaptive Management Team

Prepared by:
Salmonid Scoping Team

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SALMONID SCOPING TEAM

This report has been prepared through a collaborative process involving technical experts participating on the Collaborative Adaptive Management Team (CAMT) Salmonid Scoping Team (SST). SST participants contributing to the report include John Ferguson (Co-chair), Anchor QEA, LLC; Chuck Hanson (Co-chair), Hanson Environmental, Inc.; Mike Schiewe (Co-chair retired), Anchor QEA, LLC; Pat Brandes, U.S. Fish and Wildlife Service; Rebecca Buchanan, University of Washington; Barbara Byrne, National Marine Fisheries Service; Sheila Greene, Westlands Water District; Brett Harvey, California Department of Water Resources; Rene Henery, Trout Unlimited; Joshua Israel, U.S. Bureau of Reclamation; Daniel Kratville, California Department of Fish and Wildlife; Michael Harty, Kearns & West; Joe Miller, Anchor QEA, LLC; Meiling Roddam, National Marine Fisheries Service[1]; and Briana Seapy, Kearns & West.

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[1] Currently with State Water Resources Control Board

EXECUTIVE SUMMARY

Key information developed by the Salmonid Scoping Team (SST) and presented in Volumes 1 and 2 is summarized below under three categories: findings and gaps, areas of technical disagreement, and recommendations. The report presents results of a collaborative scientific compilation and review of information: 1) primarily related to the application of hydrodynamic simulation models used to assess local and regional changes in flow direction and water velocities in Delta channels that are affected by river inflow, water project exports, and tides; 2) juvenile salmonid migration behavior including migration rate and route selection based on tracking tagged juvenile Chinook salmon and steelhead in the Delta and scientific literature from other basins; and 3) the survival of juvenile Chinook salmon and steelhead as they migrate downstream through the lower San Joaquin River and central and south regions of the Delta. The assessment of information focused primarily on the effects of water project operations on Delta hydrodynamics and juvenile salmon and steelhead migration and survival in the lower San Joaquin River and Delta. Survival data for juvenile Chinook salmon were based on results of both coded-wire tag (CWT) and AT studies. Volume 2 presents responses to eight management questions posed by CAMT. It is important to note that the review was guided by a narrow scope assigned by CAMT that was focused on specific regions within the Delta, hydrodynamic drivers, and outcomes (Volume 1, Section 1.2).

Given the limited scope, some potentially important factors were not reviewed at all or in detail due to time or resource constraints; for example: 1) fry and juvenile rearing conditions upstream of the Delta that affect juvenile growth, health, condition, size at Delta entry, and survival; 2) a broader consideration of migration and survival on the Sacramento River and changes in hydrodynamic conditions in the north Delta; 3) a broader suite of factors thought to contribute to stress and mortality within the Delta; and 4) a broader suite of potential data gaps, findings, and recommendations for actions to benefit salmonids upstream and within the Delta. These factors were considered to be outside the limited scope of this review. The SST believes that expanding the assessment of factors affecting juvenile salmonid migration behavior and survival through the Delta and any associated research will be critical to advancing our understanding of how to improve survival and salmonid population abundance.

KEY FINDINGS AND GAPS

The key findings reflect information that emerged from, or was supported by, the literature review and analysis undertaken by the SST in the course of preparing Volumes 1 and 2. Key findings were typically characterized as having a medium or high basis of knowledge and were judged by the SST as being critical to our understanding of salmon and steelhead survival in the Delta, in the context of hydrodynamic conditions and export operations. Key data gaps reflect areas within the scope of the SST's review where the basis of knowledge was typically low or minimal. The SST placed an emphasis on gaps that, if filled, would likely improve our understanding and inform our ability to more effectively manage water project operations and hydrodynamic conditions for improved salmonid survival. The methodology used to rate basis of knowledge is described in Section 2.4.

The findings and gaps below refer to juvenile Chinook salmon and steelhead migrating through the Delta (i.e., not rearing). For through-Delta survival, San Joaquin River-origin Chinook salmon (fall-run) are discussed separately from Sacramento River-origin Chinook salmon (fall-, late-fall, spring-, and winter-run) because they experience different geography and environmental conditions (including hydrology), and steelhead are discussed separately from Chinook salmon.

It is important to emphasize that while gaps exist, results of previous survival and hydrodynamic model studies have yielded important information on geographic and temporal trends in survival and how physical conditions in the Delta may change with inflow, tides, and exports. This information constitutes a substantial body of scientific information to build upon when addressing fish and water management priorities by refining and expanding the experimental design and statistical analyses of future salmonid survival studies.

THROUGH-DELTA SURVIVAL

Through-Delta survival has been consistently low for San Joaquin River Chinook salmon, and more variable for Sacramento River Chinook salmon; survival data are limited for steelhead.

SAN JOAQUIN RIVER FALL-RUN CHINOOK SALMON

Findings

- Survival has been low (less than 0.2 [i.e., less than 20%] since 2002). For example, through-Delta survival has been less than or equal to 0.05 for 14 of 22 estimates, and less than or equal to 0.10 for 20 of 22 estimates, since 2002 (Appendix E, Figure E.2-3). Prior to 2002, juvenile Chinook salmon survival rates were typically higher in high flow years (1995, 1997, 1998, and 1999).
- Since 2002, through-Delta survival has been low (less than 0.2) even in higher flow years (2006, 2011) (Appendix E, Figure E.2-3), which is not consistent with results of earlier survival studies showing evidence of increased juvenile survival as Delta inflows increased during the migration period.
- In the South Delta, survival has been low in all routes since 2008 (Appendix E, Figure E.4-3), which is not consistent with results of the majority of earlier CWT survival studies that indicated higher survival for those migrating juvenile salmon that remained in the San Joaquin River at the head of Old River when compared to those that entered Old River at that location.
- Survival from the export facilities to Chipps Island via salvage and trucking was higher from the Central Valley Project (CVP) than the State Water Project (SWP), with a primary difference being the Clifton Court Forebay (CCF) in the SWP route (Appendix E, Figure E.4-7, Table E.4-3). Although validation of the assumption of lower pre-screen losses at the CVP

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intake compared to the SWP intake is needed, these results support a recommendation for preferential export operations using the CVP intake to benefit salmonids.

- The survival rate per kilometer from the CVP to Chipps Island via salvage was sometimes higher than the survival rate through the lower San Joaquin River reaches, but was low in absolute terms.

Gaps in Information

- Many drivers for low through-Delta survival have been hypothesized, but the role of each has not been quantified. Hypothesized factors contributing to the observed low Delta survival include increased abundance and increased metabolic rate of predatory fish such as striped bass and largemouth bass in the Delta, water project operations affecting the magnitude and timing of flow resulting in increased juvenile salmonid predation mortality, changes in Delta habitat including expansion of non-native submerged aquatic vegetation, increased water clarity, potential exposure to contaminants, and other factors. The potential contribution of these factors to salmonid mortality supports a stronger focus on investigating the mechanisms underlying salmonid mortality in different regions of the Delta and their link to water project operations (see Section 3; Appendix E, Figure E.1-1, Table E.1-1).
- Collection and analysis of data on migration and survival of acoustic-tagged Chinook salmon released in the San Joaquin River is ongoing; survival estimates have been calculated through 2012. Additional data through 2016 will be compiled and analyzed to investigate various hypotheses over observed conditions such as potential relationships between flows and export rates and survival, as well as route selection and migration rate within various regions of the lower river and Delta. Other analyses can also be done and support our recommendation to continue studies and do additional data analyses and assessment. However, because these studies were observational in nature, and were not designed to test these hypotheses, the findings from such analyses will be limited and will not obviate the need for future investigations.

SACRAMENTO CHINOOK SALMON

Findings

- Survival among release groups has been variable across years and among populations. For example, in 2013 and 2014, through-Delta survival was estimated at 0.32 to 0.35 for hatchery winter-run Chinook salmon, 0.00 to 0.30 for hatchery spring-run Chinook salmon, and 0.00 for hatchery fall-run Chinook (based on data from only one release group in 2014), whereas between 2006 and 2010, late-fall-run Chinook had through-Delta survival estimates ranging from 0.17 to 0.64 (Appendix E, Section E.2.1, Table E.2-2).

Gaps in Information

- Data for some populations (e.g., winter-run, spring-run) are more limited than for other populations (e.g., late-fall-run). The majority of experimental survival studies conducted to date have been performed using hatchery-produced fall-run and late-fall-run Chinook salmon. Acoustic survival studies using hatchery-produced winter-run Chinook salmon have been initiated only in the last four years. Little information is available on survival of wild

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salmonids or on the applicability of hatchery-produced salmonids as a representative surrogate for wild stocks. Little information is currently available on the primary drivers for differences in survival between populations; however, more is being learned about the role of environmental conditions on survival, the role of route selection (e.g., mainstem versus interior Delta routes) and migration timing and behavior on survival, and other factors affecting survival of different stocks in the Sacramento River and Delta (Appendix E, Section E.2.1, Table E.2-1, Table E.2-2).

STEELHEAD

Findings

- Based on data from 2011 and 2012, survival of acoustic-tagged juvenile steelhead migrating from the San Joaquin River (0.32 to 0.54) has been greater than that of fall-run Chinook salmon from the same years (0.02 to 0.03) (Appendix E, Section E.2.1, Table E.2-3).
- Based on data from 2009 and 2010, survival of acoustic-tagged juvenile steelhead migrating from the Sacramento River (0.47 to 0.58) has been comparable to estimates of Sacramento River late-fall-run Chinook salmon survival from the same years (0.34 to 0.64) (Appendix E, Section E.2.1, Table E.2-2).

Gaps in Information

- For both San Joaquin River and Sacramento River steelhead, relatively few data are available on survival through the Delta compared to Chinook salmon (collection and analysis of San Joaquin River steelhead data is ongoing; survival estimates have been calculated for 2011 through 2012, and will be available for 2013 through 2016). Survival estimates for juvenile steelhead migrating downstream in the Sacramento River are available for several years but do not represent a wide range of environmental conditions.

FISH SIZE

Multiple lines of evidence indicate smaller fish respond to conditions differently and usually experience lower survival than larger fish.

Findings

- Studies of juvenile fishes undertaken to develop an estimate of handling and trucking mortality found that for Chinook salmon, mortality during holding and trucking was greater (2% mortality) for juvenile Chinook salmon less than 100 millimeters (mm) than for salmon greater than 100 mm (0% mortality; Appendix E, Section E.3.2.1).
- Based on CWT fall-run Chinook salmon released in the Delta, fish size was found to be a stronger indicator of ocean recovery rates than were hydrologic variables (inflow, exports), based on analyses by Zeug and Cavallo (2013) (Appendix E, Section E.6.2.1).
- In the two years with survival data for both Chinook salmon and steelhead from the San Joaquin River, the steelhead were both larger than the Chinook salmon and had higher survival; it is unclear the extent to which fish size was the primary driver of the differences in

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survival versus other variables (e.g., species) (Appendix E, Section E.2.1, Figures E.2-3 and E.2-4, Table E.2-3).

- AT studies in the Sacramento River have found higher through-Delta survival for larger fish (Appendix E, Section E.9.2.1). Perry (2010) found a significant relationship between acoustic-tagged late-fall-run Chinook salmon and survival in the Sacramento River mainstem and Sutter and Steamboat sloughs. Newman (2003) found a positive relationship between fish size and through-Delta survival for CWT fall-run Chinook salmon migrating from the Sacramento River.
- Louver efficiency experiments show a non-monotonic (i.e., not strictly increasing or strictly decreasing) relationship between Chinook salmon size and efficiency (Appendix E, Section E.3.2.1).
- Shorter through-Delta travel times of San Joaquin River fall-run Chinook salmon were observed with increasing smolt size based on CWT fish (Appendix D, Section D.4); however, despite Chinook salmon being smaller than steelhead, migration rates (e.g., kilometers per day) of acoustic-tagged Chinook salmon released into the San Joaquin River in 2011 and 2012 were approximately twice that of steelhead (Appendix D, Section D.5.2). Average travel time between Durham Ferry and Chipps Island for steelhead in 2011 (276.7 mm fork length [FL]) was 11.08 days (SE = 0.12 days) while travel time for juvenile fall-run Chinook salmon (110.8 mm FL) was 3.02 days (SE = 0.27 days). In 2012 steelhead (233.6 mm FL), travel time was 9.41 days (SE = 0.25 days) compared to juvenile salmon (112.8 mm FL) travel time of 5.75 days (SE = 0.41 days).

Gaps in Information

- Existing tagging data do not represent the full range of sizes of wild fish because of tag burden concerns (i.e., tags are too large for smaller fish).
- The survival effect of differences in salmon and steelhead size for fish reared in the hatcheries compared to wild fish is uncertain.
- Our scope focused primarily on migrating juvenile salmonids, and we did not review information on how rearing fry or parr respond to hydrodynamic factors such as water velocity (Appendix D, Section D.4).

PROJECT EFFECTS

Water export operations contribute to salmonid mortality in the Delta via direct mortality at the facilities, but direct mortality does not account for the majority of the mortality experienced in the Delta; the mechanism and magnitude of indirect effects of water project operations on Delta mortality outside the facilities is uncertain.

Findings

- Direct mortality (at the facilities) is a combination of pre-screen and within-facility mortality (including mortality during salvage and transport), and entrainment into the pumps and water conveyance canals (Appendix E, Section E.3.2.1).

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- There is a large amount of indirect evidence of predation within the facilities including pre-screen losses in CCF, within the salvage facilities, and at release sites in the Delta (Appendix E, Section E.3.2.1). Predatory fish have been observed near and within the water project facilities, and juvenile salmon and steelhead have been collected from predator stomach samples. Additional indirect evidence includes results of mark-recapture experimental studies within CCF for both salmon and steelhead, observations of predator movement and behavior from AT studies, and observations of stationary ATs in and near the facilities thought to have been defecated by predatory fish. Indirect evidence of predation mortality associated with water project facilities and elsewhere in the Delta channels supports recommendations for reducing predation; however, such reductions should be paired with actions to improve survival in the Delta upstream of the facilities, to yield substantial increases in survival through the Delta.
- Despite implementing actions within the reasonable and prudent alternative (RPA) intended to reduce through-Delta mortality, through-Delta survival remains low (Appendix E, Section E.2, Figure E.2-3, Tables E.2-2 and E.2-3).
- Hydrodynamic monitoring and simulation modeling indicate that exports have the greatest effect on flow and velocity in the region of the Delta nearest the export facilities (Appendix B, Section B.5).
- Results of studies show that route selection is generally proportional to the flow split at channel junctions, and the effect of exports on route selection is strongest at the junction leading directly to the export facilities (i.e., head of Old River). Results of juvenile Chinook salmon survival studies using CWT and more recently (2008, 2010, 2011, and 2012) ATs have not shown a strong or consistent relationship with SWP and CVP export rates. Steelhead data are limited to only 2011 and 2012; additional data through 2016 are being analyzed for both salmon and steelhead. Survival rates for juvenile salmon since 2002 have been consistently low independent of variation in both export rates and Delta inflows.

<u>Gaps in Information</u>

- Additional analyses are needed to investigate the expected change in salmonid route selection and subsequent survival from changes in export rates (Appendix D, Section D.8).
- The evidence of a relationship between exports and through-Delta survival is inconclusive; the key findings presented in this table are supported by medium or high basis of knowledge, but our basis of knowledge on the relationship between exports and through-Delta survival is low (Appendix E, Section E.6.2.1). Since 2002, juvenile fall-run Chinook salmon survival in the south Delta has been consistently low despite restriction of export rates. Survival rates for acoustic-tagged juvenile steelhead are currently available only for two years (2011 and 2012), which are insufficient to support an analysis of the potential relationship between export rate and survival. Analysis of additional AT data for 2013 through 2016 will help further assess potential relationships for both salmon and steelhead.

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Water export operations contribute to salmonid mortality in the Delta via direct mortality at the facilities, but direct mortality does not account for the majority of the mortality experienced in the Delta; the mechanism and magnitude of indirect effects of water project operations on Delta mortality outside the facilities is uncertain.

- Estimates of entrainment mortality at the export facilities from salvage counts depend on pre-screen mortality, but data on the magnitude and variability of pre-screen mortality are unavailable at the CVP (Appendix E, Section E.3.2.1).
- There is uncertainty in the spatial and temporal variability in predation pressure and how predation pressure responds to changes in water project operations and associated habitat changes (Appendix E, Sections E.3.2, E.3.3, E.4.2.5, and E.4.3). Based on current AT technology, it is difficult to determine when, where, and if a juvenile salmonid has been preyed on within a reach of the Delta. How water project operations affect Delta flows and velocities, physical structures, and habitat conditions that in turn affect both predators and prey warrants further investigation.
- The contribution of water project operations to the total mortality of juvenile salmonids has not been quantified. Many of the mechanisms through which changes in Delta hydrodynamics and other factors related to water project operations may contribute to salmonid mortality (e.g., change in vulnerability to predation in Delta channels or change in migration routing as a result of water project operations) are uncertain.
- Estimates of direct mortality (e.g., mortality resulting from pre-screen losses and losses at the louver and salvage facilities, which are directly related to water project export operations) have been developed from CWT data by several authors and show, in general, that the magnitude of direct loss (e.g., percentage of a marked release group observed in fish salvage) is typically low for juvenile Chinook salmon (typically less than approximately 1%). However, such estimates do not include export-induced mortality prior to entering the facilities that is indirectly related to water project operations (e.g., mortality resulting from project related changes in habitat). Estimates of direct facility mortality as a proportion of total migration mortality have been as high as 5.5% for winter-run Chinook salmon and 17.5% for Chinook salmon released in the San Joaquin River (Zeug and Cavallo 2014).
- It is unknown whether equivocal findings regarding the existence and nature of a relationship between exports and through-Delta survival is due to the lack of a relationship, the concurrent and confounding influence of other variables, or the effect of low overall survival in recent years. These data gaps support a recommendation for further analysis of available data, as well as additional investigations to test hypotheses regarding export effects on migration and survival of Sacramento and San Joaquin River origin salmonids migrating through the Delta.

PHYSICAL CONDITIONS

The Delta is a complex and dynamic environment, and the relative influence of tides, inflow, and exports on hydrodynamic conditions (flow and velocity) varies temporally and spatially throughout the Delta. Project operations affect physical conditions in the Delta through various ways including Delta inflows, exports, and gate and barrier operations.

Findings

- The major rivers in the South Delta (San Joaquin, Old, and Middle) transition from a riverine environment to a tidally dominated environment in the Delta (Appendix B, Figure B.1-2).
- The hydrodynamic effect of increases in Delta inflow on flow and velocity in the South Delta is greatest at the upstream reaches of the major rivers, diminishes with distance downstream through the Delta or away from the mainstem rivers (i.e., into the interior Delta), and is affected by barriers, tidal phase, and exports (Appendix B, Figures B.5-1 through B.5-7 and B.5-13 through B.5-17).
- The hydrodynamic effect of exports on flow and velocity in the South Delta is strongest in Old River at the export facilities, in Middle River at Victoria Canal and the downstream end of Railroad Cut, and at Columbia Cut, and is affected by tidal phase, Delta inflow, and barriers (Appendix B, Figures B.5-1 through B.5-8 and B.5-13 through B.5-17).
- The effect of tides decreases with distance up mainstem rivers, and the tidally dominated region varies with Delta inflow, exports, and tidal phase (Appendix B, Figures B.5-1 through B.5-7).
- Hydrodynamic models were developed for water project planning and have typically been used for long time scales (e.g., daily) and large geographic areas (e.g., San Joaquin River flow routing).
- The application of current hydrodynamic simulation models to predictions of flow and velocity at South Delta channel junctions when encountered by migrating salmonids at specific times (i.e., on short time scales and small geographic areas) may not be reliable (Appendix B, Section B.3; Appendix C, Pages C-14 through C-163).
- The Delta Simulation Model 2 (DSM2) may be useful for assessing how exports from the South Delta, river inflows, barriers, and tides can influence the magnitude, duration, and direction of water velocities and flows within channels, depending on its accuracy relative to validation for specific areas and time scales. However, 15-minute velocities and flows estimated from DSM2 have been found to vary substantially from measured conditions and timing related to tidal conditions (Appendix C, Pages C-14 through C-231) and were not found to be accurate for assessing fish fates and behaviors at specific times and locations which would require direct measurement of flows in the field, or the application of simulation models depending on the temporal and spatial resolution needed to support analyses of specific hypotheses or management questions.
- Model validation analysis conducted for this report concluded that: 1) some locations of the South Delta validate better than others; 2) validation quality at Turner Cut varied over a period of several years; 3) validation at high inflows was poorer than at lower inflows; 4) validation was better at the daily average time step compared to the 15-minute instantaneous time step; and 5) validation using RMA 2-D was better than DSM2 on average (Appendix B, Sections B.3.1.5 and B.3.1.6; Appendix C, Pages C-14 through C-163).

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- The application of hydrodynamic models to fish behavior requires calibration and validation at appropriate temporal and spatial scales (Appendix B, Section B.3; Appendix C, Pages C-14 through C-163).
- Results of limited analysis of AT data indicate that juvenile Chinook salmon migration rate slowed in areas of the Delta with bi-directional tidal velocity compared to upstream riverine reaches with uni-directional flows (Appendix D, Section D.6). No analyses were found on a potential relationship between water project exports and juvenile salmonid migration rates within the Delta, although data are available from recent AT studies that could be used to test hypotheses related to effects of riverine flow and export rates on reach-specific migration rates.

Gaps in Information

- Model calibration and validation can be limited by insufficient data on factors such as: 1) Delta Consumptive Use; 2) South Delta bathymetry; 3) Clifton Court inflow; and 4) monitoring station calibration.
- Further model refinements and validation are needed at temporal and spatial scales appropriate for use in analysis of salmonid migration.
- The magnitude of change in flow, water velocity, or water quality needed to elicit a behavioral or survival response by migrating juvenile salmonids has not been determined.
- The specific behavioral mechanisms underlying the slowing of migration rates in tidally influenced areas are uncertain. Selective tidal surfing behavior has been hypothesized as a mechanism supporting juvenile salmonid migration through the tidal region of the Delta, but requires further analysis and investigation (Appendix D, Section D.6).

MANAGEMENT ACTIONS

- Gates and barriers influence fish routing away from specific migration corridors.
- The relationship between San Joaquin River inflow and survival is variable, and depends on barrier status and region of the Delta.
- The extent to which management actions such as reduced negative Old and Middle River (OMR) reverse flows, ratio of San Joaquin River inflow to exports (I:E), and ratio of exports to Delta inflow (E:I) affect through-Delta survival is uncertain.

FINDINGS

General

- Spatial variability in the relative influence of Delta inflow and exports on hydrodynamic conditions means that high inflow or I:E, and low exports or E:I, may differentially affect fish routing and survival in different Delta regions (Appendix B, Section B.5; Appendix E, Sections E.6 and E.2.3).

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- Uncertainty in the relationships between I:E, E:I, and OMR reverse flows and through-Delta survival may be caused by the concurrent and confounding influence of correlated variables, overall low survival, and low power to detect differences (Appendix E, Section E.2.3).
- Juvenile salmonid migration rates tend to be higher in the riverine reaches and lower in the tidal reaches (Appendix D, Sections D.3. and D.6; Appendix E, Section E.5, Figure E.5-1).

<u>San Joaquin River</u>

- <u>Barriers:</u> A barrier at the head of Old River reduces steelhead and Chinook salmon entrainment into the heads of OMR migration corridors. Historically, through-Delta survival of CWT juvenile fall-run Chinook salmon was estimated to be higher for those salmon using the San Joaquin River migration corridor, indicating, on average, a survival benefit associated with the spring installation of the Head of Old River Barrier (HORB); however, data from recent (2010 through 2012) AT studies have shown that survival has been equally low through all routes for Chinook salmon (Appendix D, Section D.11; Appendix E, Section E.4.2.1). The mechanisms affecting changes in juvenile survival among south Delta migration routes and factors that may have changed that earlier relationship in recent years remain uncertain and warrant further investigation.
- <u>Inflow</u>: Higher Delta inflow from the San Joaquin River is associated with increased survival in the San Joaquin River to Jersey Point when the HORB is in place; however, under low-flow conditions survival can be low even with the barrier in place (Appendix E, Section E.8, Figure E.8-2).
- <u>Inflow</u>: Higher San Joaquin River flow is associated with higher Chinook salmon survival to the Turner Cut junction but the effect does not always result in higher through-Delta survival because of mortality in downstream reaches (Appendix E, Section E.8, Figure E.8-1).
- <u>I:E</u>: The relationship between Delta survival of San Joaquin River Chinook salmon and I:E is variable but generally positive for lower I:E values (e.g., I:E less than 3) (Appendix E, Section E.11, Figure E.11-1). Results of these studies are confounded by the use of flow ratios since the same I:E ratio can represent different absolute flow and export rates. These results are further confounded by installation and operations of various South Delta barriers. Data are available from only two years of AT studies using steelhead (Appendix E, Section E.11-4).
- <u>Exports:</u> There was a weak positive association between the through-Delta survival of San Joaquin Chinook salmon and combined exports using the CWT data set, but comparisons are complicated by the correlation between exports and San Joaquin River inflow (Appendix E, Section E.6.2.1).

<u>Sacramento River</u>

- <u>Gates</u>: Closure of the Delta Cross Channel (DCC) gates can increase through-Delta survival by reducing the risk of juvenile salmonids migrating into the interior Delta from the Sacramento

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River; however, on flood tides at low flows, similar numbers of salmon can be diverted into the interior Delta through Georgiana Slough alone (Appendix D, Section D.12).

- Inflow: Increased Delta inflow from the Sacramento River is associated with increased through-Delta survival for Chinook salmon migrating from the Sacramento River (Appendix E, Section E.9.2.1).
- E:I: Statistical analyses suggest a weak but generally negative effect of increased E:I on survival of Sacramento River fall-run Chinook salmon, but not for late-fall-run Chinook salmon (Appendix E, Section E.10). Survival data are not available to assess potential relationships between E:I and survival for winter-run or spring-run Chinook salmon or steelhead. Uncertainty in the relationship between E:I and survival may be caused by the confounding influence of correlated variables and low power to detect differences (Appendix E, Section E.2.3).

GAPS IN INFORMATION

General

- The effects of OMR reverse flows on salmonid survival and route selection in the Delta (outside of the facilities) have had limited analysis. Data are available from the AT migration and survival studies, as well as earlier CWT data, that might be used in analyses of potential relationships between OMR reverse flows and juvenile salmonid survival. Relationships between OMR reverse flows and migration route and migration rate, as well as reach-specific and regional survival, could be tested using AT data from both Chinook salmon and steelhead.
- The relationships between water project operations and survival on various spatial and temporal scales are poorly understood. The detailed information generated from the recent salmon and steelhead AT studies, in combination with refinements in the application of hydrodynamic simulation models to fishery analyses in the Delta, offers the opportunity to conduct additional analyses at a finer spatial and temporal resolution than before; however, more data will be needed to understand patterns over a variety of conditions.

San Joaquin River

- Results of early CWT survival studies conducted using juvenile fall-run Chinook salmon released into the lower San Joaquin River downstream of Old River, and into Old River, showed evidence of higher survival to Jersey Point for those fish that migrated downstream in the San Joaquin River mainstem compared to fish migrating through Old River. Results of limited AT data from 2010 to 2012 showed evidence of equally low survival independent of route selection at the head of Old River. Reach-specific survival estimates with the HORB in place are available only for one year (2012) for both fall-run Chinook salmon and steelhead, although more recent data from 2014 to 2016 (all with the HORB in place for Chinook salmon and some of the steelhead releases) have yet to be analyzed. Further analysis of the available AT data and additional experimental studies to examine the mechanisms affecting juvenile

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- Gates and barriers influence fish routing away from specific migration corridors.
- The relationship between San Joaquin River inflow and survival is variable, and depends on barrier status and region of the Delta.
- The extent to which management actions such as reduced negative Old and Middle River (OMR) reverse flows, ratio of San Joaquin River inflow to exports (I:E), and ratio of exports to Delta inflow (E:I) affect through-Delta survival is uncertain.

salmon and steelhead survival for those fish migrating downstream in the San Joaquin River mainstem and those entering Old River are needed to assess the potential biological benefits of influencing migration route selection through installation of the HORB in South Delta channels.

- Because few observations of salmon migration survival are available for higher I:E values (e.g., I:E greater than 5), higher San Joaquin River inflow levels (e.g., Vernalis inflow greater than 10,000 cubic feet per second [cfs]), and higher export levels (e.g., combined export rate greater than 5,000 cfs), the variability in survival under these higher levels of I:E, inflow, and exports is not well-characterized (Appendix E, Sections E.2.3 and E.11).
- <u>Exports</u>: Data on potential relationships between San Joaquin River inflow and exports on migration and survival of acoustically tagged juvenile salmon and steelhead are limited to just a few years and environmental conditions; therefore, firm conclusions cannot be made from the AT data sets for San Joaquin Chinook salmon or steelhead (Appendix E, Section E.6.2.1).

CONSTRAINTS ON UNDERSTANDING

Current understanding of juvenile salmon and steelhead survival in the Delta is constrained by a variety of factors (as listed below).

<u>Findings</u>

- The nature of the I:E and E:I metrics as ratios makes it challenging to test their effects, since different sets of physical conditions may be represented with the same I:E or E:I value (e.g., both high and low inflow conditions may be associated with the same I:E value, depending on exports).
- Determining the effectiveness of management operations such as I:E, E:I, and OMR reverse flow restrictions is difficult when all observations are in the presence of those restrictions (i.e., there is no control condition to compare to the experimental condition) (Appendix E, Section E.13). Development of future experimental designs would need to consider increased operational flexibility and/or alternative approaches to the experimental design to test a range of prescribed water project operational conditions.
- There has been low variability and little replication in conditions during recent tagging studies, in particular San Joaquin River inflow and exports. Most observations of smolt survival have been at low levels of both inflow and exports, in part as a result of recent drought conditions. Furthermore, it is not possible to test the effects of changes in conditions in the absence of variability in those conditions (Appendix E, Section E.2.3). Developing the future experimental design for salmonid monitoring would need to consider prescribing flow and export conditions extending over a wide enough range to detect biological responses if such relationships exist.

CONSTRAINTS ON UNDERSTANDING

Current understanding of juvenile salmon and steelhead survival in the Delta is constrained by a variety of factors (as listed below).

- Low overall survival makes it difficult to detect changes in survival, both in general and in response to changes in management operations (Appendix E, Section E.13).
- Hydrodynamic models are developed and calibrated for specific locations, time periods and time scales, and study questions; application of simulation models for other uses (e.g., using the reviewed models in the South Delta or on the scale of fish response) is dependent, in part, on the specific hypotheses and management questions being evaluated and the resolution and accuracy needed in model predictions to support the analysis (Appendix B, Section B.3).
- Disparity between current hydrodynamic models and measurements of hydrodynamics data (flow and velocity) at key locations in the Delta (e.g., Turner Cut, Frank's Tract) limits our ability to detect patterns between changes in velocities and flows and changes in salmon survival and behavior from AT observations (Appendix C, Figures 18 through 20 and 24 through 29). Further model calibration and validation and refinements to model parameters is expected to advance the application of these models in support of fishery analyses.
- Salmon likely respond to changes in water velocities rather than to changes in flow, but hydrodynamic modeling results show larger disparities between modeled and measured conditions for velocity than for flow (Appendix C, Pages C-14 through C-163).

Gaps in Information

- Understanding the effects of water project operations on route selection and through-Delta survival of juvenile salmonids may require additional statistical analysis of route-specific survival, hydrodynamics, habitat complexity, and environmental variability. Completing the analysis of AT data through 2016 will provide the foundation for more statistical analyses using multivariate approaches involving a number of physical and biological covariates for hypothesis testing.
- Modeling of the potential biological response of particular water project operation actions has not been done (hypothetical examples of measurable objectives include: reduce migration into the Interior Delta through Turner Cut by 50%, increase juvenile survival in the South Delta to an average of 30%), which limits our ability to make short-term action recommendations that are predicted to achieve a specific biological objective and to evaluate the performance of the action in achieving the desired effect.
- Further analysis is needed to assess which hydrodynamic models best represent observed hydrodynamic or water quality changes caused by water operation decisions or other management actions, on the scale of fish perception and response; the calibration and validation of the appropriate spatial and temporal scales for biological application needs additional refinement.
- Several potential problems (gaps) have been identified in the literature relative to hydrodynamic model calibration in the South Delta, including representation of the CCF operations, South Delta bathymetry data, Delta Island Consumptive Use data, high inflow conditions, and challenges associated with estimating Delta outflow. Further refinement of hydrodynamic simulation models and their application to assessing salmonid migration and survival will improve the technical foundation for evaluation of the performance of management actions.

TECHNICAL DISAGREEMENTS

SST members agree with the key findings and gaps presented in the tables above. Technical disagreements about the characterization of information are identified in Volumes 1 and 2 and are summarized below.

Volume 1

- There was not consensus in the SST regarding the definition and application of the basis of knowledge. The basis of knowledge review rated peer-reviewed publications higher than agency or contract reports. While the assumption was made that peer-reviewed articles have more robust information, it was noted that agency reports and peer-reviewed articles can have varying degrees of robustness, the assumption is not likely true for all peer reviewed articles, and agency reports can also be peer reviewed. Furthermore, agency reports may provide better and more specific information relative to the questions we are asking and this is not reflected in the basis of knowledge definition or applications. At least one SST member felt that similar results from multiple agency reports should be rated higher than a medium basis of knowledge. Despite differences in the interpretation of weighting to be given to various sources of information among the SST, the body of scientific information available, including agency reports, peer-reviewed journal publications, discussions with technical experts, and data analyses prepared by the SST as part of preparing the gap analysis, were all used in developing findings and recommendations presented in this report.
- There was a disagreement within the SST about whether the analysis of ocean recovery rates of CWT fish (i.e., the Zeug and Cavallo [2013] analysis) is informative for Delta survival because ocean recovery rates combine Delta survival with ocean survival and incorporate assumptions about fishing effort between years. Some SST members believe that the joint probability of Delta survival and ocean survival is pertinent, although not conclusive, to Delta survival (Appendix E, Section E.6.2).
- There was disagreement within the SST about whether there is a relationship between exports and the relative survival associated with the Interior Delta route compared to the Sacramento River mainstem route, based on modeling by Newman and Brandes (2010). Some SST members believe that, despite the indeterminacy in model selection, a potential effect of exports was demonstrated (Appendix E, Section E.6.2.1). The disagreement was based, in part, on model selection that identified that relative Interior Delta survival was similarly predicted with models that did not include exports, based on the low samples sizes available.
- There was a disagreement within the SST about providing short-term recommendations for actions to improve salmonid survival at this time, noting that no modeling or analysis has been conducted to assess potential benefits to salmon or steelhead from these actions and that a more systematic process of evaluation of alternatives and priorities should precede any recommendations for actions. Some on the SST felt that the prolonged low levels of juvenile salmon survival in the South Delta warrant immediate action.

Volume 2

- There was a disagreement within the SST over whether the data provided in Volume 2 support the conclusion that improved protection of Sacramento River salmonid populations would result if the onset date of OMR reverse flow management were triggered by detection of migrants at monitoring stations located on the Sacramento River upstream of distributary junctions leading toward the San Joaquin River. Results of salmonid monitoring in the Sacramento River and San Joaquin River have shown that the seasonal timing of Delta entry for juvenile Endangered Species Act (ESA)-listed salmonids varies among years. The January 1 onset of OMR flow management coincides with the presence of winter-run Chinook salmon in most years, spring-run Chinook salmon in many years, and steelhead in some years. Some SST members conclude that although not capturing all of the seasonal variation in juvenile movement, the January 1 trigger date provides a general approximation of the migration timing during the winter months, and, based on its simplicity for triggering management actions, has utility (Management Question 3).
- In Volume 2, there is a statement that limiting OMR reverse flow to -5,000 cfs is effective at preventing increased routing into the Interior Delta, presumably resulting in increased survival. There was a disagreement over whether the data provided in Volumes 1 or 2 supported such a statement. Some felt the discussion and conclusion was based primarily on conceptual model predictions and reasoning, not on factual analysis (Management Question 3).
- There was a disagreement within the SST about the statement that short-term restrictions of exports resulting in OMR reverse flows more positive than the -5,000 cfs may do little to improve through-Delta survival for Chinook salmon due to low overall survival. The disagreement was that, since we have no evidence of the effects of OMR reverse flow restrictions on survival, we have no evidence that the continued OMR reverse flow restrictions will affect survival (Management Question 4).
- There was a disagreement within the SST about presenting the hypothesis that the influence of exports on habitat may have a stronger effect on survival than that of short-term hydrodynamic changes related to exports, since the argument is based on reasoning and not data analysis (Management Question 4).
- There was a disagreement within the SST about whether Passive Integrated Transponder (PIT) tags, which have been used extensively in salmonid studies in river systems such as the Columbia River, could expand the available evaluation methodologies; some members believe that, as a result of difficulties in PIT tag detection in larger channels (the PIT tag needs to be in close proximity to the detector to be read), the technology will not provide any better information than is currently available through existing methodologies. Therefore, there was disagreement over whether to recommend that PIT tag technologies be applied to the Delta to facilitate monitoring of biological metrics. The selection and application of specific technologies in future investigations will need to be based, in part, on the nature of the investigation, specific data needs, detection ability, and other factors (Management Question 6).

- There were no areas of formal scientific disagreement among SST members regarding the use of surrogates; however, there is disagreement among scientists in general about the usefulness of performing surrogacy comparisons in situations where only some of the pertinent types of surrogacy can be evaluated. Seven common positions on the use of surrogates are identified (Management Question 8).

RECOMMENDATIONS

The SST has identified the following recommendations for the CAMT to consider. The recommendations provide guidance on how future investigation and research efforts could be focused to build on the existing knowledge base and address key data gaps. They were developed to advance our understanding of the role of factors influencing salmonid survival through the Delta, the role of Delta conditions in salmonid fitness at the individual and population level, and opportunities to improve salmonid population abundance and status through changes to Delta conditions and water project operations.

The recommendations are informed by several overarching observations, as follows:

- The Delta is a very complicated environment in which to study and measure juvenile salmonid survival.
- While much information has been gained using the current approach, numerous key questions remain unresolved and will require new analyses and experimental approaches.
- The Delta should be perceived not as a singular region, but a suite of regions defined by different physical forcing factors. The regions are areas dominated by natural and water project inflow (upper San Joaquin River mainstem), tidal conditions (lower San Joaquin River mainstem and Delta), and exports (South Delta). Results of South Delta survival studies using juvenile Chinook salmon have shown consistently low survival over the past decade. Resolving the low observed juvenile salmonid survival may require different approaches for each region that would be integrated into a single program.
- Resolving the low survival should shift from questions developed by researchers to ones that simultaneously integrate three components: science (what can be tested), management (what needs to be tested), and operations (what can be put into place for testing). This shift in approach would support both observational studies and needed controlled experiments.
- Answering key survival and water project operation questions in the Delta is challenging, and future decisions will have to be made in the face of scientific uncertainty. Therefore, decision-support tools also need to be developed that help characterize risk and uncertainty for managers.

Continue Existing Survival Studies, Monitoring, and Analysis of Data

Discussion: The purpose of this recommendation is to continue and complete the existing analyses of route entrainment, reach survival, predation investigations, and salvage that are under way. Ongoing studies might be adapted as a long-term monitoring and adaptive management plan is developed and implemented. They are needed to provide a foundation for an expanded research program, generate information, and inform near-term management decisions, and complete ongoing research studies to maintain time series information.

Schedule: Ongoing
Management Application: Current studies provide information about through-Delta survival of Chinook salmon and steelhead, and some estimates of reach-specific survival and junction-specific routing under potentially different (but usually not controlled) inflow and export conditions. Continuing to estimate through-Delta survival will provide continuity for time series data needed to assess current status, interannual variability, and long-term trends. Ongoing research on predation is critical to identifying relationships between predator and juvenile behavior, and predator concentrations.

Investigate Short-Term Actions To Improve Salvage Facility Operations

Discussion: The purpose of this recommendation is to determine whether current operations and salvage facilities at the SWP and CVP could be improved to reduce losses to listed and non-listed salmonids entrained into the facilities. The SST understands that a great deal of effort has been directed toward improving the facilities, and facility experts would need to be involved in any future discussions. Suggestions for actions to reduce direct facility mortality based on findings in Appendix E, Section E.3.2.2 include:

- Control predator populations in CCF and behind the CVP trash racks.
- Control secondary louver efficiency by control of bypass water velocities.
- Keep primary and secondary louvers free from debris, but also reduce time when they are inoperable for cleaning.
- Improve salmon passage within the CVP, and decrease predator passage within the CVP.
- Consider alternate truck release locations of salvaged fish to prevent large predator assemblages.
- Verify the assumption that pre-screen losses at the CVP intake are 15% and substantially lower than losses at the SWP.
- Test using the CVP for export instead of the SWP to reduce losses of salmonids in CCF.

Additional suggestions include:

- Test how different CCF radial gate openings affect water inlet velocities and fish entrainment; determine whether water velocity thresholds for entrainment at the gate entrances can be identified based on literature reviews, model studies, and empirical testing; and, if new operations are identified, evaluate whether survival is increased.
- Evaluate filling the scour hole inside the CCF radial gates to reduce predator habitat and predation.
- Review the fish facilities design criteria and compare them to current state and federal design criteria; adjust facility operations or modify facilities to meet the current state and federal criteria if possible. For example, install flow control structures behind CVP louvers to improve efficiency during low export volume operations.
- Review past studies and evaluate whether new fish truck transport release operations, such as the use of net pens and barges, would be effective in reducing post-release mortality.

Schedule: Ongoing

Management Application: The goal of these actions is to reduce the proportion of fish entrained into water project facilities, reduce losses to fish that are entrained within the facilities, and enhance the survival of fish salvaged by improving truck transport and release operations. To the extent possible, responses (e.g., entrainment, mortality) should be measured before and after any modification is implemented to document the effectiveness of the modification.

Develop a Long-term Monitoring, Research, and Adaptive Management Plan

Discussion: A long-term monitoring, research, and adaptive management plan with stable and reliable funding for implementation is needed to fully assess the effects of water project operations and other Delta management actions. It is envisioned that this plan would need to be implemented for a period of at least 15 years. It should be based on monitoring, modeling, and direct manipulation of factors of interest. It will require a policy commitment to a range of management actions to be tested, agreement among managers and scientists of the level of precision needed to determine study success, and agreement that operations needed for the experimental conditions being tested can be achieved. The plan should augment and expand the scope of current studies in terms of the breadth, depth and number of analyses, monitoring studies, and experiments conducted.

The SST believes that studies that focus on causal mechanisms at appropriate time and space scales are an important approach, especially regarding understanding how fish behavior responds to local conditions.

Development of a long-term plan as envisioned here would require a number of discussions among research scientists and managers and may require a multi-pronged focus on water project operations, Delta habitat conditions, predation, and other stressors thought to contribute to the low survival observed over the past decade. Although there are a number of potential approaches to developing the long-term plan, one approach to consider would be an integrated (physical and biological) approach to monitoring and modeling, and the manipulation of treatment conditions (e.g., flow, exports, I:E ratios) within certain reaches and over specific time scales. Integration across technical disciplines (biologists, hydrodynamics experts, physical and biological modelers, and biometricians) and methods (fish tagging and modeling) would continue and expand. The plan would incorporate new information in an adaptive manner, where information gathered at one stage of the process is incorporated into the following action (i.e., data gathering or analysis, model development, or system manipulation), and the action is then adjusted based on the new information. Consideration should also be given to integrating the long-term plan with other smelt, salmon, and water management programs in the Delta and Central Valley.

Schedule: 3 to 5 years

Management Application: The long-term monitoring, research, and adaptive management plan would be used to assess the RPA actions and underlying mechanisms related to the influence of water project operations on salmonid population viability. Results of monitoring would also be applied to better understand the importance of other potential limiting factors on migration and survival of juvenile salmonids in the Delta. It would also be used to inform a broader suite of actions intended to improve juvenile salmon survival in the Delta and population productivity.

Implement the Long-term Monitoring, Research, and Adaptive Management Plan

Discussion: Implementing the long-term plan will involve conducting the analyses, monitoring, and research identified during plan development (and thereafter) to evaluate key questions and hypotheses in a methodical manner, adaptively applying the information to management actions, and developing decision-support tools for managers that help characterize uncertainty and risk. Plan implementation should emphasize timely synthesis of research and monitoring, and publishing in peer-reviewed journals. Implementing the long-term plan is needed to develop the information necessary to assess how existing water project operations directly and indirectly affect the survival of listed and non-listed salmonids in the Delta. In addition, a statistically robust, long-term program designed to investigate the underlying mechanisms affecting salmonid survival will improve the scientific basis for identifying new water project operations. It is envisioned that this plan would need to be implemented for a period of at least 15 years.

Schedule: 15+ years

Management Application: Implementation of the long-term monitoring, research, and adaptive management plan will allow water project operations to be assessed. It will reduce uncertainty, potentially identify the incremental role water projects operations have on salmonid survival through the Delta, and potentially lead to adjustments to water project operations that improve survival beyond the current levels. Information gained through implementing the long-term plan could be integrated with, and incorporated into, decision support tools used to better manage the system. It is envisioned that the long-term plan will be integrated with other major monitoring programs in the Central Valley.

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LIST OF ACRONYMS AND ABBREVIATIONS

ABBREVIATION	DEFINITION
1-D	one-dimensional, typically applied to hydrodynamic simulation models
2-D	two-dimensional, typically applied to hydrodynamic simulation models
3-D	three-dimensional, typically applied to hydrodynamic simulation models
ADCP	Acoustic Doppler Current Profiler
AT	acoustic tag
BAFF	Bio-Acoustic Fish Fence
BBID	Byron Bethany Irrigation District
BiOp	NMFS 2009 Biological and Conference Opinion for the Long-Term Operations of the Central Valley Project and State Water Project
CAMT	Collaborative Adaptive Management Team
CCF	Clifton Court Forebay
CEQA	California Environmental Quality Act
cfs	cubic feet per second
CRR	cohort replacement rates
CVP	Central Valley Project
CWT	coded-wire tag
DCC	Delta Cross Channel
Delta	Sacramento-San Joaquin River Delta
DLO	Driver-Linkage-Outcome
DRR	differential recovery rates
DSM2	Delta Simulation Model 2
DWR	California Department of Water Resources
E:I	ratio of exports to inflow
ESA	Endangered Species Act
FL	fork length
ft/sec	feet per second
HORB	Head of Old River Barrier
I:E	ratio of inflow to exports
IOS	Interactive Object-oriented Salmon Simulation model
JPE	juvenile production estimate
MWD	Metropolitan Water District
NEPA	National Environmental Policy Act
NMFS	National Marine Fisheries Service
OBAN	Oncorhynchus Bayesian Analysis model
OMR	Old and Middle River

LIST OF ACRONYMS AND ABBREVIATIONS

ABBREVIATION	DEFINITION
PIT	Passive Integrated Transponder
PVA	population viability analyses
RMA	Resource Management Associates
RPA	reasonable and prudent alternative
SalSIM	San Joaquin Salmon Life Cycle Model
SAR	smolt to adult ratios
SDWSC	Stockton Deepwater Ship Canal
SST	Salmonid Scoping Team
SWC	State Water Contractors
SWP	State Water Project
SWRCB	State Water Resources Control Board
USBR	U.S. Bureau of Reclamation
USGS	U.S. Geological Survey
USFWS	U.S. Fish and Wildlife Service
VAMP	Vernalis Adaptive Management Plan
WWD	Westlands Water District

1.0 INTRODUCTION

This report provides a synthesis of technical information regarding juvenile salmonid migration and survival in the Sacramento-San Joaquin River Delta (Delta) specifically related to operations of the State Water Project (SWP) and Central Valley Project (CVP) (Figure 1-1). For purposes of this report the Interior Delta has been defined as waters in the Delta that are outside the mainstems of the Sacramento River and San Joaquin River. We define South Delta as the San Joaquin River and channels west and south of the San Joaquin River. The report provides a review of available information, identifies gaps in existing knowledge, and provides recommendations for future actions. Volume 2 of the report addresses eight specific management questions identified by the Collaborative Adaptive Management Team (CAMT). Background information on the Delta and water project operations is presented in Appendix A. Detailed information on Delta hydrodynamics and hydrodynamic simulation models, salmonid migration behavior and survival is presented in Appendices B through E.

1.1 PURPOSE

Information provided in this report is intended to inform policy and management decisions, including future California Environmental Quality Act (CEQA)/National Environmental Policy Act (NEPA) analyses, biological assessments, and biological opinions related to water project operations in the South Delta. The report is also intended to provide CAMT and others with a technical basis for prioritizing future investigations of salmonid behavior and survival in the Delta.

1.2 SCOPE

Several factors have been hypothesized to influence the survival rates and dynamics of Central Valley Chinook salmon and steelhead populations. Some factors are directly related to water project operations such as entrainment at the salvage facilities. Some factors are indirectly related to water operations such as changes in migration route or migration rate in response to changes in water velocity or flow that result in an increased risk of predation. Other factors are completely independent of water project operations.

The scope of this investigation, as determined by CAMT, was to focus narrowly on the effects of SWP and CVP operations on salmonid migration and survival in the Delta. Water project operations considered include inflow into the Delta, exports from the Delta, temporary agricultural barriers, Delta Cross Channel (DCC) gate operations, and Head of Old River Barrier (HORB).

The primary geographic focus was on the Sacramento-San Joaquin Delta south of the San Joaquin River. The geographic scope also included those pathways and export-related facilities that provide access for Sacramento River salmonids into the Central and South Delta, primarily the DCC and Georgiana Slough.

Figure 1-1. Map of the Sacramento-San Joaquin River Delta

Many factors affecting salmonid survival are outside of the scope of this analysis. The fact that these factors are not included in the analysis should not be interpreted to mean that they are not vitally important to salmonid survival, spatial distribution, productivity or abundance. Nor should this fact be interpreted to mean that the effect of these factors on survival may not be influenced by water project operations. The Salmonid Scoping Team (SST) endorses and recommends that further consideration be given to these other project- and non-project-related factors that affect salmonid population viability.

For example, it has been hypothesized that a substantial proportion of the juvenile mortality in the Delta is the result of predation, especially inside and near the water project facilities (Clark et al. 2009), but mechanistic linkages between water project operations and conditions supporting high predation in other areas of the Delta are largely unknown. In addition, there are potential linkages between water project operations (e.g., barrier installations) and outcomes such as habitat quality, growth, and life history diversity. Similarly, factors such as riverine and Delta inflows, and habitat quality and habitat availability on the size, timing, distribution and physical condition of juvenile salmon and steelhead entering the Delta have the potential to influence the likelihood of outcomes related to potential effects of water project operation related drivers on migration behavior or survival. Water project operations resulting in changes in velocity or flow direction could affect habitat conditions in the Delta, resulting in increased mortality in some migration pathways and/or reduced growth, which could result in reduced survival of juvenile salmon at ocean entry.

The potential effects of water project operations in the Delta on reduced growth or altered migration timing that influence subsequent survival of juveniles (e.g., in the ocean) and overall population life history diversity are not evaluated here. The broad conceptual model predicts that water project operations could affect migration timing, migration rates and route selection, and locations of rearing salmonids and habitat use in the tributaries influenced by SWP and CVP operations such as the Feather, American, Sacramento, and Stanislaus rivers and Delta. Operations have the potential to constrain life history diversity as a result of altering instream flows, export operations, and other habitat conditions by favoring one type of life history attribute over others. Over time, this can represent a selective pressure that reduces diversity within a population. The cumulative effect of water project operations on juvenile salmonid mortality in and beyond the Delta, in relation to other stressors, is a major gap in our knowledge.

2.0 METHODS AND APPROACH

The SST started with a broad conceptual model developed by the South Delta Salmon Research Collaborative Effort (Figure 2-1). The initial conceptual model was refined using a Driver-Linkage-Outcome (DLO) structure (DiGennaro et al. 2012) to more explicitly identify potential linkages between project operations, salmonid migration behavior, and survival (Figure 2-2; Table 2-1 through Table 2-3).

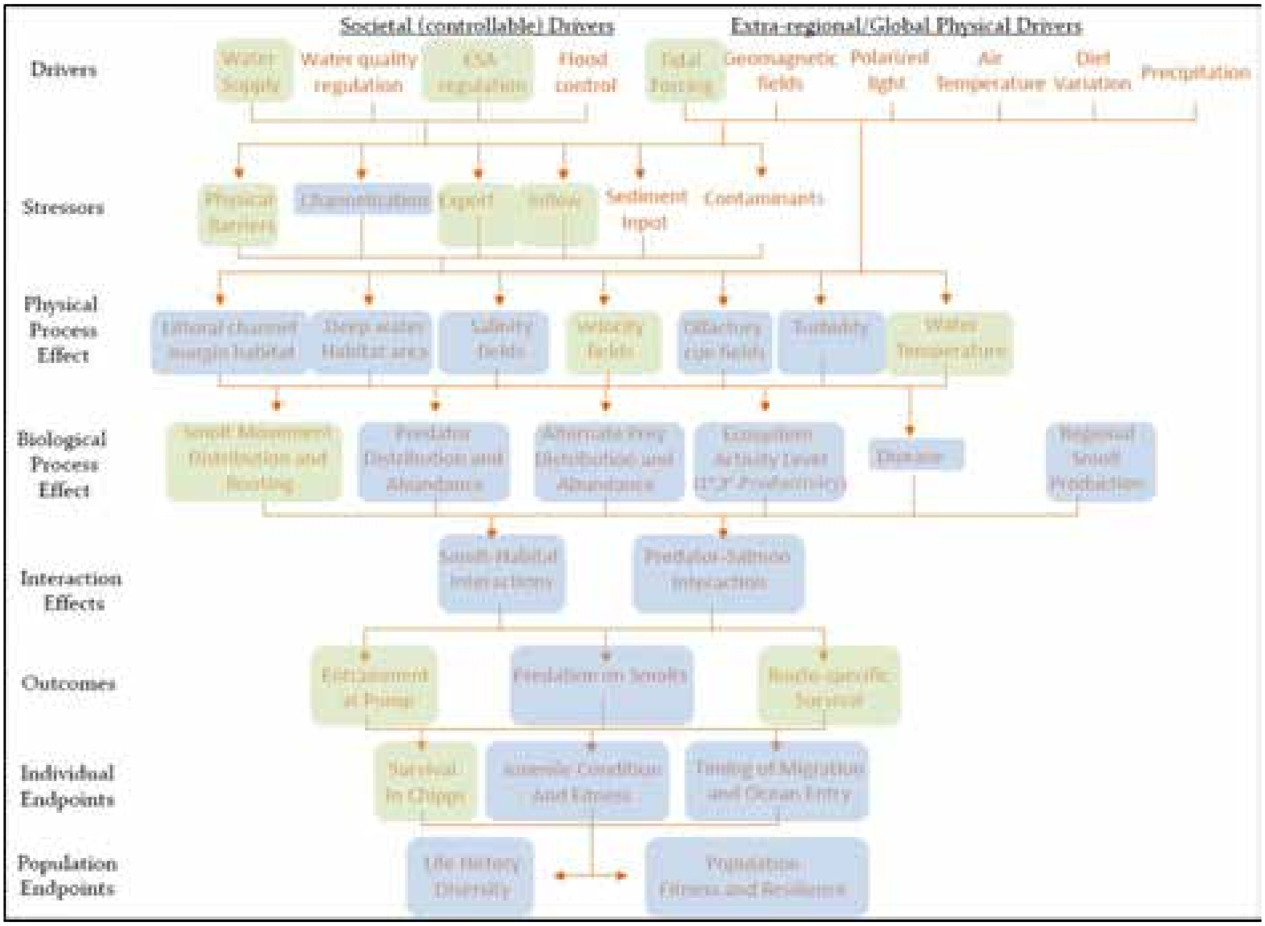


Figure 2-1. Conceptual Model from the South Delta Salmonid Research Collaborative Effort Describing Factors Affecting Survival of Juvenile Salmonids in the South Delta

Notes: Green highlights indicate model components included within the narrower scope of the SST report. Blue highlights indicate model components also potentially relevant to export effects and recommended by the SST for inclusion in an expanded research program.

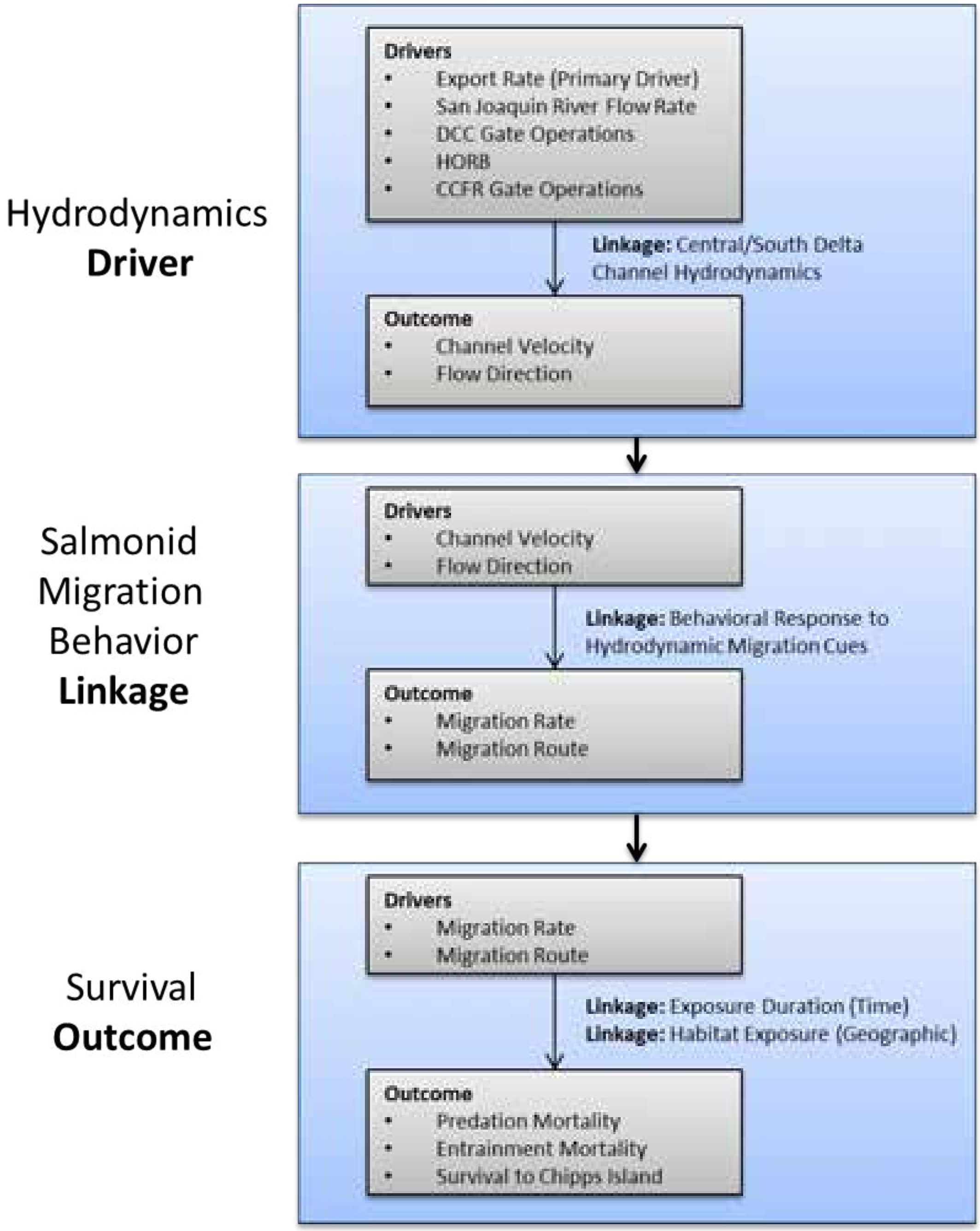


Figure 2-2. Prioritized Focal Areas and Framework Considered by SST to Evaluate Water Project Operations

Table 2-1. Hydrodynamics DLO Components for Analysis

Drivers	Linkages	Outcomes
• Exports • River inflow (Sacramento and San Joaquin) • Tide • Channel morphology	• Proximity to exports • Channel configuration/barrier deployment • Clifton Court Forebay (CCF) operation radial gate operations (e.g., opening to fill CCF and then closing to isolate the pumping plant operations from the Delta)	• Instantaneous velocities or flows • Net daily flow • Sub-daily velocity • *Percent positive flow* • *Water temperature* • *Salinity* • *Residence time* • *Source/origin of water*

Note: Red italicized text indicates DLOs that were not included in the analysis.

Table 2-2. Behavior DLO Components for Analysis

Drivers	Linkages	Outcomes
• Instantaneous flow/velocity (channels) • Instantaneous 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* – Lateral distribution in the channel – 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

Note: Red italicized text indicates DLOs that were not included in the analysis.

Table 2-3. Salmonid Survival DLO Components for Analysis

Drivers	Linkages	Outcomes
• Migration route selection • Migration rate	• Exposure to variables (e.g., habitat and predators) that affect differential survival between routes or between years for the same route • Duration of exposure to route-specific conditions that affect survival	• Mortality

Evaluation criteria (Table 2-4), modified from the DRERIP Scientific Evaluation Process (DiGennaro et al. 2012), were developed and used to characterize the basis of knowledge supporting observed relationships in the available data. Where insufficient or contradictory information existed, the issue was identified as a gap and subsequently given consideration for potential future investigation.

Table 2-4. Criterion for Assessing the Basis of Knowledge

The basis of knowledge is an objective assessment of the evidence the SST reviewed about the relationship described in the conceptual model.	
High	1. Understanding is based on peer-reviewed studies within the system and scientific reasoning accepted by most members of the SST.
Medium	2. Understanding is based on peer reviewed studies from outside the system and corroborated by non-peer-reviewed studies within the system. 3. If evidence is from a single study, regardless of publication, then understanding is medium. 4. Understanding is based on multiple non peer reviewed agency reports.
Low	5. Understanding is based on one non-peer-reviewed research report within the system or elsewhere. 6. If evidence from multiple reports is inconsistent, then understanding is low.
Minimal	7. Understanding is lacking with the scientific basis being unknown or not widely accepted by the SST.

2.1 CONCEPTUAL MODEL

A simplified DLO conceptual model was developed to illustrate current understanding of how drivers (water project operations), relate to linkages (hydrodynamics and salmon migration behavior [migration rates and route selection]) and outcomes (Delta survival). The model is shown graphically in Figure 2-2 and summarized below:

1. Water project operations, including exports, in-Delta barriers, and water project effects on Delta inflow, affect hydrodynamics in some parts of the Delta.
2. Changes in water velocities, residence time, source, and flow direction affect juvenile salmonid behavior, including migration rate and route selection.
3. Selection of different routes through the Delta and migrating at different rates (speeds) through the Delta affect survival. Water project operations also potentially influence factors responsible for differential survival among different routes. Water project effects may be direct (e.g., entrainment into the export facilities) or ecologically indirect (e.g., predator densities and distribution, alternative prey production, habitat conditions).

Due to the limited scope of the analysis (see Section 1.2) the DLOs included reflect a subset of the array of factors that affect juvenile salmonid migration behavior and survival within the Delta, as shown in Figure 2-1. The SST acknowledges that there may be additional relationships related to the potential impacts of water exports and non-project-related factors on salmon populations that are outside the scope of this analysis or were not included in this assessment as a result of limitations in available data or time for analysis.

2.2 COMPILATION AND ASSESSMENT OF INFORMATION

The SST compiled a reference library of more than 350 technical reports and scientific papers related to water project effects on Delta hydrodynamics, salmonid migration and salmonid survival. The report includes consideration of peer reviewed scientific publications, technical reports (grey literature), and unpublished data from acoustic tag (AT) survival and migration studies (e.g., six-year steelhead and Chinook salmon studies in the South Delta) and hydrodynamic models (e.g., Delta Simulation Model 2 [DSM2], RMA2). Information such as personal communications and symposia presentations has also been included but given less weight.

2.3 PREDICTED (HYPOTHESIZED) RELATIONSHIPS

The conceptual models shown in Tables 2-1, 2-2, and 2-3 were used to develop predicted (hypothesized) relationships and outcomes. These relationships were then examined based on available quantitative (statistical analyses and modeling) and qualitative study results, including observed patterns and trends in the available data that may not be statistically significant but suggest potential responses. Consideration was given to factors such as variability in study results, the range of conditions tested, elements of the experimental design such as sample size, tagging and monitoring methods, replication, stability of experimental test conditions, and consistency of results with other studies.
Available information was characterized as:

1. Consistent and supportive of the relationship predicted based on the conceptual model
2. Not consistent or not supportive of the predicted relationships, suggesting that alternative hypotheses and relationships should be considered
3. Inconsistent or inadequate to support or refute a predicted relationship

Relationships that were characterized as inconsistent or inadequate (No. 3 above) were identified as gaps in information that could be addressed in the future.

The conceptual models can also be used to identify testable hypotheses and predictions to be assessed using data or information in the scientific literature and further analysis of existing studies. The following are examples of testable hypotheses.

Null Hypothesis	Alternative Hypothesis based on Conceptual Model
Migration route selection is independent of project operations	Project operations result in changes to water velocity and flows in Delta channels that affect route selection; specifically, increased exports result in increased selection of Interior Delta routes
Survival within the Delta is independent of project operations (direct and indirect losses; ratio of exports to inflow [E:I]; ratio of inflow to export [I:E]; Old and Middle River [OMR] reverse flows; export rate)	Project operations result in changes to water velocity and flows in Delta channels that affect direct and indirect mortality
Survival within the Delta is independent of migration route selection	Survival varies among alternative migration routes; survival is reduced within Interior Delta channels when compared to the San Joaquin River mainstem

The analysis also identified study results and interpretations where there was general agreement within the SST regarding data interpretation, and where there were disagreements within the SST. Gaps in scientific understanding related to water project effects on Delta hydrodynamics, salmonid migration behavior, and survival, as well as scientific disagreements, are summarized below with additional information included in Appendices A through E.

2.4 BASIS OF KNOWLEDGE

The basis of knowledge for observed relationships was determined using criterion adapted from the DRERIP (DiGennaro et al. 2012) process, as shown in Table 2-4. The basis of knowledge is intended to provide a standardized, objective means for characterizing the level of understanding regarding a given relationship or conclusion where understanding is defined as follows:

> *Understanding: A description of the known, established, and/or generally agreed upon scientific understanding of the nature of a driver, linkage or outcome. Understanding may be limited due to lack of knowledge and information or due to disagreements in the interpretation of existing data and information; or because the basis for assessing the understanding of a linkage or outcome is based on studies done elsewhere and/or on different organisms, or conflicting results have been reported. Understanding should reflect the degree to which the model that is used to represent the system does, in fact, represent the system.*

There was not consensus in the SST regarding the definition and application of the basis of knowledge criteria. The criteria listed in Table 2-4 categorize peer-reviewed publications higher than agency or contract reports. Peer-reviewed journal articles are considered an objective and rigorous source of information because: 1) they are independently reviewed and meet scientific standards prior to being published; 2) the selection of peer reviewers is not under the control of the author; 3) the author must respond to all peer review comments; 4) author responses must meet the satisfaction of an independent editor; and 5) peer-reviewed journals have a mechanism for reader comments and dissenting opinions with author responses to be published and affiliated with the original journal article. While many agency reports are peer reviewed, the selection of reviewers and the response to reviewer comments are typically controlled by the author(s) or contracting agency, and there is no consistent or dependable manner to assess the rigor of peer review for individual agency reports. Therefore, when an agency report was the primary source of information without the corroboration of an independently peer-reviewed publication, a “low” Basis of Knowledge rating was assigned. However, agency reports may provide better and more specific information relative to the questions the SST addressed. For this reason, at least one SST member felt that results from multiple agency reports should be rated higher than a medium basis of knowledge.

3.0 RESULTS AND DISCUSSION

Results of the SST review and analyses are summarized below for seventeen topic areas related to salmonid migration and survival in the Delta. For each topic area, conceptual model predictions are provided followed by a summary of existing analyses and a summary of findings. Where significant scientific disagreements exist, they are listed. Additional information is presented in Appendices B (hydrodynamics), C (simulation model validation), D (migration behavior), and E (survival).

3.1 EFFECTS OF PROJECT OPERATIONS ON DELTA HYDRODYNAMICS

Hydrodynamic conditions, including the flow distribution, flow direction, and water velocities in Delta channels, are influenced by a variety of factors including tides, freshwater inflows, channel geometry and channel-bed characteristics, water diversions, and operation of barriers and gates. Under periods of low inflow, the system is strongly tidal with reversing flows. As inflows increase, channels become more riverine, and tidal-induced flow reversals in Delta channels are reduced. Exports can influence the direction and velocity of flow in the South Delta, with high exports causing more negative flows in OMR. DCC operations affect the balance of flow between the western and eastern/southern areas of the Delta. Opening the DCC allows flow to transfer from the Sacramento River into the Mokelumne River and then into the lower San Joaquin River and Interior Delta (DeGeorge 2013).

Flow patterns in the South Delta tend to be more complex than the north Delta due to the influence of CCF radial gate operations and exports on OMR hydrodynamics, more complex interconnected channels, the presence of South Delta temporary barriers, lower inflow from the San Joaquin River, and greater tidal excursion along the mainstem of the San Joaquin River. Flow splits at critical junctions may be affected by the conveyance characteristics of the connecting channels, tidal phasing, and installation and operation of barriers and gates (DWR 2011a, 2011b, 2015a). Bathymetry and channel and levee characteristics maintained for water conveyance also affect habitat features in both the north and South Delta.

3.1.1 Conceptual Model Predictions

Relationships between water project operations and Delta hydrodynamics are hypothesized to vary depending on a variety of factors that include:

- Water velocities in South Delta channels would change in response to exports; the magnitude of velocity change varies depending on the magnitude of export rates, tidal condition, distance from the export facilities, Delta inflow, and channel location and configuration.
- Flow direction in South Delta channels would change in response to exports; the change in flow direction varies depending on the magnitude of export rates, tidal condition, distance from the export facilities, Delta inflow, and channel location and configuration.
- Installation and operation of temporary barriers and the DCC and CCF radial gates alter the water velocities, water surface elevation (stage), and flow direction in adjacent Delta channels; these changes are greatest in the immediate vicinity of the structure and diminish with distance away from the barrier.

3.1.2 Analysis

Actual hydrodynamic measurements and predictions based on hydrodynamic simulation modeling (Appendices B and C) were used to test the hypothetical linkages between SWP and CVP exports (driver), linkages (change in channel flow), and outcomes (change in water velocity and flow direction at various geographic locations). To assess the limitations of this approach, the analysis included: 1) consideration of various simulation model frameworks and performance (validation) of model predictions of water velocities and flows compared to measured conditions at various time scales and locations within the Delta; and 2) results of simulation model predictions of changes in water velocity and flow at various locations as a function of river inflow and SWP and CVP export operations. The basis of knowledge is considered to be low because information on the relationships between water project operations and South Delta hydrodynamics among different migration routes and drivers such as exports, barriers or Clifton Court radial gate operations, and migration route velocity is based primarily on non-peer-reviewed agency reports, and because of limitations of the models and lack of calibration and validation in the south Delta channels as presented in this report (see Appendices B and C).

Existing Understanding of the Effects of Water Project Operations on Delta Hydrodynamics

DSM2 simulation modeling results were used to assess the potential impact of water project operations on Delta hydrodynamics. Results of the hydrodynamic simulations show the relative influence of tides, river inflows, and exports on hydrodynamic conditions of flow direction, magnitude, and average cross-sectional velocity within the Delta DSM2 channel reaches given the daily tidal dynamics. Results also suggest that the effect of exports is greatest in Old River immediately downstream of the export facilities and diminishes with distance downstream of the facilities. Changes in velocities are also shown upstream and downstream of the facilities in the model runs with flows and velocities increasing in reaches upstream of the export facilities, and decreasing downstream of the facilities. Based on the DSM2 modeling, exports have little to no effect on flow and velocities in other areas of the Delta such as the San Joaquin River mainstem, north Delta, and Sacramento River.

Results of DSM2 modeling showed tides are a significant factor affecting hydrodynamics in the Delta (Figure 3-1), with Delta inflow and exports affecting the geographic area and magnitude of tidal influence. Using DSM2 model scenarios from Kimmerer and Nobriga (2008), minimum and maximum flows range from +150,000 to -155,000 cubic feet per second (cfs) in the western Delta at Chipps Island, from +29,000 to -29,000 cfs in the lower San Joaquin River at the mouth of Middle River and from +2,500 to -2,900 cfs in the San Joaquin River between Upper and Lower Roberts Island (Figure 3-1; Cavallo et al. 2013). Using the same model scenarios, minimum and maximum velocities ranged from + 1.9 to -1.8 feet per second (ft/sec) in the western Delta near Jersey Point; from to +1.3 to -1.2 ft/sec in the lower San Joaquin River at the mouth of Middle River; and from +1.4 to -1.8 ft/sec between Middle and Lower Roberts Island.

A series of DSM2 one-dimensional (1-D) simulation model runs was performed to characterize the effects of SWP and CVP exports (2,000, 6,000, and 10,000 cfs) and inflows (12,000, 21,000, and 38,000 cfs) on average daily flows and instantaneous velocities within Delta DSM2 channel reaches. Results of the simulations showed:

- In the San Joaquin River mainstem, increasing exports from 2,000 to 10,000 cfs resulted in a change in instantaneous tidal minimum velocity ranging from +0.05 ft/sec just upstream of the head of Old River to -0.21 ft/sec just downstream of False River.
- In Old River, increasing exports from 2,000 to 10,000 cfs resulted in a change in instanteous tidal minimum velocity ranging from +0.54 ft/sec downstream of Paradise Cut to -1.19 ft/sec downstream of Clifton Court intake.
- In Middle River, increasing exports from 2,000 to 10,000 cfs resulted in a change in instantaneous tidal minimum velocity ranging from -0.09 ft/sec just upstream of Victoria Canal to -0.53 ft/sec just downstream of Victoria Canal.

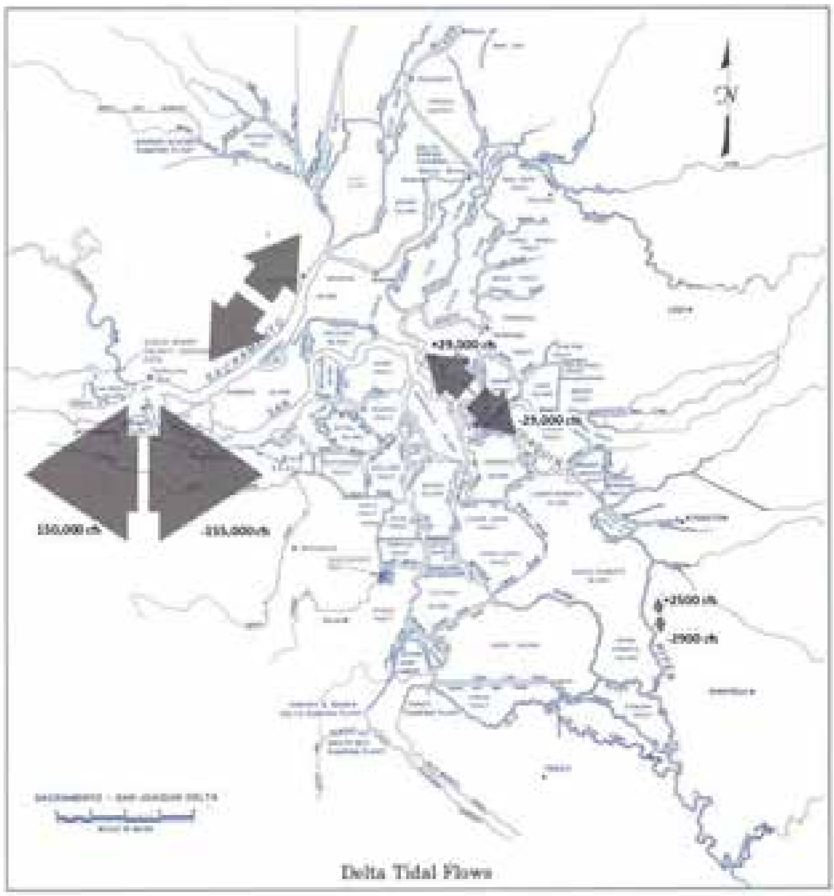


Figure 3-1. Modeled Maximum Flows at Four Locations in the Sacramento-San Joaquin Delta Using DSM2 at Low Delta Inflows of 12,000 cfs (1,495 cfs San Joaquin River Inflow and 10,595 cfs Sacramento River Inflow), High Exports of 10,000 cfs, and Head of Old River Out

Sources: Graphic from DWR (1995) Delta Atlas; model results from DSM2 scenarios from Kimmerer and Nobriga (2008).

The DSM2 model simulations were used based on average daily flow to assess the magnitude of change throughout the South Delta in response to export rates of 2,000 and 10,000 cfs. The changes in average daily flow within Delta channels as a function of three levels of Delta inflow and three levels of SWP and CVP exports are expressed as color contours representing a "heat" map of average daily flow shown in Figure 3-2. Results of these average daily flow estimates show that, particularly under low inflow conditions, the effect of increasing exports is to increase the magnitude of reverse flows in the South Delta DSM2 channel reaches. Increasing exports resulted in the greatest flow changes within Delta DSM2 channel reaches south of the San Joaquin River mainstem. The effect of increasing Delta inflow was generally a reduction in the average daily effects of exports on South Delta hydrodynamic conditions.

To further investigate the potential effects of water project operations on hydrodynamic conditions in the San Joaquin River mainstem in the South Delta and at Georgiana Slough in the North Delta, results of the 1-D DSM2 simulation model were analyzed at specific river junctions by Cavallo et al. (2013) using flow predictions at a 15-minute time step over a 24-hour period. Results show that flows are affected by river flow, exports, and tidal conditions in the San Joaquin River mainstem at the head of Old River, but downstream in the San Joaquin River mainstem, SWP and CVP exports and Delta inflow rate have much less effect and tides dominate more. At Georgiana Slough in the North Delta, Delta inflow and tides dominate and exports have little to no effect (see Appendices B and C for additional detail regarding Delta hydrodynamic simulation models). A similar junction assessment was conducted by the SST with the same model output set for velocity with similar results (Appendix B, Sections B.5.3 and B.5.4).

As river inflow increases, tidal effects on flow decrease in the upstream areas of the South Delta routes and at Georgiana Slough. As river flow decreases, the effect of tides on flow direction and velocity increase. The flows and velocities in the immediate vicinity of the north and South Delta channel junctions are complex in terms of local turbulence and the location of the hydraulic streakline in the mainstem river channel (Appendix B, Section B.4 and Figures B.4-1 and B.4-2).

In addition to modeling the effects of inflow and exports on flow magnitude and direction at various DSM2 junctions, the 15-minute DSM2 predictions for changes in water velocity were also examined. Due to limited resources to obtain the 15-minute output, we selected fewer scenario options. The model scenarios were limited to low Sacramento and San Joaquin River inflow (12,000 cfs) and low export (2,000 cfs), high inflow (38,000 cfs) and low export (2,000 cfs), and high inflow (38,000 cfs) and high export (10,000 cfs). The low inflow and high export scenario was not recommended for modeling because it was not realistic from an operations perspective. The HORB and South Delta Temporary Barriers were not installed in the model for these analyses.

With the availability of 15-minute model output, we were able to see the complexity of the hydrodynamics in the South Delta channels reflecting the variation in velocity conditions that a juvenile salmonid would encounter while migrating through the South Delta. Figure 3-3 is an illustration of the 15-minute instantaneous velocities over a complete tidal cycle for each of the DSM2 channel reaches in each route.

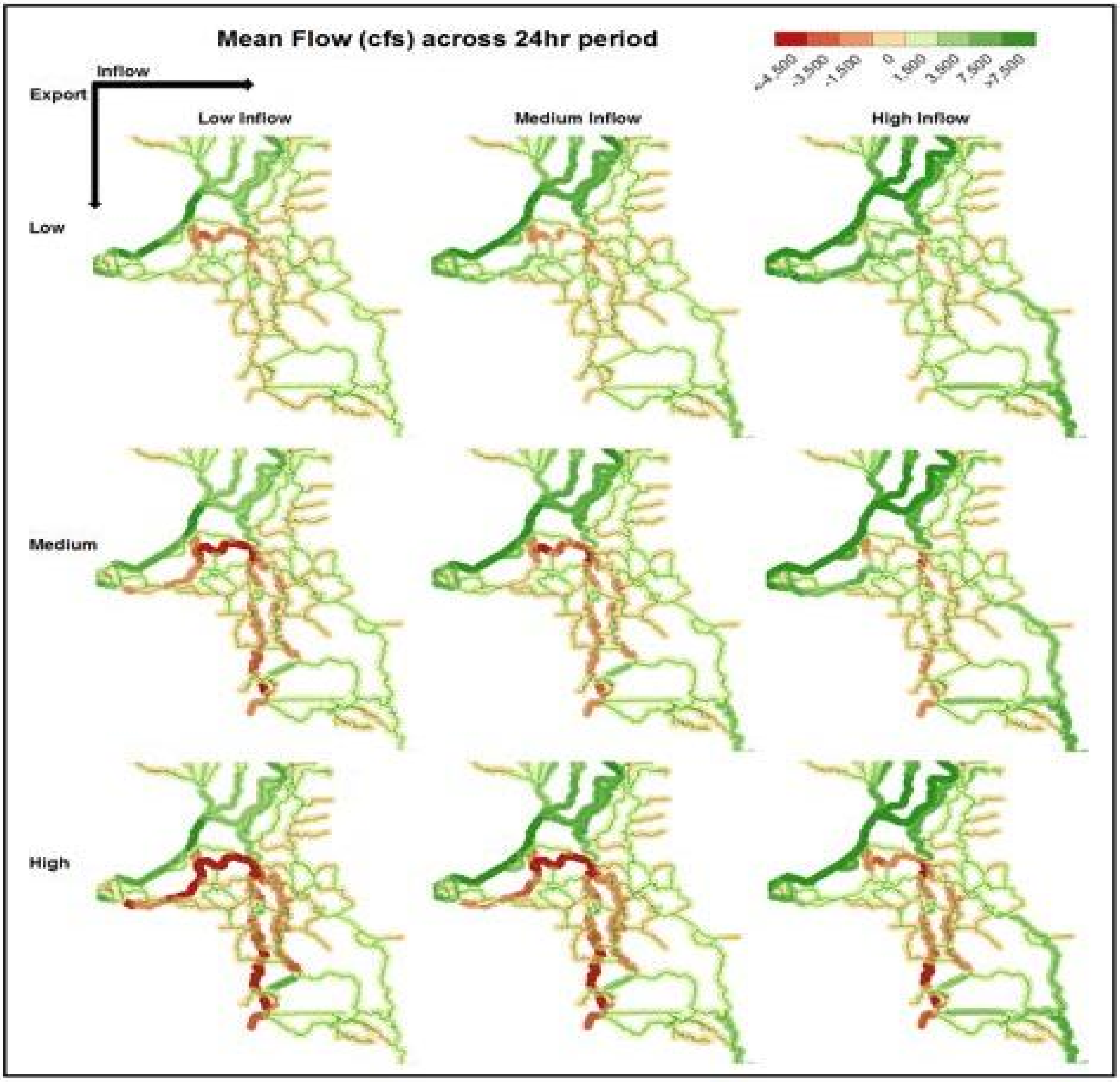


Figure 3-2. Daily Average Flow at Each DSM2 Channel at Three Export Rates and Three Delta Inflow Rates

Note: The export rates were 2,000, 6,000, and 10,000 cfs, and the Delta inflow rates were 12,000, 21,000, and 38,000 cfs.

In DSM2, the waterways are segmented into distinct channel reaches and given numbers. San Joaquin River route is made up of channel reaches 7 through 50. Old River route is made up of channel reaches 54 through 124. Middle River route is made up of channel reaches 125 through 163. The multiple lines in each graph in Figure 3-2 are the individual DSM2 channel reaches and the x axis represents time (approximately 25 hours). The tide phase reaches the upstream DSM2 channel reaches several hours later than the downstream reaches within a route, there are groups of DSM2 channel reaches that are similar in terms of amplitude and tide phase timing, compared to other groups. The hydrodynamic and geometric complexity of these South Delta channels and the interactions between San Joaquin River inflow, exports, and tides contribute to the environmental conditions and migration cues encountered during downstream passage by juvenile salmonids.

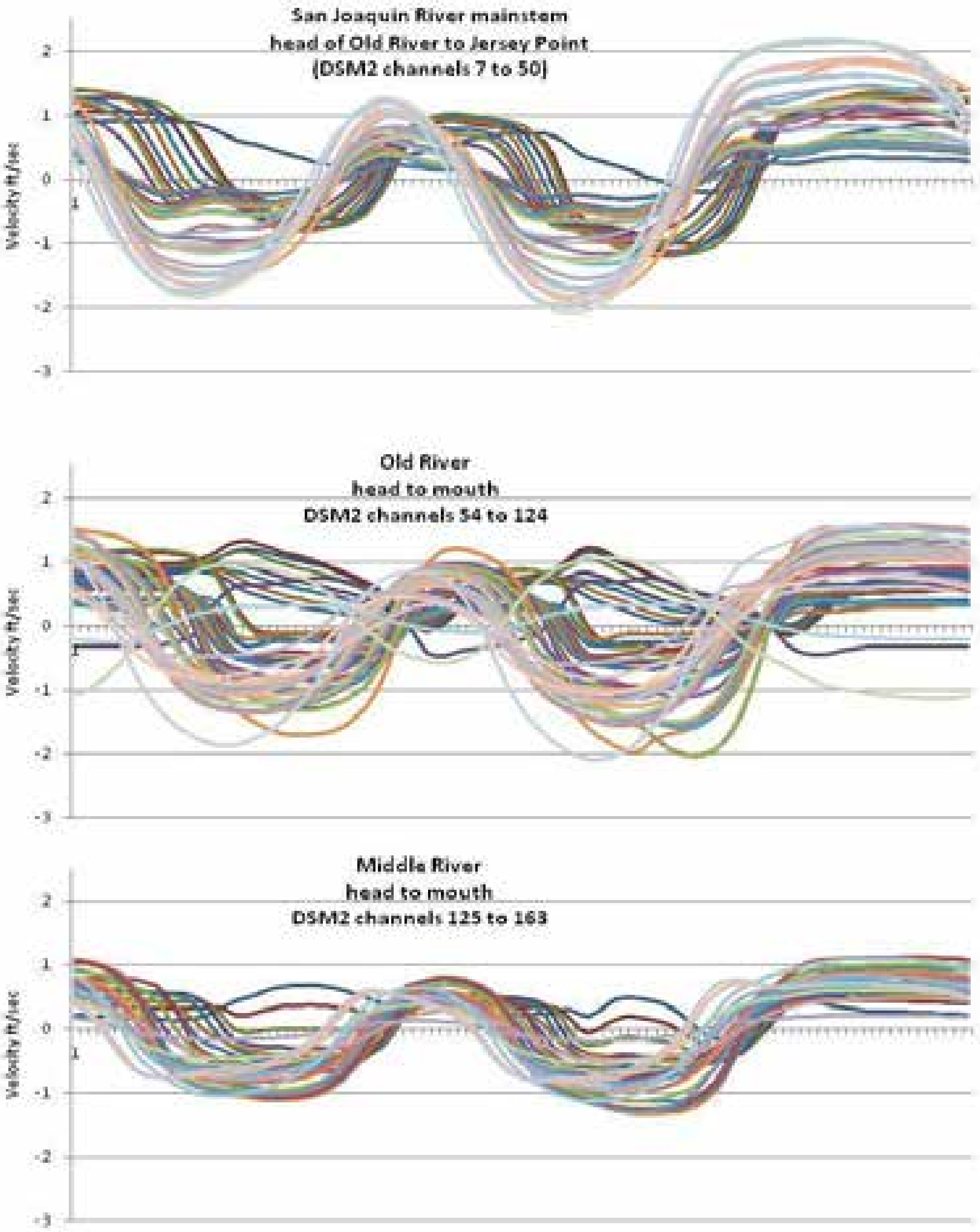


Figure 3-3. DSM2 Modeled Instantaneous 15-Minute Interval Velocity Versus Time Over One Tidal Cycle (~25 hours) in DSM2 Channel Reaches in Three Routes of the South Delta

Notes: The DSM2 channel reaches are reaches of the river as defined in the DSM2 model grid. The routes are the San Joaquin River mainstem, Old River, and Middle River. Each line represents one DSM2 channel reach within the route at the low inflow/low export model scenario. The x axis represents the time period modeled from 0 (origin) to approximately 25 hours.

Figure 3-4 and Figure 3-5 illustrate water velocity profiles for the San Joaquin River, Old River, and Middle River routes under two export and two inflow conditions showing the tidally averaged, maximum, and minimum 15-minute instantaneous velocities. Results of these analyses show that water velocities in the South Delta channels are primarily positive during the ebb tide stage (flowing downstream) in contrast to primarily negative during the flood tide stage (flowing upstream) in all three routes. These changes in velocity patterns as a function of tide are expected as the South Delta flows reverse direction between ebb and flood tide stage, which adds further to the hydrodynamic complexity encountered by juvenile salmonids migrating downstream through these South Delta routes. The reverse velocity pattern in the three South Delta routes shown in Figure 3-4 (left panel) occurred downstream of: 1) Stockton in the San Joaquin River mainstem; 2) Grant Line Canal in Old River; and 3) Tracy Boulevard in Middle River under both the low and high river inflow conditions. Tidal effects had a substantially greater influence on water velocities than differences between high and low exports under high inflow conditions in the San Joaquin River mainstem, but in Old River, export effects increased to about 35% of the tidal effect near the SWP and CVP facilities (Figure 3-4, right panel). Additional analysis of 15-minute velocity results are presented in Appendix B.

Results of the simulation analysis at the junction of San Joaquin River and head of Old River (Figure 3-6) showed little difference in water velocities upstream, downstream, and within Old River (three DSM2 channel reaches) associated with differences between the low and high export condition (at high inflow). Differences in velocities as a function of low and high river flow (at low exports) were apparent at all three locations with greater cyclic tidal variation in velocities under the low river flow condition. Increased river flow resulted in consistently high velocities at the head of Old River junction at all three of the DSM2 channel reaches included in the model analysis.

At the junction of the San Joaquin River and Turner Cut (Figure 3-7), the greatest influence on water velocities was associated with tidal phase (cyclic tidal signal) with river flow and exports having little effect on water velocities. These results show the greater influence of tides at locations further downstream in the Delta as well as the diminished effect of river flow on water velocities at the Turner Cut junction. Water velocity at Turner Cut junction DSM2 channel reaches was virtually independent of variation between low (2,000 cfs) and high (10,000 cfs) export levels in these simulation analyses.

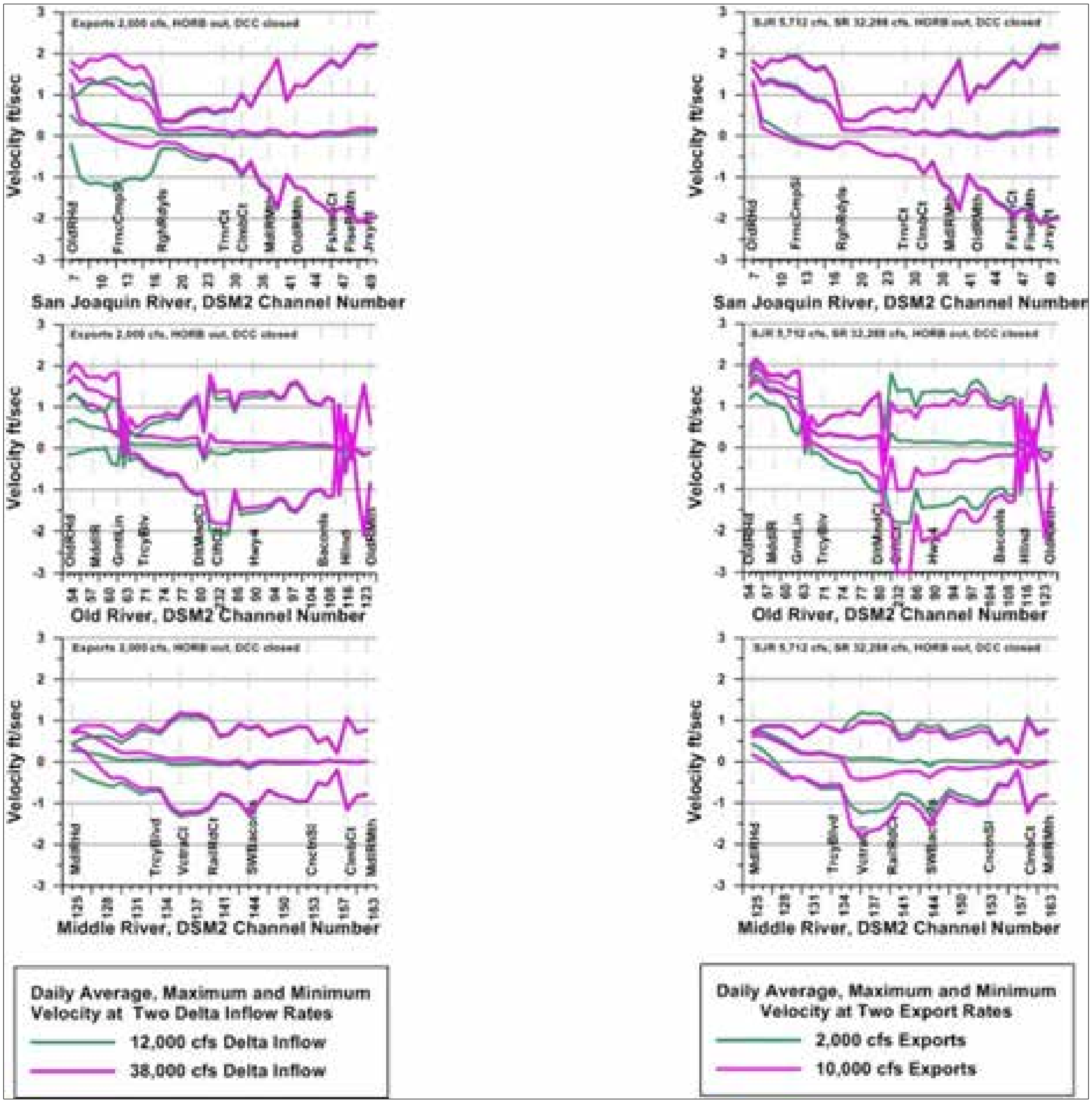


Figure 3-4. DSM2 modeled average daily velocity and instantaneous maximum velocity associated in each channel reach, in each of two routes in the South Delta. The two model scenarios were, left panels: low exports at low and high inflows, and right panels: high inflows at low and high exports. We limited the export scenarios to low exports and the inflow scenario to high inflows because high exports are not permitted at low inflows. In each graph, the upper set of lines represents the maximum velocities for the scenario, the middle set of lines represents the daily average velocities for the scenario, and the lower set of lines represents the minimum velocities for the scenario. The minimum and maximum velocities are associated with the flood and ebb tides, respectively.

Note: The three routes are San Joaquin River mainstem, Old River, and Middle River. The x axis is the serial DSM2 model channel number.

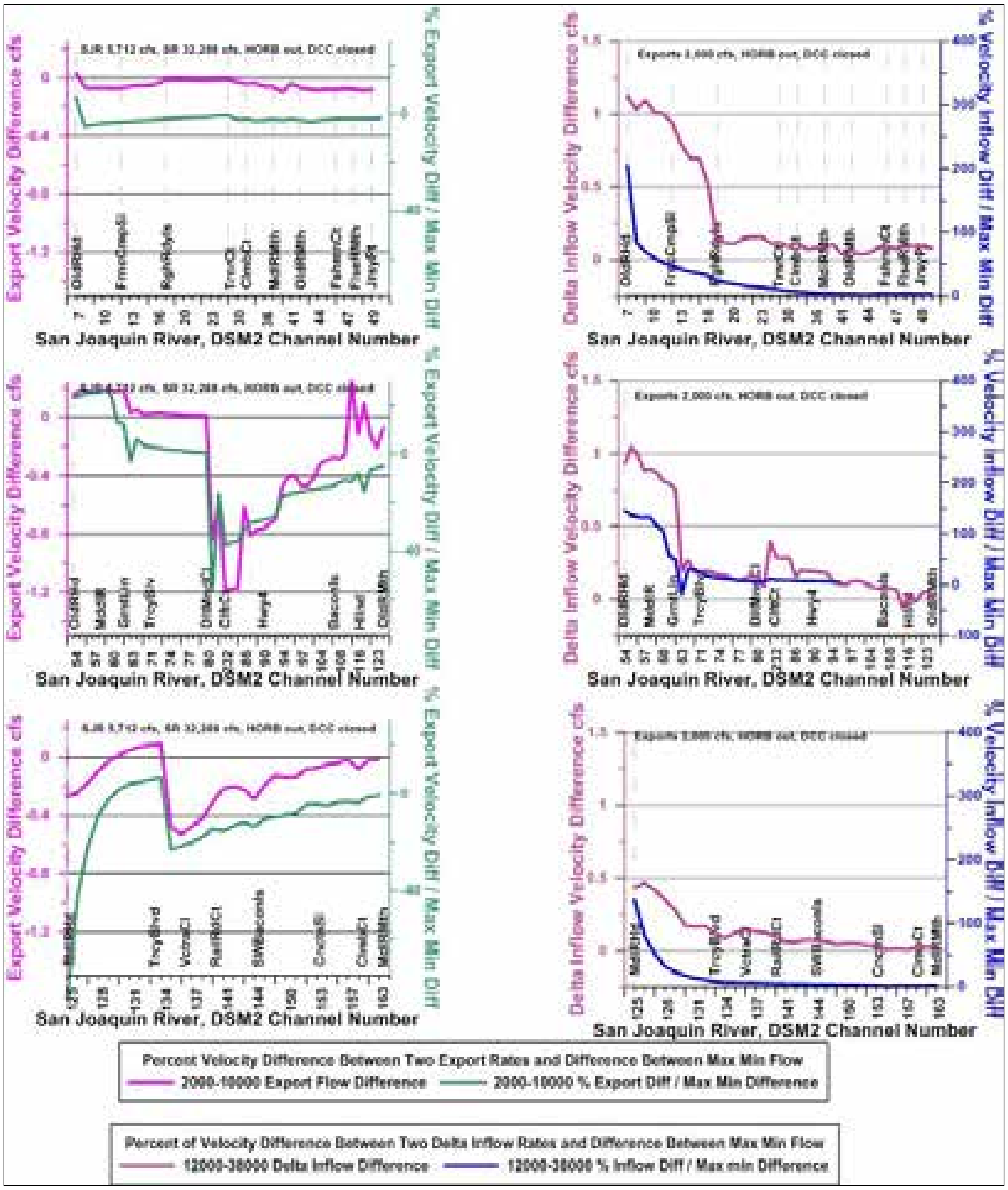
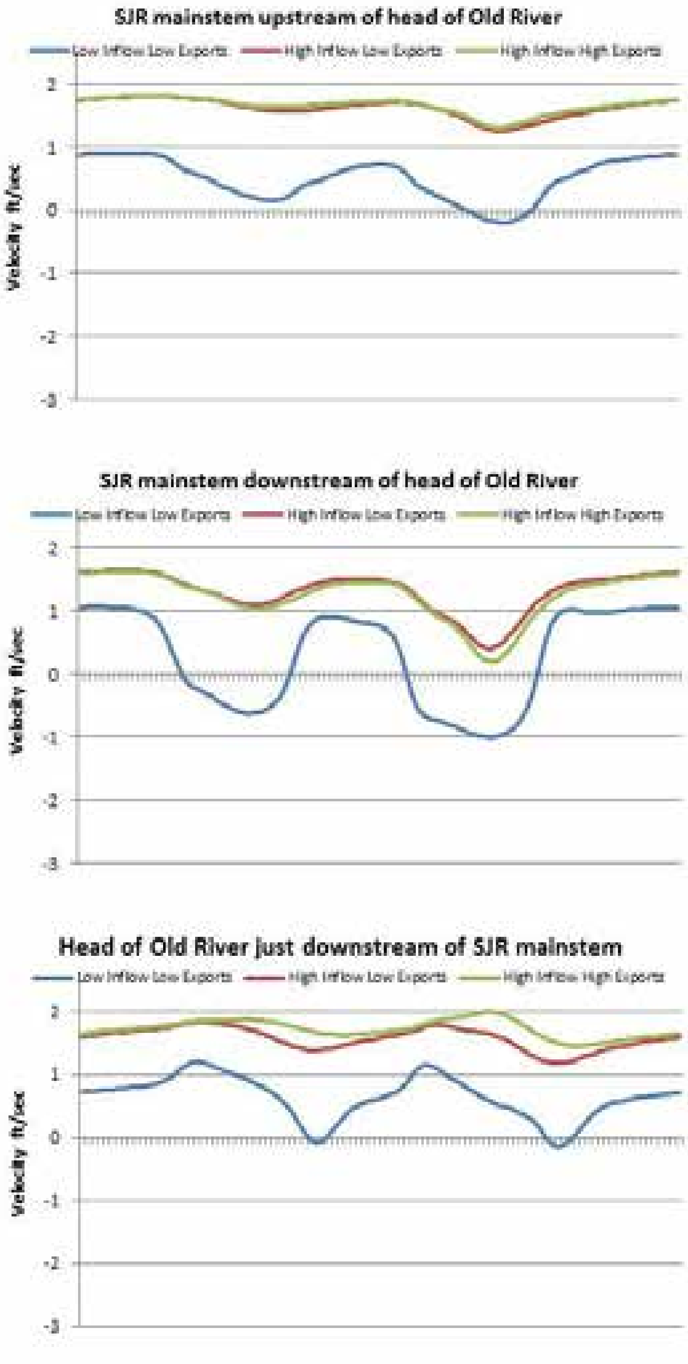


Figure 3-5. Effect of Export Rate and Delta Inflow on Tidal Velocity in the Lower San Joaquin River

Notes: All left panels represent the high inflow scenario, the difference in average tidal velocity between low and high export rate (left y axis), and the difference in daily average velocity between low and high export rate divided by the difference between instantaneous maximum and minimum velocity at the low export rate (right y axis) without the HORB. The right panels represent the difference in daily average velocity between low and high inflow rate (left y axis) and the difference in daily average velocity between low and high inflow rate divided by the difference between daily maximum and minimum velocity at the low at the low inflow rate without the HORB. All right panels represent the low export scenario. The three routes are San Joaquin River mainstem, Old River, and Middle River. The x axis is serial DSM2 channel number.


SJR mainstem upstream of head of Old River

SJR mainstem downstream of head of Old River

Head of Old River just downstream of SJR mainstem

Figure 3-6. DSM2 Modeled Instantaneous 15-Minute Velocity Versus Time Over a Complete Tidal Cycle (~25 Hours) at the Junction of the San Joaquin and Head of Old River

Notes: There are three DSM2 channel reaches at the junction (three panels). Within each panel, there are three scenarios: low inflow/low export, high inflow/low export, and high inflow/high export.

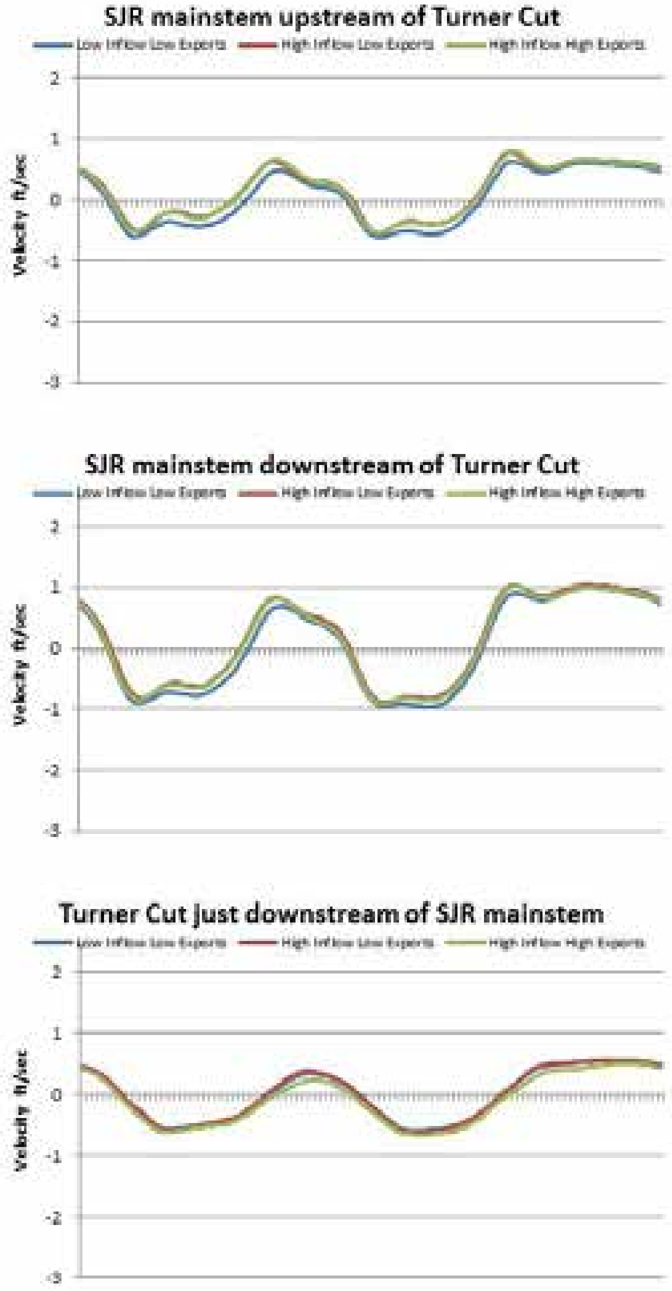
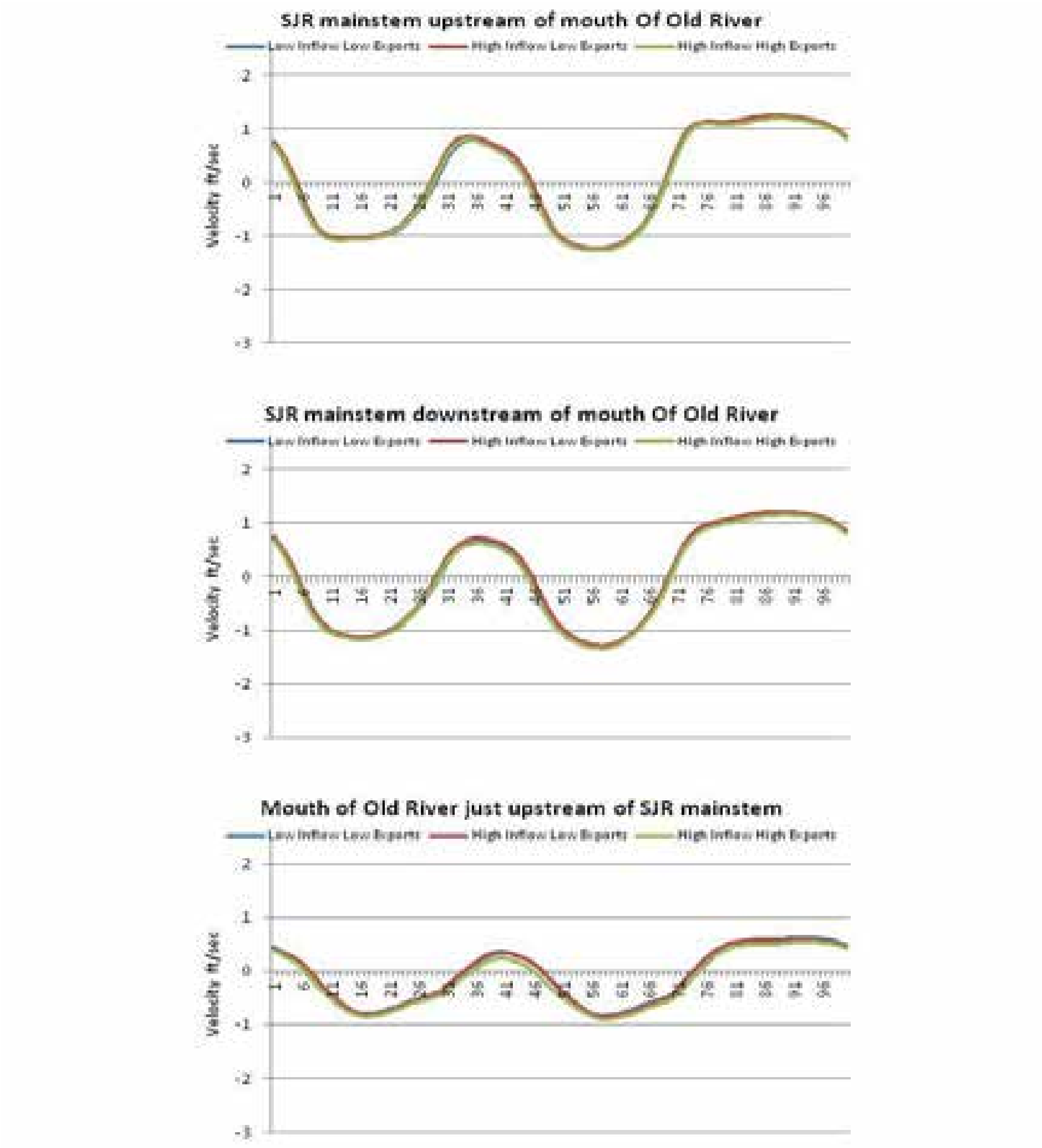


Figure 3-7. DSM2 Modeled Instantaneous 15-Minute Velocity Versus Time Over a Complete Tidal Cycle (~25 Hours) at the Junction of the San Joaquin and Turner Cut

Notes: There are three DSM2 channel reaches at the junction (three panels). Within each panel, there are three scenarios: low inflow/low export, high inflow/low export, and high inflow/high export.

Results of simulation modeling further downstream in the Delta at the mouth of Old River (Figure 3-8) showed an even stronger tidal signal (cyclic pattern in velocities) with positive (downstream) velocities on the ebb tide cycle and negative (upstream) velocities on the flood tide cycle at all three DSM2 channel reaches under all three scenarios. At the mouth of Old River there was virtually no variation in water velocities in response to either high or low river flow or high or low export rates.


SJR mainstem upstream of mouth Of Old River

SJR mainstem downstream of mouth Of Old River

Mouth of Old River just upstream of SJR mainstem

Figure 3-8. DSM2 Modeled Instantaneous 15-Minute Velocity Versus Time Over a Complete Tidal Cycle (~25 Hours) in Three Channels at the Junction of the San Joaquin River Mainstem and the Mouth of Old River

Notes: There are three DSM2 channel reaches at the junction (three panels). Within each panel, there are three scenarios: low inflow/low export, high inflow/low export, and high inflow/high export.

3.1.3 Summary of Findings

The application of hydrodynamic simulation models has proven to be a useful analytic and planning tool when applied at an average daily time step but has not yet achieved sufficient resolution for use in predicting hydrodynamic conditions experienced by a juvenile salmonid at the specific time and location when it encounters a complex channel junction in the South or Central Delta. Hydrologic simulations provide a means for evaluating local and regional changes in Delta hydrodynamic conditions associated with alternative water project management; however, the Delta channels and channel junctions are characterized by complex and dynamic conditions that complicate the development and interpretation of modeling results.

The 1-D DSM2 model, in particular, provides a tool for assessing changes in Delta hydrodynamic conditions that has been used extensively for water supply planning. Validation tests indicate that DSM2 is more accurate for predicting average daily metrics than 15-minute time step metrics (Appendices B and C). The model validates well at some locations with weaker agreement between observed and predicted flow and velocity at other locations. Factors such as simplifying assumptions for Delta consumptive water use, channel bathymetry, and complex geometry and dynamic tidal conditions contribute to variability in model validation. More complex 2-D or 3-D simulation models may be needed in some analyses to represent more complex hydrodynamic conditions on a finer time scale experienced by juvenile salmonids migrating through the Delta (Appendices B and C).

Selection of the appropriate simulation modeling tool should be based on the specific goals and objectives of an analysis, the level of resolution needed in model results, the complexities of the areas being modeled in terms of dynamic tidal and flow conditions, and channel geometry. The selected modeling tool should be calibrated and independently validated at a temporal and spatial scale appropriate for the desired analysis.

The effect of river flow is greatest in upstream riverine reaches and the effect of tides increases at downstream Delta locations. The effects of SWP and CVP exports on hydrodynamics is greatest in channels located in close proximity to the export facilities and decreases as a function of distance both upstream and downstream of the facilities.

3.1.4 Areas of Disagreement

The existing hydrodynamic models may not be useful for assessing how exports from the South Delta, river inflows, and tides may influence the magnitude, duration, and direction of water velocities within selected channels and channel junctions in the Delta at the spatial and temporal scales needed for biological studies, such as the analyses of salmon migration behavior and survival. Further model validation and refinement is needed before analysis of salmonid migration behavior and survival in response to changes in channel hydrodynamics can be conducted with confidence. Further, there is also currently no broad scientific agreement on threshold changes in flows or velocities that influence salmonid migration behavior or survival within a channel or at a channel junction. Some of the SST members felt that any change in velocity or flow resulting from water project operations could be biologically significant, while others felt that only changes above some threshold that has yet to be defined should be considered to have potential biological significance. For example, would a change in velocity at a specific location in the Delta as a result of a change in exports of 0.01 ft/sec, 0.1 ft/sec, or 1.0 ft/sec be expected to affect route selection, migration rate, or survival?

3.2 EFFECTS OF HYDRODYNAMICS ON MIGRATION RATE

Anderson et al. (2015) and others have hypothesized that the survival of juvenile salmonids migrating through the Delta varies as a function of their downstream migration rate and duration of residence in the Delta. The hypothesis assumes that the longer juvenile salmonids remain in the Delta, the greater their risk of mortality as a result of predation, entrainment into unscreened water diversions, exposure to adverse water quality conditions, and other factors. Water project operations during the juvenile migration period have the potential to affect migration rate by altering river flows through reservoir operations and releases, altering flow patterns or water velocities in the Delta through SWP and CVP exports, or installing temporary barriers.

3.2.1 Conceptual Model Predictions

The conceptual model predicts the following:

- The downstream migration rate of Chinook salmon and steelhead smolts will increase as river flow into the Delta increases.
- The downstream migration rate of juvenile salmonids will increase as water velocities increase in tributary rivers to the Delta.
- Migration rates of juvenile salmonids will be reduced in response to South Delta reverse flows as a result of increased SWP and CVP export rates (e.g., OMR reverse flows).
- Migration rates of juvenile salmonids will decrease as a result of bi-directional tidal flows and reduced downstream velocity in the Delta.

3.2.2 Analysis

Several salmonid migration studies conducted in the Pacific Northwest have shown evidence of a relationship between river flows and migration rates of juvenile salmon and steelhead. Raymond (1979) observed a decrease in migration rate of juvenile Chinook salmon and steelhead with decreasing flows associated with dams on 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.

Results of survival and migration studies in the Sacramento and San Joaquin rivers and Delta, however, suggest that the relationships between river flow and migration rates of salmonids through the Delta are more complex than in the Pacific Northwest. Williams (2006) characterized flow as a proximate factor that influences migration rate of juvenile Chinook salmon through the Delta but was not able to provide information from available coded-wire tag (CWT) studies on the relationship between migration rate and flow for riverine versus tidal regions of the estuary. Hankin et al. (2010) concluded 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." However, results of the VAMP CWT studies combine migration rates that include both riverine and tidal reaches. With the more recent application of AT technology, more precise estimates of migration rates and potential relationships with river flow have been developed. Michel et al. (2012), for example, found that water velocity and river flow were positively correlated with movement rate for juvenile late-fall-run Chinook salmon released in the Sacramento River 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 have been observed to decrease when juvenile salmonids enter the tidally dominated regions of the Delta where flows are bi-directional and the effect of river flow on water velocities is diminished.

A limited number of analyses were found that examined the potential relationship between SWP and CVP export operations, changes in channel velocities in the Delta, or the magnitude of OMR reverse flows and juvenile salmonid migration rates through the Delta. There is a growing body of scientific information from the six-year steelhead survival study, the associated juvenile salmon survival studies, AT monitoring of juvenile winter-run and fall-run Chinook salmon on the Sacramento River, the VAMP AT studies and others that can be analyzed to investigate relationships between migration rate and reach-specific and regional survival, as well as between water project operations and migration rates within the Delta. Analyses of the relationship between fish size, migration rate, and survival in South Delta channels, as well as migration rate through specific migration routes and associated survival, require further analysis.

3.2.3 Summary of Findings

Limited information from AT studies suggests a relationship exists between river flow, water velocities, and migration rate of juvenile salmonids in riverine reaches of the Delta but not within the tidally dominated regions of the estuary. Despite data being available from a number of recent studies, very little information exists on the potential relationships between water project operations and juvenile salmonid migration rates, reach-specific and regional survival, or how changes in water velocities and flow direction in the riverine versus tidally dominated regions of the Delta influence migration or survival.

Uncertainty remains regarding the following:

- How migration rates vary through specific reaches in response to variation in water project operations and inflow
- How the relationship between migration rate 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

Outside of the north Delta, it is not currently possible to predict how specific changes in flow and velocity impact migration rates. AT studies have not shown strong relationships between exports and migration rate under the conditions tested, but few analyses have focused on the relationship between exports and migration rate. Also, exports, velocities, and flows may be linked at some locations such that determining relative effects among these variables will be difficult.

3.3 EFFECT OF HYDRODYNAMICS ON 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. 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 the following:

- 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 HORB

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

3.3.1 Conceptual Model Predictions

The conceptual model predicts the following:

- Route selection at channel junctions is expected to be a function of tidal velocity, flow direction, and junction geometry resulting in route selection proportional to flow splits.
- Route selection at channel junctions varies 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 greatest in the immediate vicinity of the export facilities and diminish as a function of distance away from the facilities.

3.3.2 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, proportion of flow entering the distributary, 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 1-D DSM2. The proportion of juvenile salmon (both fall-run and late-fall-run Chinook salmon) migrating into each channel junction 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 (R2 = 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. There were fewer fish entering the single distributary (i.e., Turner Cut) in the tidally dominated regions of the Delta where both inflow and diversions had only small effects on predicted route selection. The hydrodynamics at such distributaries in tidally driven regions 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). 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.

Results of these analyses are generally consistent with the qualitative predictions from the conceptual model and prior studies (Kemp et al. 2005; Perry 2010) that route selection is generally proportional to the flow split at channel junctions and that the effect of exports on flow velocities and route selection diminishes with distance away from the facilities.

In 2012, a steelhead migration and survival study was designed and implemented in an effort to learn more about the effects of OMR reverse flows on survival through the Delta (Delaney et al. 2014). Yearling steelhead from the Mokelumne River hatchery were acoustic-tagged 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 South Delta. Unfortunately, tag detectors were not placed such that the probability of detection at all individual receivers could be determined. AT monitoring for the study show that juvenile steelhead migrates downstream through a variety of pathways and exhibit a wide range of behavioral responses to channel junctions under various export and hydrodynamic conditions (Delaney et al. 2014). The study showed that there was a higher probability of steelhead tags, located at the west end of Railroad Cut in Old River (about ten miles from the export facilities), to move south towards the export facilities as OMR reverse flows became more negative (Delaney et al. 2014).

Prior CWT studies have suggested that reducing the proportion of juvenile salmon that entered Old River would increase through-Delta survival, because survival had been shown to be, on average, greater in the San Joaquin River relative to that in Old River (Brandes and McLain 2001; SJRGA 2007). Several AT studies have been conducted within the southern part of the Delta over the past ten years to estimate reach and route-specific survival of Chinook salmon and steelhead (SJRGA 2013; Buchanan et al. 2013; Appendix E, Section E.4). Other studies assessed the benefits of a non-physical barrier, relative to increasing the proportion of fish entering the San Joaquin River at the head of Old River junction in 2009 and 2010 (Bowen et al. 2009; Bowen and Bark 2010). Results of the non-physical HORB studies conducted by Bowen et al. (2009), Bowen and Bark (2012), and the California Department of Water Resources (DWR 2015a) provided information on the potential behavioral response of juvenile migrating salmonids to the non-physical HORB; however, detailed information on water velocities, flow direction, and exports were not included as part of the analysis.

In 2011, the effects of CVP and SWP exports on route entrainment into the head of Old River on Chinook salmon (SJRGA 2013) and steelhead (Buchanan 2013) were evaluated. Variables included flow proportion, flow magnitude, velocity, and river stage. Similar analyses were conducted for the 2009 and 2010 Chinook salmon releases (SJRGA 2013). In 2009, there was a significant relationship between CVP exports and route selection at the head of Old River, when CVP export rate was the only factor considered, but when flow or velocity were accounted for in the model, the additional effect of CVP exports was not significant. In 2011, Chinook salmon route selection at the head of Old River was significantly related to flow and velocity in the San Joaquin River just downstream of the head of Old River (i.e., at San Joaquin Lathrop). Exports were considered but were not found to be significant. In 2011, no factors were significantly associated with route selection at the head of Old River for steelhead.

3.3.3 Summary of Findings

Results of hydrodynamic simulation modeling show that the proportion of flow splits at channel junctions such as Turner Cut and Columbia Cut is 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 by juvenile salmonids at these junctions along the San Joaquin River, DWR (2015b) investigated engineering solutions such as the installation of non-physical barriers in an effort to reduce route selection into Old River.

Results of fine-resolution acoustic and hydrodynamic monitoring in the Sacramento River at Georgiana Slough demonstrate the ability to predict route selection of juvenile salmonids based on the location of the fish in the channel cross-section and the hydraulic streaklines showing the proportion of the river flow entering the slough (DWR 2012). Studies that integrate salmonid migration behavior and hydrodynamics at channel junctions have not been conducted in the South Delta.

Based on the review of information, the SST concluded that:

- Juvenile salmonids encountering a channel junction typically select a migration route in proportion to the flow split, although other factors also appear to affect migration route selection (location in the channel cross-section, streakline location, and channel geometry).
- Fine-resolution AT monitoring, in combination with local hydrodynamic monitoring of flow direction and velocity, has proven beneficial in evaluating the behavioral response of juvenile salmonids encountering channel junctions along the Sacramento River at Georgiana Slough and the DCC.
- The behavioral response of juvenile salmonids encountering channel junctions along the San Joaquin River in the Delta (both channel configurations and hydrodynamics) has not been studied adequately.
- The general predictions from the conceptual model are supported by results of recent studies and analyses, although model refinements and additional monitoring and modeling should be performed to add specificity to the predictions.

3.4 EFFECTS OF TEMPORARY BARRIERS ON MIGRATION RATE AND ROUTE

During spring and summer months, DWR installs a series of temporary riprap barriers at strategic locations in the South Delta (Appendix A, Section A.1.1) 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. The temporary rock barrier has also been installed at the head of Old River in the fall to improve flows and dissolved oxygen concentrations in the lower San Joaquin River to benefit upstream migrating adult fall-run Chinook salmon.

3.4.1 Conceptual Model Predictions

The conceptual model predicts the following:

- Survival of juvenile salmonids to Chipps Island is expected to be higher in routes that avoid the Interior Delta; thus, overall survival to Chipps Island is anticipated to be higher in the presence of barriers and gates that block access to the Interior Delta routes (e.g., at the head of Old River).
- Installation of temporary barriers in the South Delta results in local changes in flows and water velocities that affect salmonid route selection and migration rates.
- Survival in localized areas where temporary barriers are installed is expected to be lower when the barriers are in because of the attraction of predators to the barrier sites.
- Barriers that result in delays in migration out of the Delta are expected to result in reduced survival.

3.4.2 Analysis

The effect of the temporary agricultural barriers in Old River near Tracy, Middle River, and Grant Line Canal (Appendix A, Section A.1.1) on juvenile salmon migration rate and survival was evaluated in 2011 (SJRGA 2013). Survival and travel times through the Delta were compared before and after the initiation of barrier installation. Total survival through the Delta to Chipps Island, as well as survival through the Old River route to Chipps Island, was higher for smolts passing Mossdale after the installation began for the OMR agricultural barriers. Travel time to CCF was also shorter after installation of the OMR barriers began (SJRGA 2013). At the Grant Line Canal barrier, more fish selected Old River and fewer fish successfully passed the barrier after installation began (passage success = 0.9972 before versus 0.9732 after, P = 0.04; SJRGA 2013).

Results from the 2011 study are somewhat paradoxical (e.g., shorter travel time and higher survival through the Old River route after barrier installation); however, because of temporal changes in conditions through the study season, effects of barriers on survival and 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 cfs to greater than 8,000 cfs. Also, comparisons were made relative to the initiation of barrier installation, which lasted from one to four weeks, depending on the barrier. Fish had relatively unimpeded passage during the early parts of installation. Most tagged fish had passed through the region before the barriers were installed.

As part of the South Delta Temporary Barriers 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 was used each year to represent actual hydrologic boundary conditions during the period that the barriers are installed.

Results of the DSM2 simulations 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 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.

The HORB is installed during the spring salmonid migration period to improve juvenile fall-run Chinook salmon survival on the San Joaquin River based on results of CWT survival studies conducted by the U.S. Fish and Wildlife Service (USFWS) (DWR 2015a; SJRGA 2007). The temporary rock barrier keeps juvenile salmon in the San Joaquin River mainstem where survival is thought to be higher than for those fish that migrate into Old River, reduces the movement of juvenile salmonids into the South Delta through Old River, and reduces exposure to potential entrainment into the SWP and CVP export facilities. SJRGA (2007) provides information on the survival relationships for CWT juvenile Chinook salmon when the HORB is installed and when it is not. Results of early CWT studies generally showed a pattern of increased juvenile survival when fish did 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 (see Section 3.7).

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

3.4.3 Summary of Findings

Results from CWT studies from 1985 to 1990 indicate installation of the HORB resulted in increased juvenile salmon survival, but acoustic telemetry data from 2010 to 2012 have generally not been consistent with that hypothesis. In most years, there was no significant difference between survival in the two routes, based on AT data, and survival has been very low in both routes. Survival of fall-run Chinook salmon from AT data was higher in the San Joaquin River route for one release group (in 2010), and higher in the Old River route for four release groups (2010 and 2011).

Although the SST did not conduct a comprehensive review of the existing study plans and data regarding 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 River 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 overall salmon and steelhead survival to Chipps Island over a range of hydrologic conditions remains unknown.

3.5 DELTA CROSS CHANNEL AND GEORGIANA SLOUGH MIGRATION ROUTE

The DCC radial gates are located on the Sacramento River upstream of Walnut Grove (Appendix A, Section A.1.1) 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 State Water Resources Control Board (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 higher mortality. Georgiana Slough is a natural channel located immediately downstream of Walnut Grove (Appendix A, Section A.1.1) that also provides a pathway for juvenile salmonids to migrate into the Interior Delta. Flow in the Sacramento River in the vicinity to these two junctions is uni-directional (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.

3.5.1 Conceptual Model Predictions

The conceptual model predicts the following:

- 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.

3.5.2 Analysis

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, 2015). Results of these studies show that DCC gate closures can decrease the number of fish entering the Interior Delta through the DCC. However, under low Sacramento River flows and bi-directional tidal flow, just as many tagged fish entered the Interior Delta through Georgiana Slough alone, as when the DCC gates are open (Perry 2010). Many tagged fish moved upstream into Georgiana Slough on flood tides.

Studies conducted in the early 1990s on the effectiveness of a non-physical (sound) barrier at Georgiana Slough showed similar results (Hanson and SLDMWA 1996). Under low river flow conditions and flood tidal stage, flow in the Sacramento River reversed direction with water moving upstream and into Georgiana Slough. Juvenile Chinook salmon released into the Sacramento River downstream of the confluence with Georgiana Slough were collected in Georgiana Slough.

During 2010 and 2011, detailed fine-grain 3-D AT monitoring was conducted in the Sacramento River as part of the Georgiana Slough non-physical barrier research investigation

(DWR 2012, 2015b; Perry et al. 2015). High-resolution 3-D AT detection provided detailed information on the precise location and migratory pathway for each of the ATs. 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.

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.

The National Marine Fisheries Service (NMFS) 2009 Biological and Conference Opinion for the Long-Term Operations of the Central Valley Project and State Water Project (BiOp) included a reasonable and prudent alternative (RPA) requiring DWR and U.S. Bureau of Reclamation (USBR) to consider engineering solutions to reduce the diversion of juvenile salmonids from the Sacramento River into the Interior and South Delta (BiOp Action IV.1.3). In response to this requirement, DWR has prepared an assessment of potential engineering approaches to improving juvenile salmon survival at various channel junctions in the Delta (DWR 2015b).

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 using ADCPs simultaneously to fine-scale fish movements. Results of velocity monitoring using ADCPs were used in local hydrodynamic simulation models to predict flow and velocity encountered by juvenile salmonids migrating through the test area.

3.5.3 Summary of Findings

The effects of DCC gate operations are well studied and understood, although several information gaps have been identified. Interest has been expressed in further examining potential alternative radial gate operations including gate closures in the fall to reduce adult fall-run Chinook salmon from straying from the Mokelumne River into the American River that would also allow some water flow into the Interior Delta to benefit water quality and other uses.

Although there have been several non-physical barrier studies conducted, conditions of low Sacramento River flow and strong tidal flow reversals have not been evaluated. 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 salmonids within the channel cross-section, channel configuration, flow, and velocity patterns have been identified as affecting route selection.

3.6 JUVENILE SALMONID SURVIVAL IN THE SOUTH DELTA

Over the past several decades, there have been a number of experimental survival studies conducted in the South Delta using juvenile Chinook salmon (Brandes and McLain 2001; SJRGA 2007, 2013; Buchanan et al. 2013; Appendix E, Section E.2). Past studies were performed using CWT juveniles released during the spring at various locations in the lower San Joaquin River and recaptured at Antioch and Chipps Island. More recent studies have used acoustic-tagged juvenile salmon and steelhead. Results of these studies are discussed in detail in Appendix E and summarized below.

3.6.1 Conceptual Model Predictions

The conceptual model predicts the following:

- Survival of juvenile salmonids varies among years with greatest survival during wet years and reduced survival in dry years.
- Survival of larger yearling steelhead is expected to be greater than that for smaller Chinook salmon smolts.

3.6.2 Analysis

Since 1998, survival studies conducted with both CWT and acoustic-tagged juvenile Chinook salmon have documented a substantial decline in survival in the lower San Joaquin River (Figure 3-9). Survival through the Delta tends to be lower than survival through comparable distances and environments for different populations (i.e., larger fish) or in different systems (Perry et al. 2010; Buchanan et al. 2013; Michel et al. 2015). Multivariate statistical analyses of the existing survival and migration data have been initiated but are not complete.

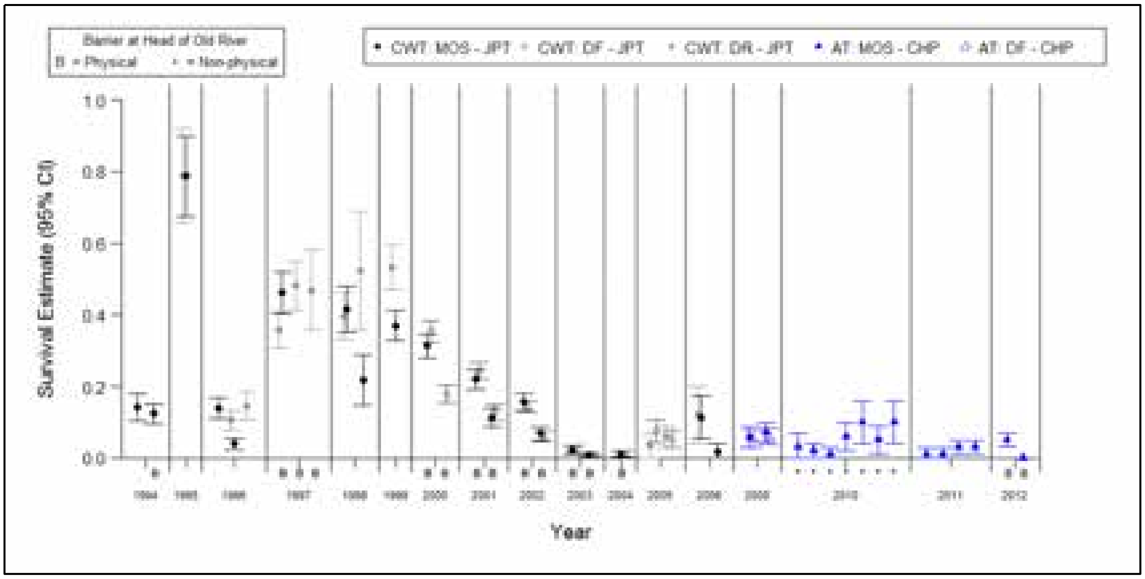


Figure 3-9. Estimated Survival of Fall-run Juvenile Chinook Salmon from Mossdale, Durham Ferry, or Dos Reis to Either Jersey Point (CWT) or Chipps Island (AT)

Note: Intervals are 95% confidence intervals, truncated to 0 if necessary.
Sources: SJRGA 2013; Buchanan et al. 2015

Results of survival studies have shown:

- Survival of acoustic-tagged fall-run Chinook salmon migrating through the Delta (to Jersey Point or Chipps Island) has been approximately 5% or less in recent years (Figure 3-9). Since 2002, survival from Mossdale to Jersey Point or Chipps Island has been less than 5% for 14 of 22 estimates, and less than 10% for 20 of 22 estimates (Appendix E, Section E.2.1.1).
- Survival to Chipps Island via export facilities is higher for the CVP than for the SWP.
- The survival rate per kilometer from the CVP to Chipps Island via salvage was sometimes higher than the survival rate through the lower San Joaquin River reaches.
- Sacramento River Chinook salmon and steelhead survival has been variable across years and among populations. For example, in 2013 and 2014, through-Delta survival was estimated at 32% and 35% for winter-run Chinook salmon, 0% to 30% for spring-run Chinook salmon, and 0% for fall-run Chinook salmon (data only for 2014), whereas between 2006 and 2010, late-fall-run Chinook salmon had through-Delta survival estimates ranging from 17% to 64%. Based on two years of data, survival of juvenile steelhead migrating from the Sacramento River (47 to 58%) has been comparable to estimates of Sacramento River late-fall-run Chinook salmon survival from the same years (34% to 64%).
- Based on data from 2011 and 2012, survival of acoustic-tagged juvenile steelhead migrating from the San Joaquin River (0.32 to 0.54) has been greater than that of fall-run Chinook salmon from the same years (0.02 to 0.03) (Appendix E, Section E.2.1, Table E.2-3).

The incremental contribution and relationships between water project operations, predation, and other stressors on the high levels of juvenile salmonid mortality observed in the South Delta is largely unknown. Results of acoustic tagging studies are beginning to provide information on reach-specific mortality; however, the underlying cause of the high mortality is uncertain.

3.6.3 Summary of Findings

Based on results of available information the SST concluded that:

- Survival of juvenile steelhead migrating through the San Joaquin River and Delta is greater than that for juvenile Chinook salmon. This finding is consistent with the conceptual model prediction that larger juveniles have greater survival, but this is based on only two years of steelhead survival data.
- Juvenile Chinook salmon survival did not increase in 2011 in response to wet hydrologic conditions when compared to dry conditions in 2012, which is not consistent with the conceptual model prediction.
- Survival of juvenile Chinook salmon has shown a declining trend with survival over the past decade, typically 5% or less for those fish migrating through the lower San Joaquin River and Delta, independent of hydrologic conditions.
- Survival of juvenile salmonids is generally greater in the Sacramento River than in the San Joaquin River, but varies with population and year.

3.7 SURVIVAL AS A FUNCTION OF ROUTE SELECTION

3.7.1 Conceptual Model Predictions

The conceptual model predicts the following:

- Route selection is a major factor in determining the probability of survival.
- Fish that migrate through Old River at its distribution point from the San Joaquin River are likely to have a lower probability of survival than those that use the San Joaquin River mainstem.
- Fish that enter the Interior Delta from distribution points farther downstream on the San Joaquin River (e.g., Turner Cut or Columbia Cut) or via Georgiana Slough are expected to have lower survival through the Delta than fish that remain on the mainstem river, whether they are migrating from the San Joaquin River or from the Sacramento River.
- Survival rates (per kilometer) are expected to vary within the Delta because of differences in habitat and predation pressure.
- Route selection is expected to be affected by the incremental effect of exports on water velocity and flow within a channel or at channel junctions.
- 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.

3.7.2 Analysis

Two primary routes through the South Delta were examined: Old River and San Joaquin River (Figure 3-10 and Figure 3-11). Migration through the CVP and SWP fish salvage facilities is a component of both routes because fish can enter the South Delta at Turner Cut or downstream. The primary differences in the routes are the upstream reaches.

Figure 3-10. Migration Routes to Chipps Island for Fish that Remain in the San Joaquin River at the Head of Old River ("San Joaquin River Route")

Notes: The migration route of salvaged fish is shown as a dashed line. The San Joaquin River mainstem subroute is shaded in red, and the Turner Cut subroute through the Interior Delta is shaded in orange.

Figure 3-11. Migration Routes to Chipps Island for Fish that Enter Old River at the Head of Old River ("Old River Route")

Notes: The migration route of salvaged fish is shown as a dashed line. The Old River subroute is shaded blue, and the Middle River subroute is shaded pink.

Migrating salmonids can enter the South Delta from the San Joaquin River via the head of Old River, Turner Cut, Columbia Cut, OMR, and False River. We did not examine junctions other than Old River and Turner Cut because there are no data on their use, but we recognize that they may be important entrances to the South Delta.

We first examined broad-scale, route-specific survival, then focused on reach-specific information to better understand patterns of survival at a smaller spatial scale.

Route Survival from the Head of Old River

At the head of Old River, fish either enter Old River and move into the South Delta or fish remain in the San Joaquin River. In many years, a temporary physical barrier (HORB) has been installed at the head of Old River to reduce the number of migrating salmon entering the Interior Delta at that junction. In 2009 and 2010, an experimental non-physical barrier (bioacoustic fish fence) was tested in place of the physical barrier (DWR 2015a). In 2012, the physical barrier was installed.

The following summarizes results of survival studies in relation to the installation of the HORB:

- From 1985 to 1990, the HORB was not installed. The fall-run Chinook salmon survival index to Chipps Island was greater for fish released in the San Joaquin River than for those released in Old River for all but one release group (Appendix E, Section E.12; Brandes and McLain 2001).
- In 2008 the HORB was not installed and AT Chinook salmon that remained in the San Joaquin River at the head of Old River had higher survival than fish that entered Old River. However, fish mortality was confounded with a high rate of premature tag failure (Holbrook et al. 2009) and there was no predator filter applied to AT data that year.
- In 2010, a bio-acoustic fish barrier was installed and the relative survival of Chinook salmon in the San Joaquin River route versus the Old River route varied throughout the study: only the first release group had significantly higher survival in the San Joaquin River. When the data were pooled across all releases, fish that took the Old River route had higher survival (SJRGA 2011).
- In 2011, no barrier was installed and survival of Chinook salmon to Chipps Island was consistently low, but was higher for two groups of tagged fish (out of five) that entered Old River during higher exports ($P < 0.05$) than for those that remained in the San Joaquin River (SJRGA 2013).
- In 2012, the Old River physical barrier was installed and survival was higher in the San Joaquin River route than in the Old River route for steelhead, but there was no difference by route for Chinook salmon (Buchanan 2015; Buchanan et al. 2015).

Reach Survival

Survival rates at the reach scale for Chinook salmon and steelhead in the San Joaquin River and Old River were examined to see how specific reaches contribute to route-specific survival. The examination used reaches and sub-reaches that generally corresponded with landmarks from previous studies and important junction locations within the South Delta as shown in Table 3-1 and Figure 3-12.

Table 3-1. Heat Map Depicting Survival Rates (S(1/km)) Through San Joaquin River Reaches to Chipps Island

	Survival estimate per km ($S^{(1/km)}$)						
	Chinook Salmon					Steelhead	
Reach Name (km)	2008	2009	2010	2011	2012	2011	2012
Durham Ferry (Release) to Banta Carbona (11)			0.999	0.994	0.975	0.962	0.967
Banta Carbona to Mossdale (10/9)			0.995	0.993	0.953	0.982	0.978
Mossdale to Head of Old River (4/5)	0.967	0.954	0.981	0.997	0.987	0.985	0.995
Lathrop to San Joaquin River at Garwood Bridge (18/15)	0.986	0.971	0.989	0.993	0.980	0.995	0.997
Garwood Bridge to SDWSC (3)	0.955	0.921	0.983	0.980	0.936	0.993	0.990

Reach Name (km)	Survival estimate per km ($S^{(1/km)}$)						
	Chinook Salmon					Steelhead	
	2008	2009	2010	2011	2012	2011	2012
SDWSC to Turner Cut Junction (15)	0.958	0.852	0.942	0.965	0.947	0.997	0.994
MacDonald Island to Medford Island (5)			0.863	0.833	0.852	0.942	0.923
Turner Cut to Jersey Point (includes Interior Delta route but not San Joaquin River) (28)	0			0	0	0.958	0.934
Medford Island to Jersey Point (21)				0.881	0.964	0.992	0.987
Jersey Point to Chipps Island (22)	0.981			0.983	0.971	0.997	0.989

Notes: SDWSC = Stockton Deepwater Ship Canal. Red boxes indicate lowest survival rate (less than 0.90 per km) and lighter boxes indicate higher survival rate (white: greater than or equal to 0.99 per km). Missing values reflect too few fish present in the reach to estimate survival, or the study was not designed to estimate parameter.

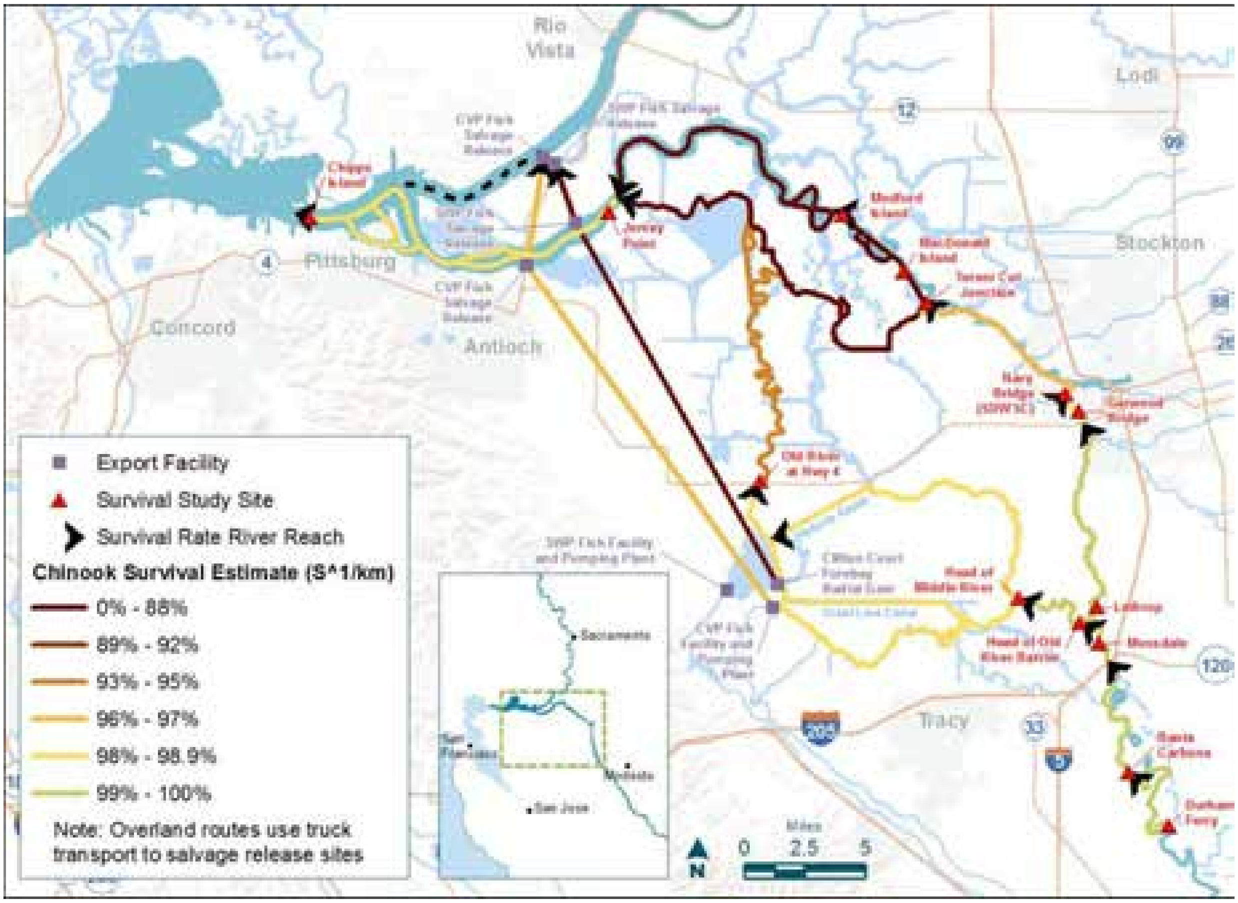


Figure 3-12. Geographical Illustration of Heat Map Survival Rate (per km) Estimates for 2011 Chinook Salmon

Note: See Table 3-1 and Table 3-2 for complete results from all years and species.

Turner Cut to Chipps Island

Survival of fish on the San Joaquin River mainstem between Turner Cut and Chipps Island is among the lowest for both Chinook salmon and steelhead (Figure 3-12). Migrating into Turner Cut resulted in even poorer survival to Chipps Island (Table 3-1; Figure 3-12). Results in 2010, 2011, and 2012 indicate that none of the 13%, 21%, or 11% of the Chinook salmon, respectively, estimated to have migrated into Turner Cut survived to Chipps Island (although some tags identified as predators were detected at Chipps Island) (SJRGA 2011, 2013; Buchanan et al. 2015). In contrast, the probability of surviving from the Turner Cut junction to Chipps Island for Chinook salmon that remained in the San Joaquin River at Turner Cut was estimated at 0.14, 0.02, and 0.14 for these three years, respectively (Appendix E, Section E.4.2.2; SJRGA 2011, 2013; Buchanan et al. 2015).

The acoustic telemetry study of juvenile steelhead that was part of the 2012 stipulation study (Delaney et al. 2014) also found that survival to Chipps Island was lower for steelhead that entered Turner Cut than for steelhead that remained in the San Joaquin River. Results from the first two years of the six-year study of acoustic-tagged steelhead (2011 to 2012) estimated the probability of surviving from the Turner Cut junction to Chipps Island as 0.43 and 0.18 for fish that entered Turner Cut, compared to 0.78 and 0.49 for fish that remained in the San Joaquin River (Buchanan 2013, 2014). This suggests that staying in the San Joaquin River at Turner Cut was beneficial for steelhead, as well as Chinook salmon.

Salmon Survival Through Old River

For survival reaches along the Old River migration route (Figure 3-12), survival rates per kilometer were often higher in the Old River to Middle River and Middle River to Highway 4 reaches, but there was considerable variability between years (Table 3-2). Survival rates for reaches leading to or bypassing the fish facilities (but not passing through the facilities) were generally comparable to those observed in the San Joaquin River for both Chinook salmon and steelhead.

Survival estimates are missing for some reaches and Chinook salmon release groups, either because the receivers were not in place to allow for survival estimation in the reach (e.g., survival to Jersey Point or Chipps Island in 2009; Table 3-1 and Table 3-2) or because too few fish were observed in the region to estimate survival (i.e., from the Highway 4 sites in 2012, when a physical barrier was installed at the head of Old River; Table 3-2).

The survival rates for fish passing into CCF were consistently low relative to other reaches for Chinook salmon and steelhead. The lowest observed survival rates for Chinook salmon, among all reaches in both the Old River route and the San Joaquin River route occurred in reaches that included the SWP and CVP fish facilities (including the Turner Cut route). Nevertheless, survival from the CVP to Chipps Island (via salvage) was sometimes higher than survival through the lower San Joaquin River reaches (Table 3-1 and Table 3-2).

Table 3-2. Heat Map Depicting Survival Rates (S(1/km)) Through Old River Reaches to Chipps Island

Reach Name/(km)	Survival estimate per km ($S^{(1/km)}$)						
	Chinook					Steelhead	
	2008	2009	2010	2011	2012	2011	2012
Old River (head) to Middle River Head (6)		0.953	0.983	0.997	0.981	0.990	0.977
Middle River Head to CVP/CCF/HWY 4 (20/21)		0.912	0.997	0.981		0.994	0.977
Old River near HWY 4 to Jersey Point (60)			0.926	0.936		0.992	0.958
CVP tank to Chipps Island (15/19)	0.845		0.972	0.969		0.988	0.973
CCF Radial Gates (interior) to Chipps Island (21/24)	0.904		0	0.83		0.979	0.924

Notes: Red boxes indicate lowest survival rate (less than 0.90 per km) and lighter boxes indicate higher survival rate (white: greater than or equal to 0.99 per km). Missing values reflect too few fish present in the reach to estimate survival, or the study was not designed to estimate parameter.

3.7.3 Summary of Findings

Results from CWT studies from 1985 through 1990 are consistent with the conceptual model predictions that through-Delta survival is higher for fish that avoid the Interior Delta, but AT data from 2010 through 2012 have generally not been. In most years, there was no significant difference between Chinook salmon survival in the two primary routes (San Joaquin River and Old River), based on AT data, and survival has been very low in both routes.

The routes that include the water export facilities tend to have the lowest survival through the Delta, including the route from Turner Cut through the Interior Delta. However, survival from the CVP to Chipps Island via salvage was sometimes higher than survival through the lower San Joaquin River reaches. Approaching the CVP appears to have high risk of predation, but successful passage to and through the salvage system enables the fish to avoid migrating through the rest of the South Delta.

Survival from the Turner Cut junction to Chipps Island has consistently been higher for fish that remain in the San Joaquin River at that junction than for fish that enter Turner Cut, for both Chinook salmon and steelhead.

Survival tends to be higher in the upstream reaches and in the San Joaquin River mainstem compared to the Interior Delta, although survival through the lower San Joaquin River reaches appears comparable to survival through Interior Delta reaches.

The linkages relating survival to migration route are not well understood. Although it is hypothesized that mortality is primarily due to predation, there is little direct information on predation rates, predator communities, and habitat characteristics that might affect predation rates throughout the South Delta.

3.8 SURVIVAL AS A FUNCTION OF MIGRATION RATE

Two differing conceptual models hypothesize how migration rate may influence juvenile salmonid survival: 1) a slow migration rate may lower survival by prolonging exposure to mortality risks such as predation and entrainment in the water project export facilities or other unscreened diversions; or 2) a slow migration rate may increase survival by increasing exposure to favorable rearing conditions in the Delta resulting in larger, healthier juveniles.

3.8.1 Conceptual Model Predictions

The conceptual model predicts the following:

- Juvenile salmonids with slower migration rate will have lower survival probabilities through the Delta.
- Juvenile salmonid migration rate is expected to be higher and more strongly related to water velocities in the riverine reaches of the Delta and slower in the tidal reaches.
- Migration rate is expected to vary among juvenile lifestages with migration rates increasing as a function of increasing fish length.
- Based on differences in size and maturity, migration rates for yearling steelhead that migrate, and do not residualize, are expected to be faster than for Chinook salmon smolts.
- Extended exposure to higher water temperatures may reduce fitness because of increased disease or increased predation rate because of heightened metabolic rate of the predators.
- Independent of temperature, prolonged exposure to regions with higher predation risk are expected to increase the probability of mortality.
- Extended exposure to the entrances to the water export facilities are expected to increase entrainment risk, but may or may not also increase the probability of being salvaged and trucked around the rest of the Delta.

3.8.2 Analysis

The XT model predicts that survival of prey (salmonids) will be proportional to migration rate in tidal reaches, as prey slow down relative to predators (Anderson et al. 2005). Several publications are available on the relationship between migration rate and survival in the Delta. It has been observed in the north Delta that slower migration rates are correlated with increased mortality of juvenile Chinook salmon (e.g., Perry et al. 2010). Cavallo et al. (2012) observed in an experimental study that large increases in flow were followed by increased migration rates and higher survival for juvenile Chinook salmon in the lower Mokelumne River, but the survival effect was not consistent across reaches.

The majority of information pertaining to the South Delta comes from CWT and AT studies (Holbrook et al. 2009; SJGRA 2010, 2011, 2013; Buchanan 2013, 2014; Buchanan et al. 2013, 2015). We examined migration rates and survival in the San Joaquin River and Old River for the same reaches described in Section 3.7. We also explored observed patterns in travel time and survival from Mossdale to Chipps Island and Jersey Point, using data from CWT studies from 1996 through 2006 (Newman 2008).

Migration rate (kilometers per day) in the San Joaquin River tended to be faster for both Chinook salmon and steelhead in the upstream reaches (Lathrop to SDWSC and Old River to the head of Middle River) compared to downstream reaches. The predominantly tidal reach between the upstream entrance of the SDWSC and the Turner Cut junction tended to have slower rates of travel. The reach from the CCF gates to Chipps Island (via salvage at SWP) had the slowest travel rates for steelhead.

Analysis conducted by the SST used simple linear regression to compare survival estimates of CWT fall-run Chinook salmon from the Mossdale area of the San Joaquin River to Jersey Point with travel time. The survival data are actually differential recovery rates (DRR) of CWT fish released in 1996 through 2006 upstream in the San Joaquin River (i.e., Mossdale, Durham Ferry, or Dos Reis) relative to those released at Jersey Point, and recovered in the Chipps Island trawl or in ocean fisheries (Newman 2008). Travel time was calculated as a weighted average of observed delay from release to recapture, for all individuals recaptured from a release group; Dos Reis release groups and ocean recoveries were omitted from the travel time calculations. Comparison of the DRR to average travel time showed no significant relationship between travel time and survival for these CWT data ($P = 0.52$; $r = 0.17$; Figure 3-13).

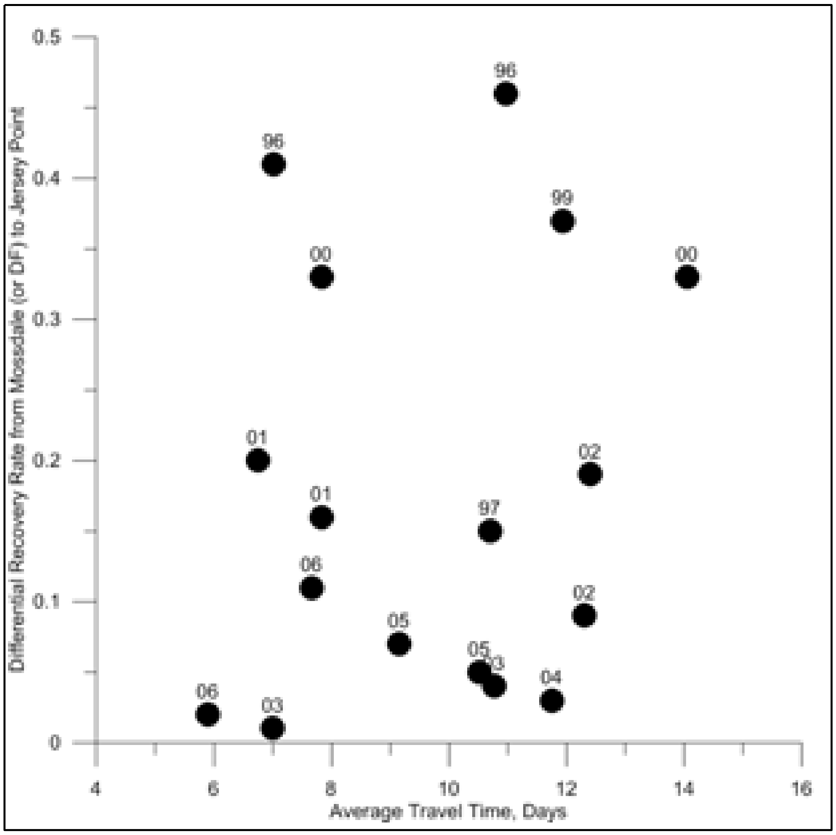


Figure 3-13. Average Travel Time of Specific Releases of Fall Chinook Salmon Versus an Estimate of Survival Based on a Ratio of Recovery Fractions for Upstream Releases to Downstream Releases at Jersey Point for the Mossdale to Jersey Point Reach

Note: Data plotted by Sheila Greene (Westlands Water District).

Results of the survival and migration studies conducted on the Sacramento River (Michel et al. 2015) showed evidence of a weak relationship between migration rate and survival for AT late-fall-run Chinook salmon produced in the Coleman hatchery and released into the upper Sacramento River at Battle Creek or Jelly's Ferry and monitored downstream to the Golden Gate as shown below:

Year	Overall % Survival	Mean Successful Migration Movement Rate (km/day)
2007	2.8	23.5 (+/- 3.6)
2008	3.8	17.5 (+/- 1.5)
2009	5.9	17.5 (+/- 1.1)
2010	3.4	21.9 (+/- 2.1)
2011	15.7	36.0 (+/- 3.0)

3.8.3 Summary of Findings

A positive association between migration rate and survival was observed in AT data for various regions of the Delta: north Delta (Perry et al. 2010) and lower Mokelumne River (Cavallo et al. 2012). Preliminary SST analysis of South Delta data observed this pattern in some reaches in the San Joaquin River (Lathrop to SDWSC) and SDWSC to Turner Cut (for steelhead only), and in the Old River between the heads of Old and Middle rivers. However, the migration rate-survival relationship was not consistent in all reaches, years, and data sources. The expected positive relationship between migration rate (kilometers per day) and survival was not observed from SDWSC to the Turner Cut junction for AT Chinook salmon. CWT Chinook salmon data from San Joaquin River releases showed no relationship between DRR (i.e., survival index) and travel time from upstream San Joaquin River sites to Chipps Island (Figure 3-13).

Although there are several years of data on survival and migration rate in some reaches of the San Joaquin River, we do not yet have a general understanding of the relationship between migration rate and survival in all regions of the Delta.

3.9 SURVIVAL AS A FUNCTION OF EXPORT RATE

Increased export rates have been hypothesized to draw more fish into the South Delta and into the water export facilities, decreasing survival through the Delta to Chipps Island. The effects of exports on juvenile salmonid survival may be direct effects (e.g., losses at the export facilities) or indirect effects (e.g., losses that occur in the Delta that are affected in some way by water project operations such as changes in Delta hydrodynamics that result in mortality through mechanisms such as predation or entrainment at unscreened water diversions).

3.9.1 Conceptual Model Predictions

The conceptual model predicts the following:

- Direct mortality is a function of export rates.
- Pre-screen loss is higher at the SWP than at the CVP because fish must navigate CCF outside the SWP.
- Pre-screen loss is higher for Chinook salmon than for steelhead because Chinook salmon are smaller.
- Louver efficiency is higher at higher export levels.
- Salvage can be used as a surrogate for entrainment rates.
- The rate of indirect mortality in the Delta will increase as export rates increase.

3.9.2 Analysis

A central issue confounding the ability to identify and isolate the influence of export and inflow on juvenile survival is the correlation of inflow and export rates across the range of conditions tested during acoustic telemetry and CWT survival studies. Mean values of San Joaquin River inflow at Vernalis during the VAMP management periods from 2000 through 2011 ranged from 2,280 cfs in 2009 to greater than 20,000 cfs in 2006; average observed export rates from the same periods ranged from 1,330 cfs to 5,750 cfs (Figure 3-14). Correlation between inflow and exports was r = 0.60 throughout the VAMP study; however, without the first observation from 2006, correlation was considerably higher (r = 0.98) (Figure 3-14). Newman (2008) also reported that "exports and flows were highly positively correlated" (r = 0.88) in his analysis of VAMP and pre-VAMP CWT data. Inflow is also partially confounded with the status of the HORB because the barrier cannot be installed when flows are greater than 5,000 cfs or operated when flows are greater than 7,000 cfs.

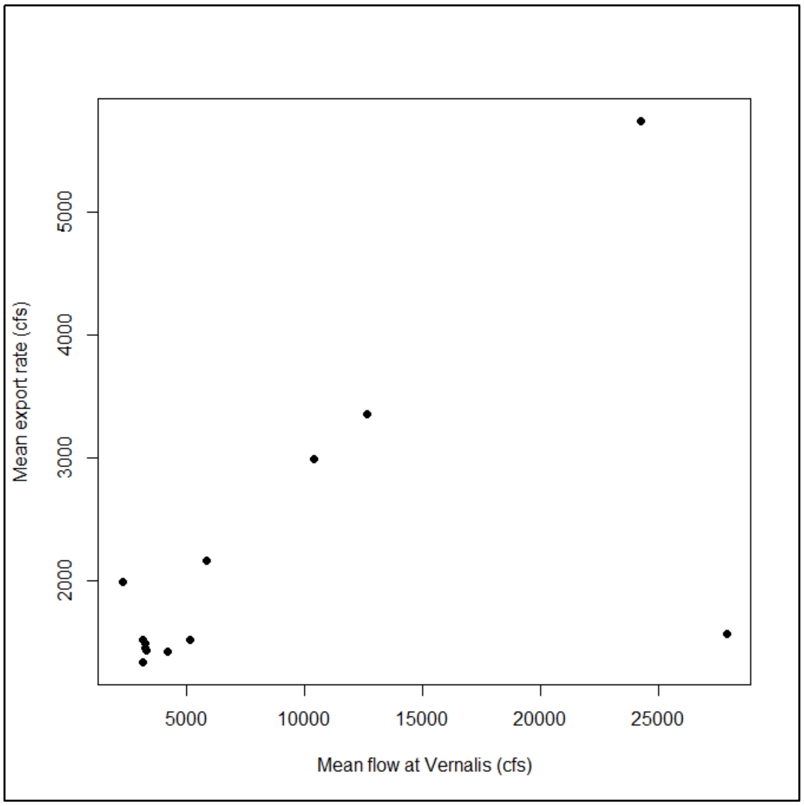


Figure 3-14. Observed Mean Inflow and Exports During VAMP Period, 2000 Through 2011

Note: Reproduced from SJRGA (2013).

The high correlation between covariates confounds estimation of the effects of the individual covariates. Single-variable analyses can identify observed relationships between individual covariates and survival, but will not be able to determine which covariates actually drive survival or account for multicollinearity. A multi-covariate analysis may be more appropriate to determine the relative effects of inflow, exports, and the barrier on survival, but will still be hindered by the degree of correlation among the covariates. Separating the effects of inflow and exports on survival is further complicated by the practice of increasing upstream reservoir releases to provide water for anticipated increased export rates.

A large number of survival studies have been conducted using CWT and more recent ATs to assess the potential relationships between SWP and CVP export operations and the migration and survival of juvenile Chinook salmon and steelhead (Brandes and McLain 2001; Baker and Morhardt 2001; Newman 2008; Newman and Brandes 2010; Perry et al. 2010, 2012; Perry 2010; Delaney et al. 2014; Zeug and Cavallo 2013, 2014; SJRGA 2007, 2013; Buchanan et al. 2013; Appendix E, Section E.6.2). Most of the available data on the survival of fish in the San Joaquin River relative to export levels were collected in the lower portion of the export range. More than 80% of the tests were conducted when exports were less than 4,000 cfs.

Many of the current management metrics for regulating export rates are based on a ratio between Delta inflow and exports such as the Delta E:I or San Joaquin River I:E. When these regulatory measures are in place, there is a high correlation between flows and exports. Therefore, distinguishing between the effects of exports and inflow on juvenile survival through correlation is difficult. No causal conclusions can be made from observational data and correlation analysis. The association between exports and survival has not been analyzed using rigorous statistical methods. These data are being processed and formal statistical analysis has been initiated.

The SST evaluated available CWT and AT data using visual inspection of scatterplots. Scatterplots are used to observe broad patterns in the data, but are not conclusive. The preliminary graphical analysis provided by the SST is meant to suggest possible relationships based on existing data, but is not meant to provide final conclusions on the existence and type of relationships between survival and inflows or exports.

Chinook Salmon

For Sacramento River late-fall-run Chinook salmon, Newman and Brandes (2010) reported evidence of a negative relationship between exports and the relative survival of Chinook salmon released in the Interior Delta compared to those released in the Sacramento River mainstem. However, they also reported equal support for a model that replaced exports with E:I, and nearly equal support for a simpler model that excluded exports entirely. They suggest that the indeterminacy of the modeling results may have resulted from a low signal-to-noise ratio in the data. In particular, there was a large amount of variability in the relative survival estimates that was unexplained by exports.

Newman (2003) reported a negative effect of exports on survival of Sacramento River fall-run Chinook salmon through the Delta, as well as significant effects of flow, salinity, temperature, tide, turbidity, and position of the DCC gate. Perry (2010) modeled survival of

AT late-fall-run Chinook salmon migrating through various routes in the Sacramento River as a function of flow, exports, and fish length, and found no effect of exports on survival in Interior Delta routes; he did not explore the possible effect of exports on survival in mainstem routes.

Simple single-variable graphical analyses using both CWT and AT data from San Joaquin River Chinook salmon also show equivocal patterns in survival and exports (Figure 3-15). Based on the CWT data, survival to Jersey Point appears to increase as exports increase for exports less than approximately 4,000 cfs, despite considerable variability not explained by export rate (Figure 3-15). However, this pattern does not appear to hold for the AT data, and is complicated by an unbalanced study design of export levels (i.e., many low export observations and few high) and the correlation between flow and exports. Unlike the CWT data, there does not appear to be a positive relationship between exports and survival using only AT data. Whether this is due to changes in study methodology or to changes in the system over time is not known (most CWT studies predate AT studies). Using either CWT or AT data alone or combined, there is considerable variation in survival estimates from Mossdale to Jersey Point for export levels less than 4,000 cfs, whereas the survival estimates for higher export levels are consistently low (upper left plot in Figure 3-15).

Similar patterns are observed for survival from Mossdale to Chipps Island from AT data (top right plot in Figure 3-15). This pattern is consistent with a factor-ceiling relationship, in which high levels of exports restrict the range of survival values, but low levels of exports impose no such restriction, and other factors control survival at low levels of exports. However, although the data suggest such a relationship may be possible based on a visual inspection of the scatterplots, it is important to note that there are only two survival observations for export levels greater than 4,000 cfs, and the low survival estimates observed for these two export levels are well within the range of observations at lower export levels.

Although it is possible that both the observed survival estimates for high export levels (i.e., greater than 4,000 cfs) were low because high export rates impose a low maximum survival, it is also possible that the limited range of the observed survival estimates was due to chance.

To explore that possibility, we ran simulations by randomly selecting two observations, without replacement, from the pool of estimated survival probabilities from low export levels (less than 4,000 cfs), and computed the frequency of observing only estimates less than the maximum observed for the higher export levels (i.e., less than or equal to 0.07). The event of observing only survival estimates less than or equal to 0.07 occurred in only 10% of 100,000 simulations, indicating a low probability of observing two such low estimates only by chance. This exercise supports the hypothesis that a high export rate imposes a maximum on through-Delta survival, although there remains uncertainty about the value of the maximum survival possible.

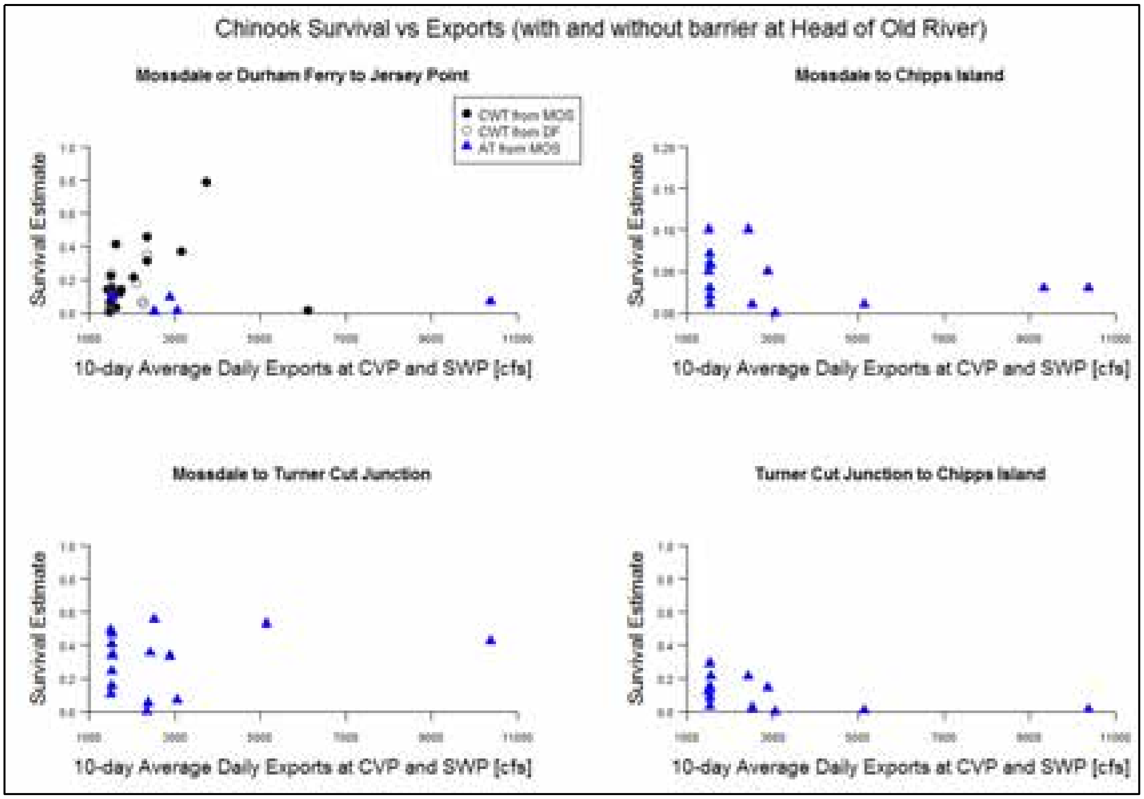


Figure 3-15. Estimated Survival of Fall-Run Chinook Salmon Versus the 10-Day Average of Daily Exports at CVP and SWP, Under all Barrier Conditions at the Head of Old River

Notes: Export rates are measured from the final day of release at Durham Ferry or Mossdale, downloaded from www.water.ca.gov/dayflow/. Before 2002, SWP omits Byron Bethany Irrigation District (BBID) intake; in 2002, SWP = Banks Pumping Plant flow; after 2002, SWP includes BBID. Survival from Mossdale or Durham Ferry to Jersey Point and Chipps Island includes all routes.

There is some indication that survival from Turner Cut to Chipps Island may decrease with increasing exports (Figure 3-15), but there is considerable variation in survival estimates at the lowest export level (1,500 cfs). Again, this is consistent with a factor-ceiling relationship in which the export rate restricts the maximum survival possible while other variables control the mean survival. However, as on other spatial scales, there are only two observations at exports greater than 5,000 cfs. Further analysis is warranted that accounts for barrier status at the head of Old River and intra-annual variation. Additional years of data are likely to be required to clarify any relationship between exports and survival.

During the VAMP study (2000 through 2011), low export rates were maintained during the spring outmigration period, resulting in low velocities at the primary louvers at the CVP Tracy Fish Collection Facility, which do not maintain high facility efficiencies. To compensate, the CVP attempted to increase the primary bypass ratio during these times, which resulted in increased secondary channel velocities, and higher recovery rates of Chinook salmon (USBR 2008). Gingras (1997) found higher survival for Chinook salmon in CCF when exports were higher. Nevertheless, visual inspection of simple scatterplots of estimated facility survival, from entrance at the CVP trash racks or CCF radial gates to Chipps Island, plotted against export rates show no well-defined trend, based on AT data from the VAMP study and the 2012 Chinook salmon tagging study in the South Delta (Figure 3-16). For survival from the CVP trash racks to Chipps Island, both the highest and lowest survival estimates were observed for the lowest levels of exports, whether restricted to CVP exports or to combined CVP and SWP exports (top row, Figure 3-16). This suggests that at very low export levels, a combination of factors that are not directly related to exports determine survival through the CVP. For average CVP export rates greater than 2,000 cfs (or combined exports greater than 5,000 cfs), survival from the CVP trash rack to Chipps Island was between 0.10 and 0.25, suggesting that export rates in this range may impose a restriction on the survival probabilities possible, but there does not appear to be a relationship between export rate and average survival probability (Figure 3-16). It is possible that a related factor determines survival at these export rates. Additional observations in this range (e.g., CVP greater than 2,000 cfs) may provide more insight into the relationship between exports and survival through the CVP facility. For survival through CCF to Chipps Island, survival was at or near 0 for all observations, except for one of the highest export levels (Figure 3-16). No survival estimates are available from the SWP trash racks to Chipps Island because acoustic telemetry receivers were not placed at the SWP trash racks.

On a population level, Zeug and Cavallo (2014) explored the factors affecting salvage of juvenile Chinook salmon at the CVP and SWP, and found that increased export rate was associated with increased salvage rates at both facilities for Chinook salmon from both San Joaquin River releases and Sacramento River releases. By estimating entrainment and direct mortality at the facilities from the salvage numbers, they concluded that increased exports result in increased facility mortality (including pre-screen loss, entrainment loss, and within-facility loss). Kimmerer (2008) came to similar conclusions for winter-run Chinook salmon, and found that the estimated proportion of winter-run juveniles exiting the Delta that were salvaged increased with increased export flows. The proportion of total loss in the Delta due to exports varied depending on pre-screen survival (i.e., survival from pre-screen loss and canal entrainment loss) (Kimmerer 2008; Zeug and Cavallo 2014). Zeug and Cavallo (2014) also noted that relating water diversions to the proportion of population loss due to entrainment is complicated by having few observations at higher export rates (i.e., only three observations of San Joaquin River entrainment loss for exports greater than 4,000 cfs).

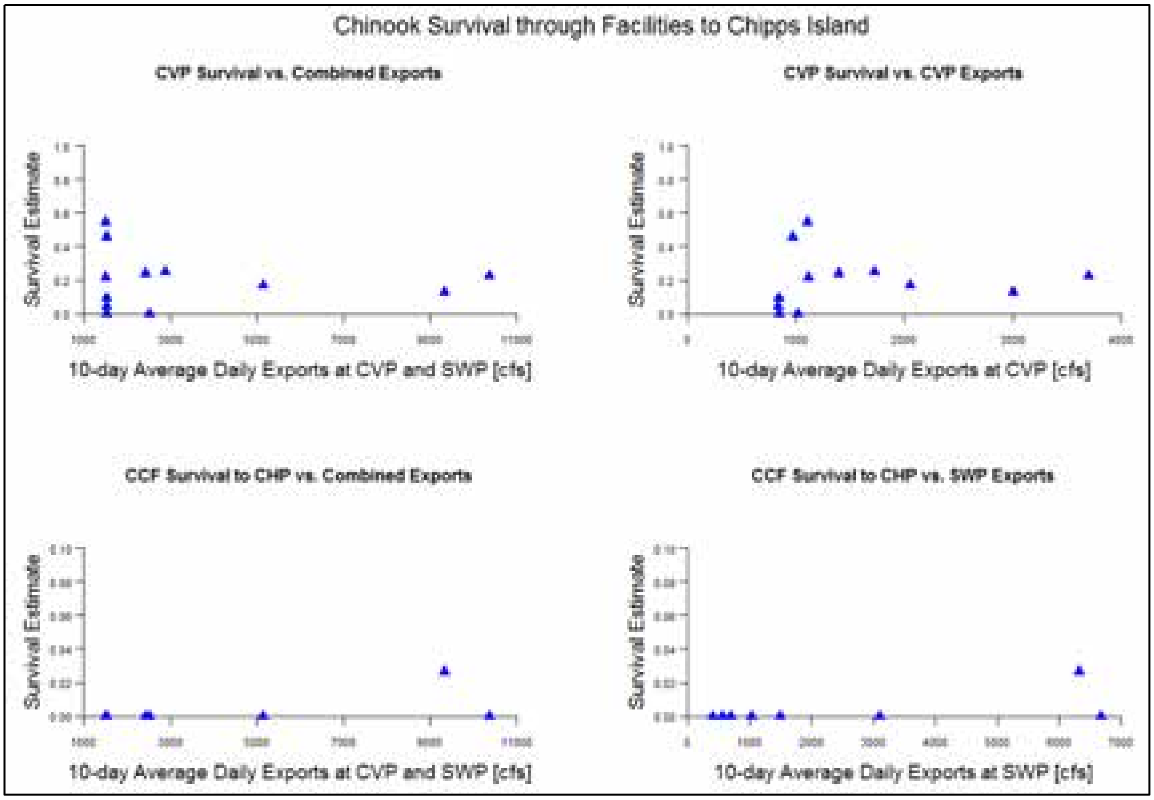


Figure 3-16. Estimated Survival of Fall-Run Chinook Salmon Based on Data from 2008 and 2010-2012 AT Studies, Versus the 10-Day Average of Daily Exports at CVP and SWP

Notes: Survival is from trash racks for CVP, and from radial gates at entrance to CCF for SWP. Survival from CCF to Chipps Island is through the SWP. Export rates are measured from the final day of release at Durham Ferry, downloaded from www.water.ca.gov/dayflow/. Export rate at SWP includes BBID diversions.

San Joaquin River Steelhead (Indirect Losses)

No published analysis of steelhead survival through the South Delta is available in the peer-reviewed literature. Visual inspection of the two years of survival estimates of acoustic-tagged steelhead through the South Delta (i.e., from Mossdale to Jersey Point or Chipps Island) shows an indeterminate relationship between combined export rates and survival (Figure 3-17). Survival from Mossdale to Chipps Island is slightly higher for higher levels of exports (greater than 3,500 cfs), but also higher for the lowest levels of exports observed during the two study years (2011 and 2012).

There was little variability in export levels during the study periods compared to the variability observed during the multi-decade Chinook salmon studies (Figure 3-17). When only evaluating survival on the San Joaquin River route from Mossdale to the Turner Cut junction, there was no indication of a relationship between exports and survival (Figure 3-17). From the Turner Cut junction to Chipps Island, and including routes from the Turner Cut junction through the salvage facilities, survival decreases as exports increase from approximately 2,500 cfs to 3,000 cfs, but is higher for export rates greater than 3,500 cfs (Figure 3-17). It is not known from only two years of data if the non-linear relationship observed is representative of all conditions, or if the variability in the survival estimates primarily reflects other variables such as inflow, status of the HORB, fish condition, or other factors, or simply interannual and seasonal variability. Based on visual inspection of Figure 3-17, there is no suggestion of a factor-ceiling relationship between exports and survival on any spatial scale. Additional AT data and analysis are needed including both higher and lower export levels.

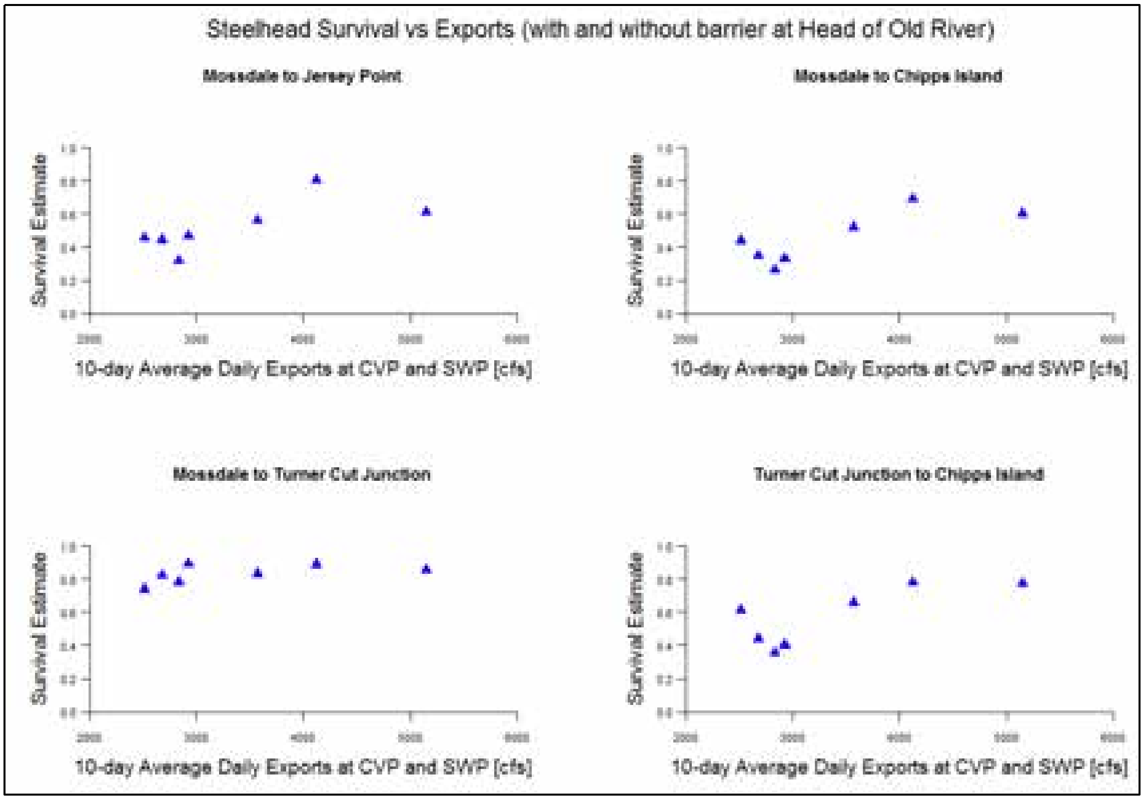


Figure 3-17. Estimated Survival of Steelhead Based on Data from 2011 and 2012 AT Studies, Versus the 10-Day Average of Daily Exports at CVP and SWP, Regardless of Barrier Status at the Head of Old River

Notes: Export rates are measured from the final day of release at Durham Ferry, downloaded from www.water.ca.gov/dayflow/. Export rate at SWP includes BBID intake. Survival from Mossdale to Jersey Point and Chipps Island includes all routes.

Survival of steelhead through the export facilities may be related to export rates. There is a higher probability of acoustic-tagged steelhead entering the CVP facility when flows through the CVP were higher (Karp et al. 2014). Scatterplots of estimated facility survival to Chipps Island from entrance at the CVP trash racks or CCF radial gates plotted against export rates for acoustic-tagged steelhead show a positive association between the CVP export rate (less than or equal to 4,000 cfs) and survival through the CVP to Chipps Island (Figure 3-18). Broadly speaking, there is a similar pattern for the SWP. A wide range of survival estimates is observed for low export rates while the few observations at higher export rates have relatively high survival (0.75 to 0.86) with little variation (Figure 3-18, bottom row).

However, there are insufficient data to adequately characterize a relationship, because there are only three observations at combined export rates greater than 4,000 cfs and because two years of observations are insufficient to reflect interannual variability. No survival estimates are available from the SWP trash racks to Chipps Island because acoustic telemetry receivers were not located at the SWP facility.

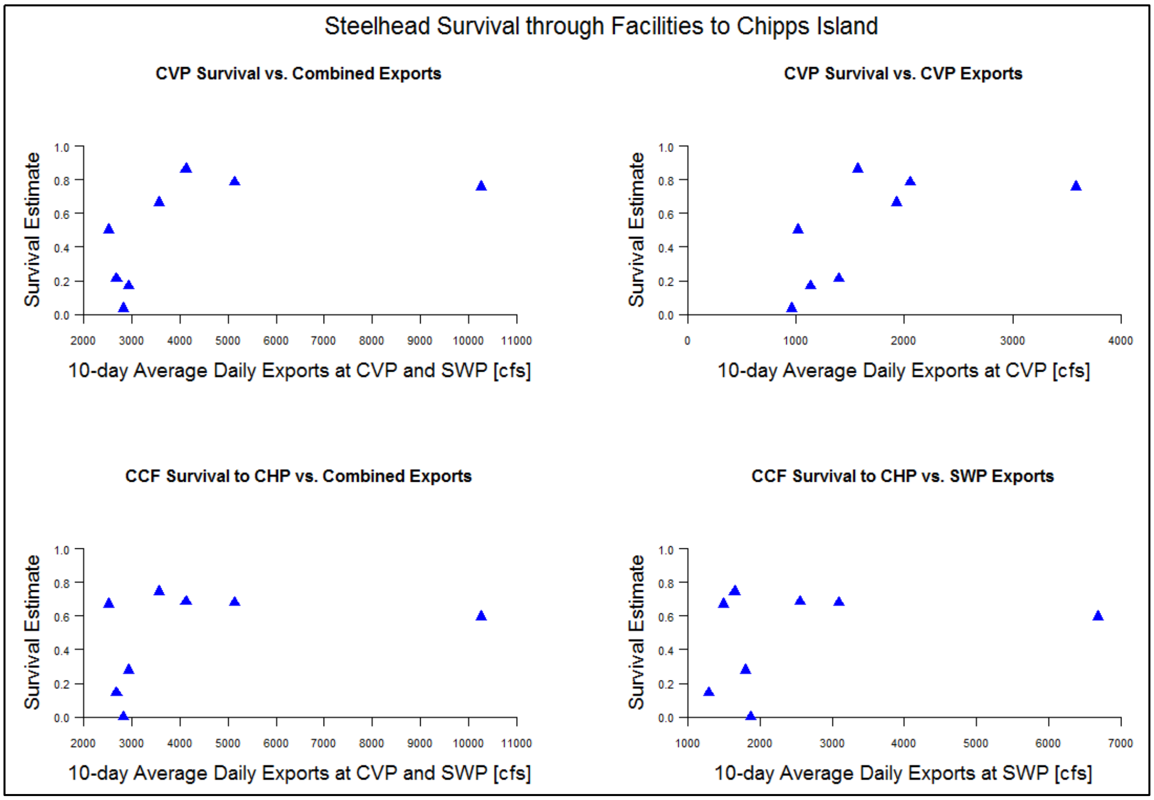


Figure 3-18. Estimated Survival of Steelhead Based on Data from 2011 and 2012 AT Studies, Versus the 10-Day Average of Daily Exports at CVP and SWP

Notes: Survival is from trash racks for CVP, and from radial gates at entrance to CCF for SWP. Survival from CCF to Chipps Island is through the SWP. Export rates are measured from the final day of release at Durham Ferry, downloaded from www.water.ca.gov/dayflow/. Export rate at SWP includes BBID diversions.

Direct Losses

Water project operations include CCF, export facilities (CVP and SWP), and intake canals leading to the facilities (Figure 3-19). Salvage facilities are located on the intake canals for the Tracy Fish Collection Facility (CVP) and John F. Skinner Delta Fish Protection Facility (SWP). These facilities are similar in design, using a primary louver system to direct fish out of the intake canals (primary channel) and into secondary channels. A secondary louver system or fish screen on the secondary channels directs fish into holding tanks, where fish are concentrated. At regular intervals throughout the day and night or as needed, fish in holding tanks are transferred to transport trucks and hauled to release sites on the lower Sacramento and San Joaquin rivers (Figure 1-1), and released through a pipe.

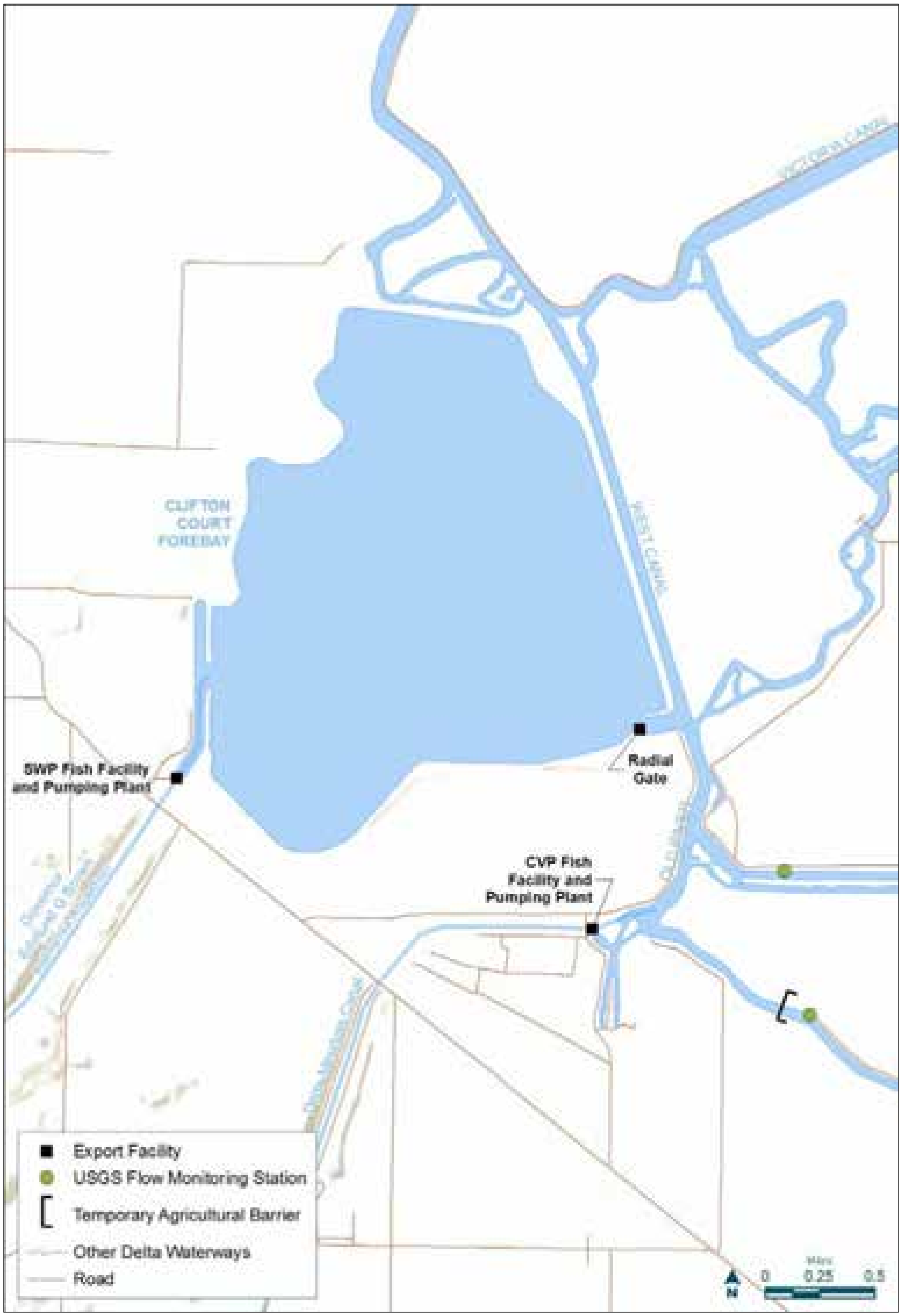


Figure 3-19. Location of CVP and SWP Fish Salvage Facilities Relative to CCF

The SWP and CVP salvage facilities differ in that the SWP facility is preceded by a large forebay (i.e., CCF) where water is collected and stored during high tides to maintain adequate water elevations for pumping. Although this forebay allows more flexibility for the timing of pumping relative to tidal stage, Chinook salmon and steelhead suffer higher mortality rates in CCF compared to the salvage facilities at either the CVP or SWP (i.e., from the trash racks at the entrance of the facilities through release after salvage). A multi-channel primary intake at the SWP salvage facility allows greater control over intake velocities and therefore more effective fish salvage than available at the CVP.

One of the challenges of evaluating impacts at the salvage facilities is correctly identifying fish (e.g., race, tributary of origin) that enter the facilities relative to those that enter and leave the Delta. For many years, genetic tissue sampling for winter-run salmon has occurred at the fish facilities, and has occurred for the spring-run more recently (Banks et al. 2014; Harvey et al. 2014). Genetic sampling of winter- and spring-run Chinook salmon has also occurred for 3 years for fish entering the Delta at Sacramento (2009, 2010, and 2011) and is also being conducted in 2016. Genetic tissue has not been consistently sampled from juvenile salmon entering, in, and leaving the Delta. Additional analyses of these samples could provide an opportunity to better enumerate the proportional loss of winter-run and spring-run salmon entering the fish facilities. Tissue sampling for salmon that enter and leave the Delta would help put the genetic information obtained at the fish facilities in perspective and would improve abundance estimates. Efforts are also being conducted in 2016 to obtain improved estimates of Sacramento trawl capture efficiency using captures of both AT and CWT juvenile winter-run Chinook salmon. The improved capture efficiency estimates, in combination with results of the 2016 genetics testing, will allow more accurate estimates of the numbers of juvenile winter-run Chinook salmon migrating into and surviving in the Delta.

No reliable estimates are available of the proportion of the juvenile steelhead population salvaged at the facilities for either the Sacramento River or San Joaquin River populations. NMFS has used a proportional loss approach to define the incidental take limit for direct export losses of juvenile winter-run Chinook salmon as 2% of the estimated number of juvenile winter-run entering the Delta from the Sacramento River based on the juvenile production estimate (JPE) calculated each year. Using a proportional approach, the losses at the export facilities are adjusted each year to account for variation in the annual production of juvenile winter-run Chinook salmon. A similar approach is used to estimate the proportion of juvenile spring-run Chinook salmon lost based on recapture of tagged surrogates at the salvage facilities.

Kimmerer (2008) evaluated the proportional losses of Chinook salmon resulting from direct project operations based on an analysis of CWT juvenile salmon released into the upper Sacramento River and subsequently recaptured in the fish salvage operations or in the USFWS Chipps Island trawls. Assuming a pre-screen loss in CCF of 80%, the mean salvage related loss was 10% at the highest levels of exports analyzed by Kimmerer (2008). This approach is consistent with results of experimental pre-screen loss studies reported by Kano (1990), Gingras and McGee (1997), and Clark et al. (2009). Zeug and Cavallo (2014) expanded the numbers of CWT salmon observed at the SWP and CVP fish salvage facilities to account for louver efficiency and pre-screen losses in order to develop estimates of total expanded loss for each CWT group as a percentage of the number of fish released. Results showed that the average total loss, expanded for louver efficiency and pre-screen losses, were 0.84% for late-fall-run, 0.2% for winter-run, and 0.03% for fall-run Chinook salmon released into the Sacramento River. The proportion of salvaged fall-run Chinook salmon released into the San Joaquin River was higher, as would be expected given the proximity of the river to the South Delta export facilities, with a mean total loss estimated to be 1.4%.

Zeug and Cavallo (2014) used a statistical modeling approach to assess factors related to entrainment into the SWP and CVP export facilities. Exports and other environmental variables used in the analysis were averaged over a seven-day period prior to the median capture date in the Chipps Island trawl based on results of AT monitoring indicating the average duration of salmonid migration through the Delta was 6.4 days (Michel et al. 2012). Separate statistical models were developed for the SWP and CVP export facilities. Results were expanded to estimate the proportion of the juvenile population at risk of loss. The model predicted a significant increase in salvage as diversion rate increased. There was a significant negative relationship between flow and salvage and a positive relationship between distance from release to export facilities and salvage at the CVP.

Efforts have been made to minimize direct mortality, including fish guidance away from pumps and into salvage facilities, and pumping schedules designed to limit the attraction of migrating fish to the facilities. Assessing the effects of these actions is hampered by several considerations. First, there is little direct data on fish mortality from entrainment, pre-screen mortality (at the CVP), or within-facility mortality. Instead, estimates of loss are computed based on salvage counts or salvage rates, and assumed parameters that represent pre-screen or within-facility mortality, some but not all of which are based on historical tagging studies; thus, loss estimates are constrained to increase as the effectiveness increases of an impact-reduction action that can promote migration survival (i.e., salvage). The quality of the assumed relationship between salvage and loss may vary between and within water years and salmon runs, making it difficult to monitor effects of management decisions on direct mortality with accuracy and precision. Second, there is considerable uncertainty about the population-level effects of direct mortality (i.e., the proportion of the migrating population that actually enters and is lost at the facilities). Third, all of the spatially precise acoustic telemetry data and much of the CWT data come from the period when export facilities have been operated to limit negative impacts on migrating salmon populations. This means there is relatively little variability in export rates during the salmon outmigration, and thus little opportunity to detect a survival relationship with export rate. It is notable that even during the period of export operations reductions designed to improve salmon survival, salmon survival has remained low through the Delta (especially for fall-run Chinook salmon).

Results of Chinook salmon CWT survival studies show that the percentage of an experimental release group that is recovered in SWP and CVP fish salvage operations is low (typically less than 1%) but these estimates do not account for mortality within the rivers and Delta prior to encountering the export facilities. Zeug and Cavallo (2014) provide an analysis of 749 CWT releases totaling more than 28 million juvenile Chinook salmon into the Sacramento River and found that on average 0.068% were recovered in SWP and CVP salvage operations. Late-fall-run Chinook salmon were recovered at a rate of 0.2%, winter-run at a rate of 0.05%, and fall-run at a rate of 0.01%. Results of the CWT analysis for juvenile fall-run Chinook salmon released into the San Joaquin River showed 0.6% of fish in 313 releases totaling more than 7 million fish were recovered in salvage operations (Zeug and Cavallo 2014). When Zeug and Cavallo (2014) estimated the proportional loss of the overall migration mortality accounted for by the CVP and SWP exports, they found it ranged from less than 1% to 17.5%, depending on race, export levels, and where the fish were released.

Clifton Court Forebay Gate Operations

The conceptual model predicts the following:

- Increased flow and water velocities resulting from opening the CCF radial gates result in increased salmonid entrainment into CCF and increased salvage.
- Increased water velocities and turbulence within CCF downstream of the radial gates result in increased vulnerability to pre-screen losses as a result of predation.

The 2,200-acre CCF is operated as a regulating reservoir within the tidal region of the South Delta for SWP water export operations (Clark et al. 2009). Water is diverted from Old River and West Canal into the CCF intake through five radial gates (each 20 by 20 feet). Diversion (gate opening) is timed to occur as the flooding tide reaches the CCF intake and through the early part of the ebb tidal cycle. The frequency that the radial gates are opened to flood CCF depends on the SWP export rate, the volume of water storage in CCF, and tidal conditions. When the difference in water surface elevation between Old River and CCF is greatest, water velocities through Clifton Court Canal typically exceed 15 ft/sec at flow rates typically ranging between 10,000 and 15,000 cfs (Clark et al. 2009). After CCF has been filled, the radial gates are closed and water exports are made from storage within CCF.

When CCF gates are initially opened, water velocities and flow entering CCF is high and juvenile salmonids in the immediate area of the gates would be vulnerable to entrainment into CCF and the salvage facility. Juvenile salmonids would continue to be vulnerable to entry into CCF as long as the radial gates remain open. Gingras and McGee (1997) also observed striped bass moving into and out of CCF while the radial gates were open. When the gates are closed, salmonids are not vulnerable to entrainment into the SWP. In contrast, hydrodynamics in Old River and West Canal are continuously affected by CVP export rates but at a substantially lower rate than occurs when the CCF gates are opened. The hydrodynamic simulation models that are currently in use do not use actual measured flow or velocity entering CCF but rather rely on estimates of flow predicted by differential storage or stage. Further, analyses of relationships between export rates and salmonid salvage at the SWP and CVP facilities and survival through the Delta have relied on average export rates for both facilities, typically over a period of one to two weeks as if CCF did not exist.

<u>Pre-Screen and Facility Losses</u>

Pre-screen loss occurs on the facility side of the trash racks at the CVP and downstream of the radial gates at the entrance to CCF and is assumed to be caused by a large predator population adjacent to and within the salvage facilities. The seasonal and interannual variability of the pre-screen loss is unknown. The evidence of loss due to predation comes from a variety of sources, as follows:

- There is indirect evidence from outside of the Delta that illustrates that salmonid predators aggregate at areas where migrating smolts are concentrated (Rieman et al. 1991; Ward et al. 1995; Sabal 2014). Within the Delta, Brown et al. (1996) observed that predators are abundant near intakes, screens, and louvers at the CVP and SWP facilities.
- During a one-month beach-seining effort in 1992, more than 80% of the fish sampled from CCF were striped bass that were large enough to prey on juvenile Chinook salmon (Brown et al. 1996).
- Gingras and McGee (1997) observed large numbers of predator-sized striped bass move back and forth through the CCF radial gates on very short timescales.
- Estimates of pre-screen mortality at the SWP ranged from 63% to 99% for a series of tagged Chinook salmon releases between 1976 and 1993 (Gingras 1997).
- Studies conducted with tagged steelhead estimated pre-screen mortality between 78% and 82% (Clark et al. 2009). These pre-screen mortality rates were considerably higher than those estimated for steelhead once they had entered the SWP John F. Skinner Delta Fish Protection Facility salvage facility (26%; Clark et al. 2009).

In the 2010 VAMP study, a large number of detections at the CCF radial gates of ATs originally inserted into juvenile fall-run Chinook salmon were classified as predator detections based on assumed behavioral differences between Chinook salmon and predators such as striped bass. When detections classified as coming from predators were included in survival analysis, the estimated probability of passing through the CCF entrance channel to the interior CCF was 0.74 (SE = 0.04); without those "predator-type detections," the estimated probability of entering CCF was reduced to approximately 0.28 to 0.36 (SE = 0.05), depending on the status of gate opening upon arrival in the entrance channel. In both cases, estimated survival from the radial gates to Chipps Island was very low: 0 without the predator-type detections, and 0.01 with the predator-type detections (SJRGA 2011).

The pre-screen loss at the CVP intake (upstream of the trash rack) is based on an unsupported assumption of 15% constant loss for juvenile salmonids. No quantitative studies have been conducted to determine the actual pre-screen loss at the CVP intake for either juvenile Chinook salmon or steelhead; available estimates do not distinguish between pre-screen loss and failure to be guided by the primary louvers.

The CVP Tracy Fish Collection Facility salvage facilities also provide favorable habitat for predatory fish, primarily striped bass. Striped bass reside around and inside the bypass channels of the salvage facility in higher densities than typically observed in natural settings. These predatory fish take advantage of low velocity holding areas provided by facility structures to prey on smaller fish drawn into the facility, including juvenile salmonids (Liston et al. 1994; Vogel 2010; Sutphin et al. 2014). Mobile monitoring in 2010 suggested predation was still an issue in front of the CVP trash racks, with a total of 37 ATs detected near this location, although it is unknown if more tags were deposited elsewhere (SJRGA 2011).

Salvage

Salvage rates and the survival of salvaged salmon and steelhead have been estimated, but there is considerable uncertainty about the number and proportion of salmonid migrants that are salvaged annually, and the population-level effect of salvage operations. From recent AT studies in the South Delta, it appears that most of the juvenile Chinook salmon and steelhead mortality within the Old River migration route occurred after the fish entered CCF or the CVP or migrated past Highway 4 on Old River:

- For juvenile Chinook salmon in 2010 and 2011 (but not 2012) (SJRGA 2011, 2013; Buchanan et al. 2015)
- For juvenile steelhead in 2011 and 2012 (Buchanan 2013, 2015; Buchanan et al. 2015)

In each of these cases, survival from Mossdale to the export facilities or Highway 4 (annual average = 0.66 to 0.77 for Chinook, 0.55 to 0.78 for steelhead) was considerably higher than total survival from Mossdale to Chipps Island through the Old River route (annual average = 0.04 to 0.07 for Chinook, 0.07 to 0.52 for steelhead). Furthermore, approximately three times as many Chinook salmon, and three to nine times as many steelhead, entered the facilities as arrived at Highway 4 (annual averages). This observation, combined with low survival from the facility entrances or Highway 4 to Chipps Island, suggests that the greatest proportion of mortality in the Old River route in these studies occurred after juvenile salmonids either passed through the CVP trash racks or entered CCF.

In acoustic telemetry studies, among the fish that went to the facilities, similar proportions of Chinook salmon went to the CVP as to CCF in 2010 and 2011 (SJRGA 2011, 2013). Nevertheless, for Chinook salmon in 2010 and 2011, estimated transition probabilities from the CVP trash rack to Chipps Island were higher than from CCF to Chipps Island, indicating higher mortality due to some combination of pre-screen loss, entrainment loss, and facility loss at CCF and SWP than at the CVP (SJRGA 2011, 2013). In 2012 when the HORB was in place, very few Chinook salmon were observed entering the Old River route, none were detected at CCF, and only one at the CVP (which was later detected at Chipps Island)

(Buchanan et al. 2015). In contrast, more steelhead went to CCF than to the CVP in both 2011 and 2012, and no more than 10% of the tagged steelhead detected at Chipps Island came via the CVP in these years (Buchanan 2013, 2015).

Despite the high mortality observed through the salvage facilities in these studies, the route through the CVP salvage, holding tank, and truck transport often represented the majority of the tagged Chinook salmon observed at Chipps Island from San Joaquin River acoustic telemetry studies. In 2010 and 2011, over 60% of the tagged salmon detected at Chipps Island came through the salvage facilities and truck transport at CVP (SJRGA 2011, 2013). In 2010, 19 of the 20 acoustic-tagged juvenile Chinook salmon that survived to Chipps Island via the Old River route, and 29 tagged salmon that survived to Chipps Island via all routes combined, came by way of the CVP (Buchanan et al. 2013), suggesting that survival through the CVP was higher than through all alternative routes.

3.9.3 Summary of Findings

The conceptual model predicted that increased export rates would result in decreased survival through the Delta to Chipps Island. Findings from CWT and AT data for Chinook salmon have been inconsistent and data for steelhead are limited. Findings include:

- A negative relationship between export rate and through-Delta survival was found for Sacramento River fall-run Chinook salmon from CWT data (Newman 2003), although more recent AT data from late-fall-run Chinook salmon showed no relationship (Perry 2010).
- The relative success of the Interior Delta route compared to the Sacramento River mainstem route to Chipps Island was negatively related to export rate, but a model that omitted export rate accounted for the variability in the data equally well as the export models (Newman and Brandes 2010).
- CWT data from San Joaquin River fall-run Chinook salmon provide moderate evidence of a positive relationship between through-Delta survival and export rates, but may be due to the high correlation between exports and San Joaquin River inflow (Newman 2008; SJRGA 2007).
- AT data from San Joaquin River fall-run Chinook salmon provide moderate evidence that high export rates are associated with low through-Delta survival, but there are few observations at high export rates, and considerable variability in survival estimates at low export rates.
- Comparison of CWT ocean recovery rates with measures of Delta hydrodynamics, including export rates, found no evidence of a relationship but reflect both Delta and ocean survival (Zeug and Cavallo 2013).
- Only two years of steelhead AT data have been analyzed, and they depict an indeterminate relationship between export rates and through-Delta survival.
- CWT and AT survival studies have been conducted using Central Valley Chinook salmon for over four decades with survival studies using steelhead being conducted

using ATs over the past six years. The majority of these experimental studies focus on survival within the tributary rivers and Delta and have not been used to quantify the incremental effect of water-project-related impacts (lethal and sublethal) on the overall population dynamics, abundance, or resilience of the species.

- Direct mortality of juvenile Chinook salmon due to export operations (e.g., pre-screen losses, entrainment, and salvage) appears to be low based on results of CWT recoveries analyzed by Zeug and Cavallo (2014).
- The incremental contribution of export operations and associated changes in flows and velocities in the Delta to indirect mortality (i.e., water project operations-related mortality that occurs outside the facilities and CCF) has not been quantified.
- At present, we do not adequately understand how survival varies in response to export rates. Limited information is available on the following:
  - Influence of export rates on the relative survival in different routes through the Delta for San Joaquin River salmonids
  - Interannual and within-season variability in survival at high export rates on various spatial scales

3.10 SURVIVAL AS A FUNCTION OF DELTA INFLOW

Delta inflow has been hypothesized as an important factor affecting juvenile downstream migration through the rivers and Delta. As shown in Section 3.1 and Appendix B Section B.5 and Figure B.5-8, inflow to the Delta has a larger effect on hydrodynamic conditions upstream in the more riverine reaches of the tributary rivers and a diminishing effect further downstream as tidal influence becomes a stronger factor affecting Delta hydrodynamics.

3.10.1 Conceptual Model Predictions

The conceptual model predicts the following:

- Increased Sacramento River inflow is associated with increased survival to Chipps Island for Chinook salmon and steelhead migrating from the Sacramento River.
- A positive relationship exists between San Joaquin River inflow and through-Delta survival for both salmon and steelhead.
- A stronger relationship between San Joaquin River inflow and survival exists in upstream regions of the San Joaquin River and Interior Delta compared to downstream regions where tidal conditions become more dominant.

3.10.2 Analysis

There have been a large number of CWT and more recently AT studies designed to examine the relationships between Delta inflow from the Sacramento and San Joaquin rivers and survival of juvenile salmonids migrating through the Delta to Chipps Island (SJRGA 2007, 2013; Buchanan et al. 2013; Appendix E). However, Delta inflow is highly correlated with export rates and distinguishing between effects of exports and inflow is difficult (see Section 3.9; Appendix E, Section E.2.3). To date, results of most of these survival studies have been limited to examining correlations between Delta inflow during the period that an experimental group of tagged salmonids are migrating downstream and their estimated survival at Chipps Island. For CWT fish there is no ability to assess the migration route or reach-specific survival.

Survival as a Function of Sacramento River Inflow

The relationship between Sacramento River inflow and survival through the Delta for Chinook salmon has been explored separately by Newman (2003) and Newman and Rice (2002) using CWT data from fall-run Chinook salmon, and Perry (2010) using AT data for late-fall-run Chinook salmon. Newman and Rice (2002) report a slight positive effect of Sacramento River flow on survival, but caution that the flow effect was confounded by salinity. Newman (2003) modelled survival of fall-run Chinook salmon using Sacramento River discharge measured at Freeport and found a positive effect of flow on survival, along with significant effects of exports, tide, temperature, salinity, turbidity, and position of the DCC gate. Perry (2010) modeled survival of late-fall-run Chinook salmon using Sacramento River discharge just downstream of Georgiana Slough. He found a positive relationship between Sacramento River discharge below Georgiana Slough and survival in both the Sacramento River mainstem and Sutter and Steamboat sloughs for late-fall-run Chinook salmon, as well as between fish length and survival.

Kimmerer (2008) and Zeug and Cavallo (2014) investigated the effect of Sacramento River inflow on salvage rates for CWT hatchery Chinook salmon. Kimmerer (2008) found no relationship between proportional salvage or total salvage and Sacramento River flow for winter-run Chinook salmon. Zeug and Cavallo (2014) reported that the probability of collecting any fish in salvage was negatively associated with Sacramento River inflow for both the CVP and SWP, and the number of salmon salvaged was also negatively associated with inflow for CVP salvage of winter-run, late-fall-run, and fall-run Chinook salmon. Assuming that salvage and entrainment vary together, this suggests that entrainment loss is also negatively associated with Sacramento River inflow.

Results of AT survival studies for late-fall-run Chinook salmon on the Sacramento River (Michel et al. 2015) over four low-flow years (2007 through 2010) and one high-flow year (2011) showed overall survival ranged from 2.8 to 5.9% under low-flow conditions but increased to 15.7% under high-flow conditions in 2011. The observed increase in survival in 2011 under high-flow conditions was consistent with the trend predicted by the conceptual model.

Survival as a Function of San Joaquin River Inflow

The presence of the physical rock barrier at the head of Old River depends partly on San Joaquin River inflow. The rock barrier cannot be installed at flows greater than 5,000 cfs, and cannot be operated (e.g., without wash-out) at flows greater than 7,000 cfs. Because the barrier restricts route selection at the head of Old River, and may affect downstream survival due to flow effects and predator distribution (DWR 2015a), this restriction means that any effect of San Joaquin River inflow on survival may depend on the status of the barrier (SJRGA 2007). In addition, the effect of inflow is expected to be stronger in the upstream reaches of the San Joaquin River because tides override the influence of San Joaquin River inflow on hydrodynamics further downstream in the Delta (see Section 3.1).

Zeug and Cavallo (2014) investigated the effect of San Joaquin River inflow on entrainment of San Joaquin River fall-run Chinook salmon in the CVP and SWP, based on CWT release sizes and salvage numbers. They found no effect of flow on entrainment at the SWP. At the CVP, they found a positive association between flow and the probability of observing fish in salvage (Zeug and Cavallo 2014). This finding is counter to the conceptual model's prediction, but may partially reflect a positive correlation between exports and inflow during CWT studies.

Chinook Salmon

The 2006 VAMP report (SJRGA 2007) reported results showing a stronger relationship between CWT salmon through-Delta survival and San Joaquin River inflow when the HORB was installed compared to when the HORB was not installed. A relationship has also been reported between adult fall-run Chinook salmon escapement to San Joaquin River tributaries and spring flow in the San Joaquin River two and a half years earlier when juveniles were migrating downstream; however, the strength of the flow-escapement relationship is based on years when river flow was extremely high (flood conditions; SJRGA 2007). Newman (2008) found a significant effect of San Joaquin River inflow at Vernalis in predicting fall-run Chinook salmon survival to Jersey Point, with higher inflows associated with higher survival estimates, based on CWT data. However, because the HORB cannot be installed when San Joaquin River flows are high (greater than approximately 5,000 cfs), the effect of inflow is confounded with the effect of the barrier. Newman (2008) recommended further exploration. Zeug and Cavallo (2013) found no support for a hydrologic model (including both exports and inflow) of an index of joint Delta survival and ocean survival using ocean recovery rates, but caution that variability in ocean survival may swamp the signal of any relationship between Delta inflow and Delta survival.

These modest relationships between CWT salmon survival and Delta inflow are not consistent or robust. For example, 2006 and 2011 were high-flow years and 2012 was a low-flow year, but survival estimates to Chipps Island in the high-flow year (2011) were similar to those in the low-flow year (2012) (Figure 3-9). The HORB was absent in 2011 because of the high flows and most acoustic-tagged Chinook salmon (60%) reaching the head of Old River continued migrating down the San Joaquin River, while approximately 40% entered Old River at that junction; survival to Chipps Island was low in both routes (less than or equal to 0.04) (SJRGA 2013). The barrier was in place during the low-flow year of 2012, and most tagged Chinook salmon remained in the San Joaquin River, but survival was very low (Figure 3-9). This pattern is consistent with an interaction between an inflow effect and a barrier effect, in which the effect of inflow depends on the barrier. However, distinguishing between an inflow effect and a barrier effect, and describing any interaction between them, is complicated because the HORB cannot be operated or installed during high-flow conditions. Thus, any barrier-inflow interaction effect must be interpreted only for inflow less than 7,000 cfs (the highest inflow for which the barrier may be operated).

The relationships between survival of CWT and acoustic-tagged Chinook salmon and average 10-day San Joaquin River flow at Vernalis are shown in Figure 3-20 for all years, regardless of status of the HORB. Results for survival between Mossdale or Durham Ferry and Jersey Point were characterized by high variability, especially at river flows greater than 10,000 cfs. Results of AT survival studies (upper right panel) showed no clear pattern between survival and river flow. A relatively strong positive relationship between inflow and survival appears to exist for the reach between Mossdale and Turner Cut, whereas there appears to be a negative relationship between flow at Vernalis and survival from Turner Cut to Chipps Island. However, these results are based on only visual inspection of data from only four to five years, depending on the reach. With a physical barrier in place, there are only two survival estimates available on this spatial scale, which is too few observations to characterize the variability in reach-specific survival. Thus, it is not currently possible to determine the relationship between Vernalis inflow, the barrier, and survival in different regions of the Delta. There is a lack of data on reach-specific survival in the presence of a physical barrier as well as reach-specific survival at high inflow levels.

Steelhead

Visual inspection of the few steelhead data available shows an overall increase in survival from Mossdale to Jersey Point or Chipps Island as San Joaquin River inflow increases (Figure 3-21). The increase is noticeable on the reach scale from the Turner Cut junction to Chipps Island, but not from Mossdale to Turner Cut. Of the two years of steelhead data, 2011 was a high-flow year in which the HORB was absent, and 2012 was a low-flow year in which the rock barrier was installed and operating. Survival to the Turner Cut junction was similar in both years (Figure 3-21). Overall, survival to Chipps Island was slightly lower in 2012.

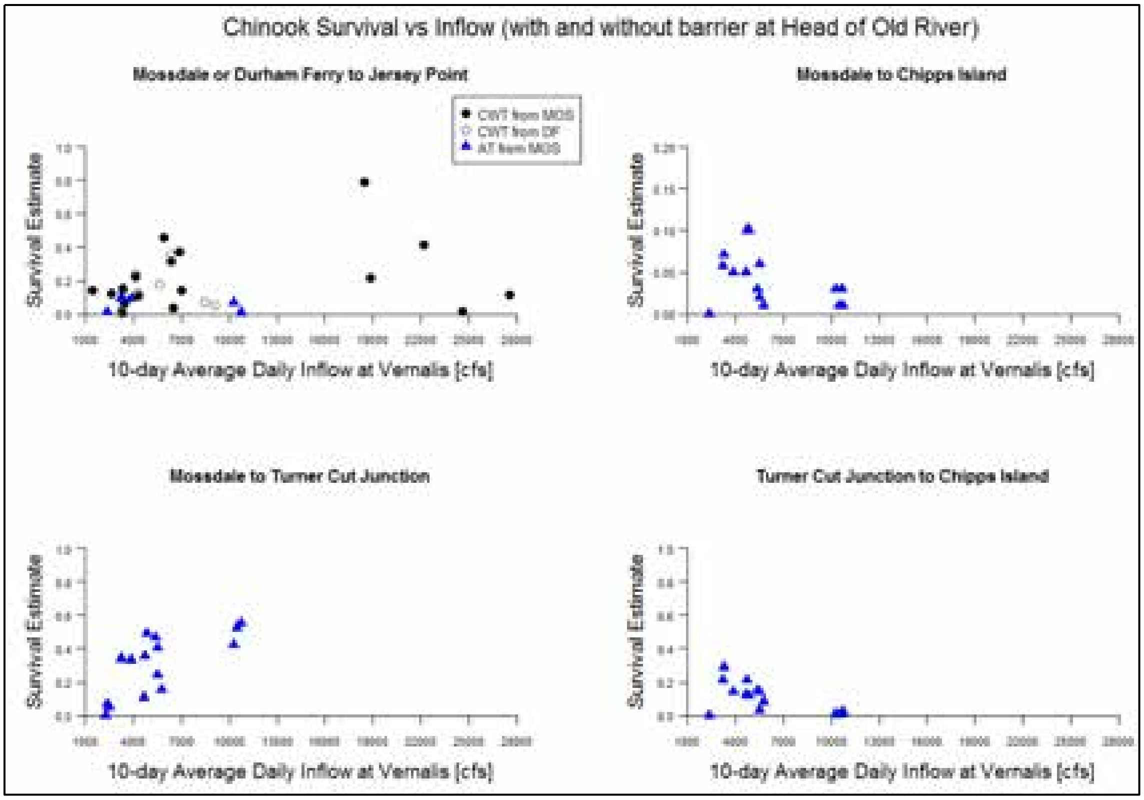


Figure 3-20. Estimated Survival of Fall-Run Chinook Salmon Versus the 10-Day Average of Daily Average Inflow at Vernalis, for All Barrier Status Conditions at the Head of Old River

Notes: Inflow data are measured from the final day of release at Durham Ferry, downloaded from www.water.ca.gov/dayflow/. Survival from Mossdale to Jersey Point and Chipps Island includes all routes.

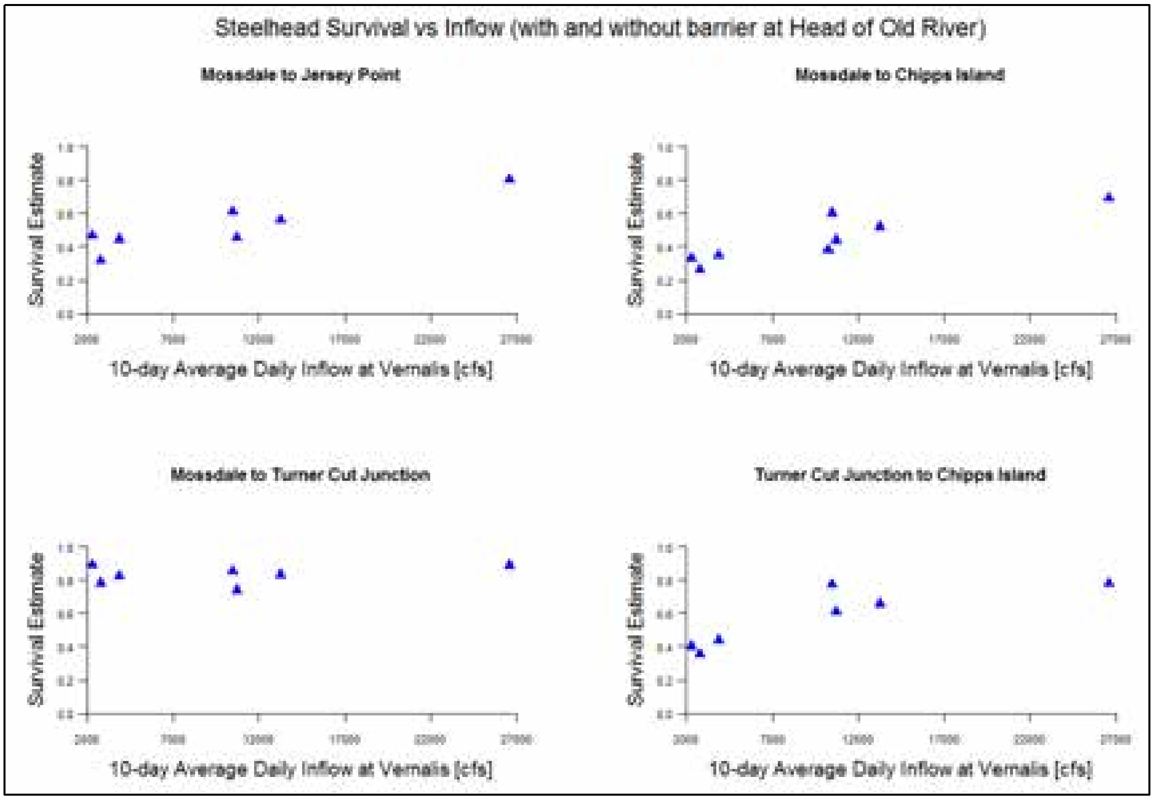


Figure 3-21. Estimated Survival of Steelhead Based on Data from 2011 and 2012 AT Studies, Versus the 10-Day Average of Daily Exports at CVP and SWP, Regardless of Barrier Status at the Head of Old River

Notes: Inflow data are measured from the final day of release at Durham Ferry, downloaded from www.water.ca.gov/dayflow/. Survival from Mossdale to Jersey Point and Chipps Island includes all routes.

The spatial pattern observed for steelhead is in contrast to the pattern observed for fall-run Chinook salmon, where a positive relationship between inflow and survival was observed from Mossdale to the Turner Cut junction, but a possible negative relationship was observed from the Turner Cut junction to Chipps Island. One difference between Chinook salmon and steelhead from the acoustic telemetry studies is that steelhead have been observed successfully reaching Chipps Island after entering the South Delta at Turner Cut, whereas no Chinook salmon that have entered Turner Cut have been observed at Chipps Island (Table 3-2; Appendix E, Section E.4.2).

3.10.3 Summary of Findings

The concept of higher survival associated with higher inflow is supported by tagging studies of juvenile salmonids on some spatial scales but not on others. Inflow appears to affect survival more in the upstream reaches where the environment is more riverine, and less in the downstream reaches that are more tidal (see Section 3.1).

Although inflow is a factor in juvenile salmonid migration survival through the Delta, it is not the only factor influencing survival, and it is unlikely that survival can be controlled through inflow alone. The low Chinook salmon survival in 2006 and 2011, both high-flow years, contributes substantially to the uncertainty in the flow-survival relationship.

3.11 SURVIVAL AS A FUNCTION OF THE SAN JOAQUIN INFLOW:EXPORT RATIO

The BiOp (NMFS 2009) included a requirement (RPA IV.2.1) that limits SWP and CVP export rates during April and May to a fraction of the San Joaquin River flow at Vernalis. The I:E varies among years in response to hydrologic conditions up to a ratio of 4:1. The ratio is intended to reduce the potential effects of SWP and CVP exports on downstream migrating juvenile steelhead that emigrate from the San Joaquin River tributaries and pass through the Delta during April and May.

3.11.1 Conceptual Model Predictions

The conceptual model predicts that:

- Delta survival increases with I:E, and the relationship may depend on the status of the HORB.
- The relationship between I:E and survival may vary in different regions of the Delta.

3.11.2 Analysis

The Bureau of Reclamation has conducted experimental survival studies using hatchery-produced yearling steelhead since 2011 (six-year steelhead survival study). Results have undergone preliminary analyses for 2011 and 2012, and are in the process of being analyzed for 2013 through 2016. Additional data are also available from experimental survival studies conducted using CWT juvenile fall-run Chinook salmon (e.g., SJRGA 2007) and more recently using acoustic-tagged juvenile Chinook salmon (SJRGA 2011, 2013; Buchanan et al. 2013, 2015).

For most of the available survival estimates of through-Delta survival, the I:E ratio was less than 5. The ratios tested for fish released into the San Joaquin River ranged from 0.99 to 17.9. Results from CWT studies and preliminary results from acoustic telemetry studies have shown a limited positive relationship between I:E ratio and survival of San Joaquin fall-run Chinook. The 2006 VAMP report compared a CWT survival index (Durham Ferry or Mossdale to Jersey Point) to the San Joaquin River I:E for San Joaquin River Chinook salmon, and found a significant positive association when the HORB was in place (slope = 0.22, $P < 0.05$), and no significant relationship when the barrier was not in place (SJRGA 2007).

The available estimates of survival through the Delta, from either CWT or AT data, were plotted against the 10-day average I:E (Appendix E, Section E.11.2). The correlation between inflow and exports observed in these data complicates predictions of survival versus I:E. Visual inspection of scatterplots of the available survival estimates through the Delta to Jersey Point show that most estimates are for 10-day average I:E less than 5. Aside from the status of the HORB, there is considerable variability in survival for I:E les than 5. However, the maximum observed survival estimate to Jersey Point increased to 0.46 as I:E increased from 1 to 3, while only low survival estimates (range = 0.01 – 0.14) were observed for I:E of approximately 4. The highest survival estimate to Jersey Point (0.79), from Chinook salmon CWT data in 1995, was observed for I:E = 5.0; lower estimates were observed for I:E = 9.4 and approximately 16 to 18, but these estimates were nevertheless higher than many of the survival estimates for I:E less than 5. All estimates for I:E greater than 4.5 were from CWT studies.

In general, estimated survival to Jersey Point tended to increase with I:E when the HORB was installed, but no estimates for I:E greater than 3 were observed with the barrier. For survival to Jersey Point, a similar pattern in survival estimates was observed for I:E as for inflow for I:E less than 5: a general increase in the maximum observed survival estimate, and considerable variability about the mean survival estimate below this maximum.

Zeug and Cavallo (2014) compared salvage models for CWT Chinook salmon using inflow and water diversion rates (exports) as separate factors to models using the ratio of exports to inflow, and found that the ratio (I:E) did not account for the variability in salvage rates, as well as including inflow and exports separately. The available AT survival estimates from San Joaquin River Chinook salmon from the CVP trash racks to Chipps Island for acoustic-tagged Chinook salmon demonstrate considerable variability relative to I:E. Most exhibit very low survival estimates for I:E greater than 3, but the highest survival estimates also occurred for I:E greater than 3.

3.11.3 Summary of Findings

Findings show a complicated relationship with considerable variability, based mostly on provisional visual inspection of scatterplots:

- CWT Chinook salmon data show increased through-Delta survival for higher levels of I:E, up to approximately I:E = 3, in the presence of a physical barrier at the head of Old River, but no relationship in the absence of the barrier (SJRGA 2007).
- AT Chinook salmon data show a similar pattern for I:E less than 3, but mostly in the absence of a physical barrier at the head of Old River.
- Both CWT and AT Chinook salmon data show more variability, but mostly lower, through-Delta survival estimates for I:E between 3 and 5, all in the absence of a physical barrier at the head of Old River.
- Few observations from tagging data are available for I:E greater than 5, and all are from CWT data.

- Comparison of adult Chinook salmon escapement to the San Joaquin River basin between 1951 and 2003 with San Joaquin River I:E two and a half years before adult return showed a positive association (years 1951 through 2003; SJGRA 2007; updated by the SST through 2012); I:E values ranged up to greater than 300 during this time period, although most observations were less than 10.

3.12 SURVIVAL AS A FUNCTION OF THE DELTA EXPORT:INFLOW RATIO

The Delta E:I is a regulatory requirement in the SWRCB Water Quality Control Plan D-1641. The ratio of SWP and CVP export rates to total Delta inflow during the winter and spring is limited to 35%, while the E:I ratio during the remainder of the year is limited to 65%.

3.12.1 Conceptual Model Predictions

The conceptual model predicts the following:

- Exports are expected to have a negative effect on survival, and inflow a positive effect on survival.
- As the ratio of exports to inflow increases, survival is expected to decrease.
- Direct mortality in the facilities affects only fish that enter the South Delta, so the relative survival in the South Delta route to survival in the Sacramento River mainstem and San Joaquin River route is expected to also decrease as E:I increases.

3.12.2 Analysis

Newman and Rice (2002) found that increases in the ratio of exports to Sacramento River inflow were associated with lower survival of Sacramento River fall-run Chinook salmon through the lower Sacramento River and Delta, but the effect was small and not statistically significant. For late-fall-run Chinook salmon released into the northern Interior Delta (i.e., Georgiana Slough), Newman and Brandes (2010) reported nearly equal support for three models of the relative survival of Interior Delta releases to Sacramento River mainstem releases that used either the ratio of exports to Sacramento River inflow, exports alone, or no exports. Zeug and Cavallo (2014) found that the E:I explained less variation in salvage rates of hatchery CWT fish from the Sacramento River than using measures of exports (E) and inflow (I) separately.

Cunningham et al. (2015) used data on salmon stock abundance (adult escapement and juvenile run estimates) to calibrate a lifecycle model for Sacramento River Chinook salmon, and concluded that juvenile outmigration survival through the Delta depended on the E:I for fall-run Chinook salmon, but not for the spring-run or winter-run Chinook salmon. For the fall-run Chinook salmon, Delta survival was estimated to decrease as the E:I increased (Cunningham et al. 2015).

3.12.3 Summary of Findings

Findings have generally shown a negative relationship between E:I and survival for Sacramento River Chinook salmon, but evidence is sometimes weak or the relationship is non-statistically significant:

- E:I has a small, non-statistically significant negative effect on survival of fall-run Chinook salmon (Newman and Rice 2002).
- Models using E:I to account for variation in CWT recovery data had approximately the same, or less, support from the data as models that used either exports alone or no measure of exports for late-fall-run Chinook salmon (Newman and Brandes 2010), and less support from the data as models that used exports and inflow separately for fall-run, late-fall-run, and winter-run Chinook salmon (Zeug and Cavallo 2014).
- A stage-structured lifecycle model found a negative effect of E:I on survival through the Delta for fall-run Chinook salmon but not for spring- or winter-run salmon (Cunningham et al. 2015).

3.13 MIGRATION AND SURVIVAL AS A FUNCTION OF OLD AND MIDDLE RIVER FLOWS

SWP and CVP exports can result in reverse flows occurring in OMR, depending on other Delta hydrologic conditions such as inflow from the San Joaquin River. Although flows in OMR 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 are identified as an important factor affecting juvenile salmonid migration through the Delta in the BiOp (NMFS 2009).

3.13.1 Conceptual Model Predictions

The conceptual model predicts the following:

- Increased negative OMR reverse flow is expected to draw fish from the Sacramento River or lower San Joaquin River into the South Delta and toward the export facilities, and to prevent fish that have entered the South Delta from navigating northward through Delta channels to exit the Delta.
- Increased negative OMR reverse flow is expected to decrease through-Delta survival of Sacramento River and San Joaquin River salmon and steelhead.
- For San Joaquin River fish that have already entered the South 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 salvage route.

3.13.2 Analysis

A recent study with juvenile steelhead was undertaken to assess the relationship between OMR flows and behavior and survival in the San Joaquin River mainstem and South Delta (Delaney et al. 2014). Results of this study may apply to Sacramento River origin salmonids that reach the San Joaquin River mainstem and South Delta, but studies to assess how OMR flows affect 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 flows, specifically, impact the migration rate and routing and survival of juvenile salmonids in the Delta. However, the SST did not specifically evaluate effects of OMR flows on survival.

3.13.3 Summary of Findings

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 and 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. Salmonid survival rates in the South Delta are so low that any protection afforded by an OMR reverse flow restriction of -5,000 cfs will be small until background survival rates improve. Most AT survival and migration studies have focused on through-Delta survival rather than reach-specific survival in the OMR corridor, and no statistical analysis of the association between OMR reverse flows and either through-Delta survival or reach-specific survival has been performed.

3.14 USE OF SURROGATES

Conducting CWT survival studies requires a large number of juvenile salmonids to support a mark-recapture experimental design (typical group sample sizes range from 25,000 to 100,000 fish each). AT survival and migration studies require smaller sample sizes (typically 500 to 5,000 fish). To date, juvenile Chinook salmon and steelhead used in these studies have almost exclusively been obtained from Central Valley fish hatcheries. The validity of the use of hatchery stocks as a surrogate for wild salmonids is a key management question (see Volume 2, Management Question 8).

3.14.1 Conceptual Model Predictions

The conceptual model predicts that migration behavior and survival of juvenile salmonids produced in hatcheries and tagged is representative of migration of wild salmonids.

3.14.2 Analysis

Virtually all of the Chinook salmon and steelhead survival studies conducted in the Central Valley have used hatchery-origin juvenile salmonids as a surrogate for wild populations. Although limited comparative studies have been initiated to test the underlying assumption that the migration behavior and survival of hatchery reared juvenile salmonids is representative of wild stocks, and that one race of Chinook salmon is representative of other races, there are currently only limited data to validate the use of surrogates in experimental survival studies. Michel et al. (2012) conducted a set of comparative survival studies in the Sacramento River using wild and hatchery-produced salmon and found, in general, that survival rates were similar for the two test groups, although the variation in survival within a reach was greater for wild produced salmon when compared to hatchery salmon.

In the short term, hatchery-origin fish may be the only readily accessible source of study fish for large-scale survival studies. Therefore, there will likely be a long-term need for data to further address the use of hatchery salmonids in survival studies as being representative of their natural-origin unmarked counterparts. At present, there are insufficient data to build a reliable, accurate correction factor for translating the survival of surrogate populations to other natural-origin salmonids in the Delta. However, some recent releases of acoustic-tagged, wild, juvenile winter-run Chinook salmon offer an opportunity to conduct a comparison with acoustic-tagged, hatchery juvenile winter-run Chinook salmon. Also, naturally produced fall-run Chinook salmon juveniles from the Sacramento River could be collected and tagged in comparative studies with hatchery-produced juvenile fall-run Chinook salmon. Adequate sample sizes and number of replicates needed for robust comparisons would be a requirement of these comparisons.

3.14.3 Summary of Findings

Limited comparative studies of migration behavior and survival for hatchery and wild salmonids have begun, but require expansion to assess relationships for both the Sacramento and San Joaquin river systems and for various races of Chinook salmon in addition to steelhead. There is currently insufficient information from comparative migration and survival studies to assess how representative hatchery-produced salmonids are as surrogates for wild stocks.

For the development of the Best Available Science in Endangered Species Act (ESA) applications, the direct use of target species rather than surrogates should be considered as the first (and best) option to answer test questions related to behavior and survival; however, often this is not possible or allowed. In these situations, the use of surrogates should be accompanied by a description of the evidence that supports their use. This issue is addressed comprehensively by Murphy and Weiland (2014). The evidence should be described explicitly in the development of assumptions associated with the specific study design or evaluation. In situations where it is unclear that a surrogate species is representative of a target species or population, the relationship between the two should be further evaluated to determine the efficacy of using surrogates, or the uncertainty characterized in the study proposal and final reports for managers.

3.15 EFFECTS OF PROJECT OPERATIONS ON WATER QUALITY GRADIENTS AND BEHAVIOR (MIGRATION CUES)

Water quality gradients, such as salinity, may be one of the cues used by juveniles for downstream migration. To the extent that water project operations alter these migration cues, juvenile salmonids may enter false pathways or be delayed in passing through the Delta and therefore may be more vulnerable to sources of mortality.

3.15.1 Conceptual Model Predictions

The conceptual model predicts the following:

- Water quality gradients provide an important migratory cue for juvenile salmonids affecting route selection.
- Water project operations affect Delta hydrodynamics and water quality gradients resulting in false migration cues and pathways contributing to migration delays and reduced juvenile survival.

3.15.2 Analysis

Salmonids are known to use olfactory cues and potentially other water quality gradients to help guide migration throughout their lifecycle (Hasler and Wisby 1951; Dittman and Quinn 1996). A variety of potential water quality gradients that may affect salmonid migration through the Delta exist such as salinity, water temperature, and turbidity gradients.

Water project operations such as opening or closing the DCC radial gates, installation of agricultural barriers, reservoir releases, and South Delta export operations alter the geographic distribution and concentrations of various water quality constituents that potentially affect migration rates or routes for salmonids in the Delta. For example, releases from upstream project reservoirs, in combination with changes in Delta exports, influence the magnitude of Delta outflow and the associated salinity gradients in the western Delta and Suisun Bay.

Water project operations, particularly upstream reservoir releases for export in the South Delta, may affect water temperature with the greatest effects occurring in upstream tributaries and diminishing downstream in the Delta. The extent of the influence has been identified as a knowledge gap and is presently under investigation (K. Gleichauf, Stanford University, personal communication). 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 and survival.

The effects of temperature on the migration of juvenile salmonids may in turn have effects on overall juvenile life history strategies. For example, in the Columbia and Snake rivers, migration timing in Chinook salmon and steelhead was strongly and inversely correlated with flow and significantly influenced by temperature, as well as date of ocean entry and prior travel time (Berggren and Filardo 1993). In the Stanislaus River, smolt migrant size was found to be negatively associated with temperature and positively associated with discharge (Zeug et al. 2014). The velocity at which a change in swimming behavior is detected in Chinook salmon smolts (response velocity) has also been shown to increase with increasing water temperature (Enders et al. 2009).

3.15.3 Summary of Findings

A substantial body of information is available on the relationships between exposure of salmonids to concentrations of various water quality constituents on spawning, egg incubation, juvenile rearing in tributaries, and smolting, but there is a paucity of information on the relationships between various water quality gradients and constituents as migration cues for juveniles within the estuary. Studies have not been conducted to investigate water quality gradients and migration rate, route selection, or survival within the Delta. Although review of the effects of water quality gradients on juvenile salmonid migration and survival was not the focus of this study, the SST recommends that further consideration be given to the effects of water quality in the Delta on salmonid migration and survival.

3.16 LIFE HISTORY STAGES AND STRATEGIES

Chinook salmon and steelhead inhabiting the Central Valley rivers express a wide range of life history characteristics. Adult migration timing varies among Chinook salmon runs, juvenile rearing may involve a rapid downstream dispersal as fry soon after juveniles emerge from redds, upstream rearing for a period of months in natal and non-natal habitats prior to migrating downstream to the ocean as young-of-the-year smolts, and rearing in upstream areas for an extended period migrating downstream at age one or two. The diversity of life history characteristics is thought, in part, to be an adaptation to variable environmental conditions such as inter- and intra-annual variation in precipitation and runoff, as well as to extend the period of ocean entry to improve juvenile survival.

3.16.1 Conceptual Model Predictions

The conceptual model predicts the following:

- Diversity in life history expression for juvenile salmonids (variable rearing strategies in the rivers and Delta, variable migration timing, variable size at migration) contribute to increased population-level survival.
- Water project operations, including river flows, seasonal gate and barrier operations, and Delta export operations have the potential to constrain and reduce life history diversity and survival.

3.16.2 Analysis

A characteristic of healthy and robust salmonid populations is that they display a broad diversity of life history attributes (McElhany et al. 2000). Chinook salmon express a wide range of juvenile life history patterns in which some juveniles migrate downstream soon after emergence as fry to rear in the lower river reaches and Delta before emigrating to coastal waters (fall-, spring-, and winter-run Chinook salmon), while others rear in upstream habitats for an extended period, migrating downstream as fully developed smolts, or for some runs, as yearlings (steelhead, late-fall-run, fall-run, winter-run, and spring-run Chinook salmon). The wide diversity in juvenile life history tactics is thought to convey an evolutionary advantage to the populations by a wide geographic dispersal adapted to variable environmental conditions in juvenile rearing habitat and at the time of ocean entry (Goertler 2014; Beechie et al. 2006; Greene et al. 2010; Schroeder et al. 2015).

There have been significant analytical advances in recent years in the ability to use isotope ratios from otolith micro-chemistry to determine the natal stream, hatchery versus wild origin, and juvenile life history contributing to observed adults returning to a river to spawn (Barnett-Johnson et al. 2008; Sturrock et al. 2015; Weber et al. 2002). Results of recent analyses based on otolith micro-chemistry have shown evidence that salmon that migrate downstream as fry in wet years contributed a substantially greater proportion (greater than 20%) to subsequent adult returns to Central Valley rivers than in dry years (Sturrock et al. 2015).

The Delta serves both as rearing habitat for fry and as a migration corridor for smolts and yearlings. Acoustic telemetry studies to date have focused on larger, migrating salmonids that can accommodate an AT. Limited studies using half CWT were conducted in the past to assess survival of Chinook salmon fry (fish less than approximately 60 millimeters [mm]) in the Delta. Results of these early fry survival studies have not been used in assessing alternative management strategies for salmonids in the Delta or for assessing the relationships between water project operations and fry survival or contribution to the ocean fishery or spawning escapement. These attributes include, but are not limited to, seasonal diversity in migration timing and geographic diversity in rearing strategies and habitat use in the upstream tributaries and Delta.

3.16.3 Summary of Findings

Life history diversity has been identified as an important attribute of healthy and robust salmonid populations. No survival studies or analyses were identified that specifically examined the relationships between water project operations and life history diversity of Central Valley salmonids. Limited studies have been conducted to examine fry survival in the Delta, but results of these early studies may not reflect current environmental conditions in the Delta or current water project operations. Although review of the effects of water project operations on salmonid life history diversity was not the focus of this study, the SST recommends that further consideration be given to the effects of water project operations and facilities in the Delta on salmonid life history diversity.

3.17 COHORT AND POPULATION DYNAMICS AND OUTCOMES

3.17.1 Conceptual Model Predictions

The conceptual model predicts that water project operations have the potential to reduce salmonid survival in the Delta and adversely impact subsequent adult abundance in the ocean and escapement to Central Valley rivers (population-level affects).

3.17.2 Analysis

To date, survival studies conducted in the Central Valley rivers and Delta have focused on estimating survival of juvenile salmon and steelhead from an upstream release site such as Durham Ferry to a downstream detection site such as Chipps Island or the Golden Gate. In addition, only limited analyses have been conducted to assess survival of CWT marked salmon from each of the release groups in the ocean, other than as a comparison of survival estimated for juveniles based on trawling at Antioch and Chipps Island with survival estimated from commercial and recreational fishery recaptures of CWT salmon in the ocean and spawner escapement, as well as the CWT analyses reported by Zeug and Cavallo (2014).

Studies or tools that incorporate information from throughout the salmonid lifecycle (e.g., temporal and spatial distribution of cohorts, ocean survival) would help put the juvenile survival results into a broader population-level context. Information on the population-level consequences of various sources of juvenile mortality is limited, and the relationship of those sources to water project operations is unknown.

Analytical tools are available, and have been used to a limited extent, to assess how factors in the Delta ultimately affect adult abundance (e.g., Interactive Object-oriented Salmon Simulation [IOS] model) (Cavallo et al. 2011; Zeug et al. 2012), Oncorhynchus Bayesian Analysis (OBAN) model (Hendrix 2008), and the San Joaquin Salmon Life Cycle Model (SalSIM; CDFW 2005; Marston 2012). In addition, NMFS has developed a lifecycle model for winter-run Chinook salmon (Hendrix et al. 2014) and is currently developing additional lifecycle models that address other salmon runs on both the Sacramento and San Joaquin rivers. Lifecycle models for each race of Chinook salmon could be used to assess which management actions in the Delta and upstream could be implemented to meet or make progress towards species recovery. In addition, the lifecycle models could incorporate information from population viability analyses (PVAs), cohort replacement rates (CRRs), smolt to adult ratios (SARs), and other output metrics that would be useful to managers in tracking the status of various management actions and as a decision-making tool to provide a structured framework for prioritizing research and actions, and evaluating performance of actions in achieving survival and abundance targets (see Volume 2, Management Question 6). Once these additional lifecycle models have been calibrated, validated, and peer reviewed, it is expected the suite of analytical tools available will prove valuable in investigating the effects of project-related entrainment and other sources of mortality on the population dynamics of Central Valley Chinook salmon. These models are also expected to provide a stronger analytical framework for identifying hypothesized mechanisms affecting juvenile survival and future research priorities, and serve as a basis for identifying testable hypotheses and appropriate experimental designs for future experiments, monitoring, manipulation, and data analyses. To date, efforts devoted to lifecycle modeling have been limited to Chinook salmon; no steelhead lifecycle model has been developed for the Central Valley.

3.17.3 Summary of Findings

Lifecycle models are needed that reflect species-specific life history characteristics within the Sacramento and San Joaquin river systems. Mechanistic lifecycle models could be used to identify the change in Delta survival necessary to support population persistence or recovery. They can also be used in assessing the relative contribution of water project operations and other potential factors affecting the habitat conditions, migratory behavior, and survival of juvenile salmonids in the Delta. These models could also be used as an analytic tool for identifying hypotheses and potential mechanisms and linkages that are priorities for future research. NMFS and others have developed, or are currently developing, salmon lifecycle models that can be applied to Central Valley salmon stocks; however, the application of these models in the past for use as a technical basis for comparing alternative management strategies, assessing the relative contribution of different sources of potential mortality within the Delta, comparing potential benefits between water project operational management, habitat enhancements, and management targeted on non-project stressors has been limited.

Lifecycle models have been developed for Chinook salmon on both the Sacramento and San Joaquin rivers; no steelhead lifecycle model is available for the Central Valley, although models have been developed to address residency versus anadromy (Satterthwaite et al. 2009).

3.18 DISCUSSION AND SUMMARY OF KEY FINDINGS

3.18.1 Discussion

There appears to be little relationship between SWP and CVP exports and survival of San Joaquin River fall-run Chinook salmon through the Delta for export rates less than 4,000 cfs. There is moderate evidence that survival is low for export rates greater than 4,000 cfs, but there are only two observations for this higher range of export rates, and the variability in survival estimates at lower export levels suggests that two observations are too few to adequately represent the possible distribution of survival for the higher range. If we want to be sure that survival is low at high export levels, then more observations must be taken at high export levels. On the other hand, if those high export levels are far outside the range of levels being considered by managers, then taking more data to characterize the survival response at those levels is of limited use.

We have investigated the relationship between water project operations and survival of juvenile salmonids migrating through the Delta. We explored several mechanisms by which water project operations may affect survival, namely direct mortality at the facilities, migration route, and migration rate. We also examined patterns in survival, inflow, and export data for evidence of correlative relationships independent of migration route and rate. We used our conceptual model to predict relationships that we expected to see in the data and, where feasible, incorporated findings from the ecological literature or other systems into our review. Nevertheless, assessment of the support for a conceptual model of how a particular system works necessarily requires examining data from that actual system, and so a statistical assessment of data from the Delta was required. We used existing statistical assessments from published journal articles and agency reports, and briefly discussed preliminary and informal statistical assessment of data newly compiled by the SST for this report.

The following limitations of a statistical approach are well known: 1) correlation does not mean causation; and 2) variability in the true relationships may mask those relationships on certain spatial or temporal scales. The variability in relationships and the large number of possibly confounding factors have ramifications for data interpretation. Even if the hypothesized relationship exists, statistically significant results may not be attainable on all spatial and temporal scales, or may require many years of data over a wide range of conditions. This type of situation is observable in comparisons of through-Delta survival in different migration routes: survival was higher in the San Joaquin River route than in the Old River route in some years, but not in other years. Additional data under a range of inflow and barrier conditions may help clarify the relationship between migration route and survival, although it is likely that more years will be required if survival remains low in both routes. In some cases, however, conclusions can be made even in light of variability. For example, it appears safe to conclude that fish should stay out of Turner Cut when migrating down the San Joaquin River.

For planning future studies, a power analysis can be helpful to determine how many observations will be necessary to detect a relationship if it exists; however, a power analysis requires precise definition of the relationship to be detected (e.g., effect size) and the level of acceptable error (significance). A study will be most useful if managers and researchers agree on these objectives during the planning stage, rather than after the data have been collected. In particular, performing a power analysis after a study is complete to assess why no statistically significant result was found is inappropriate and will give invalid results; confidence intervals of estimated effect sizes are recommended as an alternative to hypothesis tests (e.g., Levine and Ensom 2001).

The Delta is a complex system, and the available data demonstrate the difficulty of coming to firm conclusions about relationships between drivers and outcomes in such a system. Relationships are likely to be complicated by high variability, interactions with other factors, multicollinearity between explanatory variables, and possibly non-linear characteristics. These issues, combined with the very low survival observed in recent years, make it difficult to identify and characterize any relationship that may exist, such as between export rates or route selection and survival. Tagging studies that may clarify the existence or nature of such a relationship will require several features including larger sample size, many replicates over multiple years, and observations at widely varying levels of explanatory variables. Sample size (i.e., size of release group) must be large enough that sufficient fish survive to downstream reaches to both estimate survival and capture the uncertainty of the estimate; the many different migration route options available to fish in the Delta mean that even larger sample sizes will be necessary to estimate survival in the downstream reaches of the less popular routes. However, it is important to note that using a few large release groups will not be sufficient to characterize a relationship; many observations are required, rather than a few (albeit precise) observations. The high variability observed in the system means that any single estimate will be insufficient to characterize the survival response at a particular level of the explanatory variable (e.g., exports); thus, multiple years of data will be required, covering the range of conditions that may be expected to be encountered. In a highly managed system in which extreme conditions are rare, it may take many years to collect data from enough conditions to detect a relationship with desired precision and level of significance. During that time, the system may undergo a regime change or the population may be extirpated.

An alternative is to artificially create extreme conditions in order to detect a relationship (Schindler and Hilborn 2015). However, low survival and interacting factors mean that those artificial extreme conditions would need to be created multiple times to characterize the variability of the response (e.g., survival). A power analysis can be used to guide study planning by informing the number of observations and sample size necessary. However, a power analysis is implemented to address a precisely defined question such as how many observations are necessary to detect an effect of size X with an error rate of Y and significance level of Z, assuming a particular relationship exists and that the variability of the relationship is known. Thus, to be most useful, a study should be designed with thoughtful input from managers on what question (quantitatively defined) they want answered, as well as researcher a priori understanding of the system. Studies may be designed to answer multiple questions, but a separate power analysis will be necessary for each objective.

Long-term, large-scale studies are challenging to fund and implement, and risk regime change during the duration of the study. Very low survival with resulting low, effective sample sizes in downstream reaches, and high levels of uncertainty in results, complicate matters further. A complement to large region-wide survival studies is a study that targets survival in a particular region such as Frank's Tract or lower Old River. Although survival in these regions should be estimable from a region-wide study (if appropriate receiver locations are used), low survival is likely to preclude attaining reliable results in all years. Careful use of supplemental releases closer to the downstream reaches of special interest, in addition to upstream releases at historical release sites, has the benefit of providing adequate data to estimate survival in reaches that are poorly understood while continuing the useful time series of upstream or region-wide survival. Similar types of modifications to existing or historical studies may be feasible to address knowledge gaps in the conceptual model.

Warnings against using correlation to conclude causation are ubiquitous in the scientific literature, and appear occasionally in the more restricted world of fisheries literature, as well. Yet management decisions must be made before the question of causation is finally decided. Hilborn (2016) presents examples of cases in which even strong correlation was mistakenly taken as evidence of causation and later found to be faulty. He suggests that a useful alternative to using correlation as evidence of causation is to use multiple working hypotheses and for managers to identify policies that are "robust to the range of alternative hypotheses" (Schindler and Hilborn 2015; Hilborn 2016). A formal risk analysis may be useful to compare competing management decisions under an expanded suite of hypotheses.

With that advice in mind, it behooves us to consider a range of hypotheses. One hypothesis, which underlies the scope of this analysis, is that the water export operations determine survival of juvenile salmonids migrating through the Delta via short-term effects on routing and migration rate. If true, then survival of salmon passing through the Delta can be manipulated via adjustments to water project operations, including export rates, upstream reservoir releases, and gates and barriers within the Delta. The following are alternative hypotheses: 1) Delta survival is primarily a function of water temperature; and 2) Delta survival is primarily a function of predation pressure that itself depends on the size and composition of the predatory fish community. Additionally, water project operations may be affecting survival via long-term effects, or short-term effects not expressly considered in this report, including:

- Effects on the population of invertebrates, phytoplankton, and zooplankton, which in turn affect trophic resources, ecosystem productivity, and water equality (Jassby and Powell 1994; Jassby et al. 2002; Grimaldo et al. 2009)
- Effects on river channel geometry and riparian vegetation, and the extent of these effects on salmonid survival via changes in cover, refugia, and water temperature (Tabor and Wurtsbaugh 1991)
- Effects on water temperature, turbidity gradients, and water quality gradients in various regions of the Delta, via effects of river flow and water velocity
- Effects of actions that support water project operations (e.g., levee maintenance, installation of riprap on shorelines) on the Delta ecosystem, and the resulting effects on juvenile salmonid survival

The potential effects of some of the water project operations listed above are not detectable from short-term survival studies and comparisons to export or inflow rates.

If one or more of these alternative hypotheses is true, either in place of or in combination with our investigated hypothesis of short-term effects via migration routing and migration rate, yet management actions focus only on the short-term hypothesis, then it is unlikely that short-term modifications will be sufficient to return salmon survival through the Delta to desired levels. Adaptive management that allows for multiple hypotheses and focuses on desirable outcomes is more likely to be successful than policies that rely on a single hypothesis for which even the correlative analyses provide inconsistent evidence.

3.18.2 Summary of Key Findings and Gaps

Key findings and gaps are summarized in Table 3-3. These are the same findings and gaps presented in the Executive Summary. The key findings reflect information that emerged or was supported by the process of literature review and analysis undertaken by the SST. Key findings are typically characterized as having a medium or high basis of knowledge, and were judged by the SST as critical to our understanding of salmon and steelhead survival in the Delta in the context of hydrodynamic conditions and export operations. Key data gaps highlight areas within the research scope identified by the SST where our basis of knowledge is typically low or minimal with a particular emphasis on gaps that, if filled, would likely improve our understanding of the relationship between salmonid survival in the Delta and hydrodynamic conditions and exports, and/or inform our ability to more effectively manage Delta operation and hydrodynamics for improved salmonid survival. The methodology used to rate basis of knowledge is described in Section 2.4.

The findings below refer to juvenile Chinook salmon and steelhead migrating through the Delta (i.e., not rearing). For through-Delta survival, San Joaquin River-origin Chinook salmon (fall-run) are discussed separately from Sacramento River-origin Chinook salmon (fall-, late-fall-, spring-, and winter-run) because they experience different geography and environmental conditions (including hydrology), and steelhead are discussed separately from Chinook salmon.

Table 3-3. Summary of Key Findings

THROUGH-DELTA SURVIVAL

Through-Delta survival has been consistently low for San Joaquin River Chinook salmon, and more variable for Sacramento River Chinook salmon; survival data are limited for steelhead.

SAN JOAQUIN RIVER FALL-RUN CHINOOK SALMON

Findings

- Survival has been low (less than 0.2 [i.e., less than 20%] since 2002). For example, through-Delta survival has been less than or equal to 0.05 for 14 of 22 estimates, and less than or equal to 0.10 for 20 of 22 estimates, since 2002 (Appendix E, Figure E.2-3). Prior to 2002, juvenile Chinook salmon survival rates were typically higher in high flow years (1995, 1997, 1998, and 1999).
- Since 2002, through-Delta survival has been low (less than 0.2) even in higher flow years (2006, 2011) (Appendix E, Figure E.2-3), which is not consistent with results of earlier survival studies showing evidence of increased juvenile survival as Delta inflows increased during the migration period.
- In the South Delta, survival has been low in all routes since 2008 (Appendix E, Figure E.4-3), which is not consistent with results of the majority of earlier CWT survival studies that indicated higher survival for those migrating juvenile salmon that remained in the San Joaquin River at the head of Old River when compared to those that entered Old River at that location.
- Survival from the export facilities to Chipps Island via salvage and trucking was higher from the CVP than the SWP, with a primary difference being CCF in the SWP route (Appendix E, Figure E.4-7, Table E.4-3). Although validation of the assumption of lower pre-screen losses at the CVP intake compared to the SWP intake is needed, these results support a recommendation for preferential export operations using the CVP intake to benefit salmonids.
- The survival rate per kilometer from the CVP to Chipps Island via salvage was sometimes higher than the survival rate through the lower San Joaquin River reaches, but was low in absolute terms.

Gaps in Information

- Many drivers for low through-Delta survival have been hypothesized, but the role of each has not been quantified. Hypothesized factors contributing to the observed low Delta survival include increased abundance and increased metabolic rate of predatory fish such as striped bass

THROUGH-DELTA SURVIVAL

Through-Delta survival has been consistently low for San Joaquin River Chinook salmon, and more variable for Sacramento River Chinook salmon; survival data are limited for steelhead.

and largemouth bass in the Delta, water project operations affecting the magnitude and timing of flow resulting in increased juvenile salmonid predation mortality, changes in Delta habitat including expansion of non-native submerged aquatic vegetation, increased water clarity, potential exposure to contaminants, and other factors. The potential contribution of these factors to salmonid mortality supports a stronger focus on investigating the mechanisms underlying salmonid mortality in different regions of the Delta and their link to water project operations (see Section 3; Appendix E, Figure E.1-1, Table E.1-1).

- Collection and analysis of data on migration and survival of acoustic-tagged Chinook salmon released in the San Joaquin River is ongoing; survival estimates have been calculated through 2012. Additional data through 2016 will be compiled and analyzed to investigate various hypotheses over observed conditions such as potential relationships between flows and export rates and survival, as well as route selection and migration rate within various regions of the lower river and Delta. Other analyses can also be done and support our recommendation to continue studies and do additional data analyses and assessment. However, because these studies were observational in nature, and were not designed to test these hypotheses, the findings from such analyses will be limited and will not obviate the need for future investigations.

SACRAMENTO CHINOOK SALMON

Findings

- Survival among release groups has been variable across years and among populations. For example, in 2013 and 2014, through-Delta survival was estimated at 0.32 to 0.35 for hatchery winter-run Chinook salmon, 0.00 to 0.30 for hatchery spring-run Chinook salmon, and 0.00 for hatchery fall-run Chinook salmon (based on data from only one release group in 2014), whereas between 2006 and 2010, late-fall-run Chinook salmon had through-Delta survival estimates ranging from 0.17 to 0.64 (Appendix E, Section E.2.1, Table E.2-2).

Gaps in Information

- Data for some populations (e.g., winter-run, spring-run) are more limited than for other populations (e.g., late-fall-run). The majority of experimental survival studies conducted to date have been performed using hatchery-produced fall-run and late-fall-run Chinook salmon. Acoustic survival studies using hatchery-produced winter-run Chinook salmon have been initiated only in the last four years. Little information is available on survival of wild salmonids or on the applicability of hatchery-produced salmonids as a representative surrogate for wild stocks. Little information is currently available on the primary drivers for differences in survival between populations; however, more is being learned about the role of environmental conditions on survival, the role of route selection (e.g., mainstem versus interior Delta routes) and migration timing and behavior on survival, and other factors affecting survival of different stocks in the Sacramento River and Delta (Appendix E, Section E.2.1, Tables E.2-1 and E.2-2).

STEELHEAD

Findings

THROUGH-DELTA SURVIVAL

Through-Delta survival has been consistently low for San Joaquin River Chinook salmon, and more variable for Sacramento River Chinook salmon; survival data are limited for steelhead.

- Based on data from 2011 and 2012, survival of acoustic-tagged juvenile steelhead migrating from the San Joaquin River (0.32 to 0.54) has been greater than that of fall-run Chinook salmon from the same years (0.02 to 0.03) (Appendix E, Section E.2.1, Table E.2-3).
- Based on data from 2009 and 2010, survival of acoustic-tagged juvenile steelhead migrating from the Sacramento River (0.47 to 0.58) has been comparable to estimates of Sacramento River late-fall-run Chinook salmon survival from the same years (0.34 to 0.64) (Appendix E, Section E.2.1, Table E.2-2).

Gaps in Information

- For both San Joaquin River and Sacramento River steelhead, relatively few data are available on survival through the Delta compared to Chinook salmon (collection and analysis of San Joaquin River steelhead data is ongoing; survival estimates have been calculated for 2011 through 2012, and will be available for 2013 through 2016). Survival estimates for juvenile steelhead migrating downstream in the Sacramento River are available for several years but do not represent a wide range of environmental conditions.

FISH SIZE

Multiple lines of evidence indicate smaller fish respond to conditions differently and usually experience lower survival than larger fish.

Findings

- Studies of juvenile fishes undertaken to develop an estimate of handling and trucking mortality found that for Chinook salmon, mortality during holding and trucking was greater (2% mortality) for juvenile Chinook salmon less than 100 mm than for salmon greater than 100 mm (0% mortality; Appendix E, Section E.3.2.1).
- Based on CWT fall-run Chinook salmon released in the Delta, fish size was found to be a stronger indicator of ocean recovery rates than were hydrologic variables (inflow, exports), based on analyses by Zeug and Cavallo (2013) (Appendix E, Section E.6.2.1).
- In the two years with survival data for both Chinook salmon and steelhead from the San Joaquin River, the steelhead were both larger than the Chinook salmon and had higher survival; it is unclear the extent to which fish size was the primary driver of the differences in survival versus other variables (e.g., species) (Appendix E, Section E.2.1, Figures E.2-3 and E.2-4, Table E.2-3).
- AT studies in the Sacramento River have found higher through-Delta survival for larger fish (Appendix E, Section E.9.2.1). Perry (2010) found a significant relationship between acoustic-tagged late-fall-run Chinook salmon and survival in the Sacramento River mainstem and Sutter and Steamboat sloughs. Newman (2003) found a positive relationship between fish size and through-Delta survival for CWT fall-run Chinook salmon migrating from the Sacramento River.

FISH SIZE

Multiple lines of evidence indicate smaller fish respond to conditions differently and usually experience lower survival than larger fish.

- Louver efficiency experiments show a non-monotonic (i.e., not strictly increasing or strictly decreasing) relationship between Chinook salmon size and efficiency (Appendix E, Section E.3.2.1).
- Shorter through-Delta travel times of San Joaquin River fall-run Chinook salmon were observed with increasing smolt size based on CWT fish (Appendix D, Section D.4); however, despite Chinook salmon being smaller than steelhead, migration rates (e.g., kilometers per day) of acoustic-tagged Chinook salmon released into the San Joaquin River in 2011 and 2012 were approximately twice that of steelhead (Appendix D, Section D.5.2). Average travel time between Durham Ferry and Chipps Island for steelhead in 2011 (276.7 mm fork length [FL]) was 11.08 days (SE = 0.12 days) while travel time for juvenile fall-run Chinook salmon (110.8 mm FL) was 3.02 days (SE = 0.27 days). In 2012 steelhead (233.6 mm FL) travel time was 9.41 days (SE = 0.25 days) compared to juvenile salmon (112.8 mm FL) travel time of 5.75 days (SE = 0.41 days).

<u>Gaps in Information</u>

- Existing tagging data do not represent the full range of sizes of wild fish because of tag burden concerns (i.e., tags are too large for smaller fish).
- The survival effect of differences in salmon and steelhead size for fish reared in the hatcheries compared to wild fish is uncertain.
- Our scope focused primarily on migrating juvenile salmonids, and we did not review information on how rearing fry or parr respond to hydrodynamic factors such as water velocity (Appendix D, Section D.4).

PROJECT EFFECTS

Water export operations contribute to salmonid mortality in the Delta via direct mortality at the facilities, but direct mortality does not account for the majority of the mortality experienced in the Delta; the mechanism and magnitude of indirect effects of water project operations on Delta mortality outside the facilities is uncertain.

<u>Findings</u>

- Direct mortality (at the facilities) is a combination of pre-screen and within-facility mortality (including mortality during salvage and transport), and entrainment into the pumps and water conveyance canals (Appendix E, Section E.3.2.1).
- There is a large amount of indirect evidence of predation within the facilities including pre-screen losses in CCF, within the salvage facilities, and at release sites in the Delta (Appendix E, Section E.3.2.1). Predatory fish have been observed near and within the water project facilities, and juvenile salmon and steelhead have been collected from predator stomach samples. Additional indirect evidence includes results of mark-recapture experimental studies within CCF for both salmon and steelhead, observations of predator movement and behavior from AT studies, and observations of stationary ATs in and near the facilities thought to have been defecated by predatory fish. Indirect evidence of predation mortality associated with

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water project facilities and elsewhere in the Delta channels supports recommendations for reducing predation; however, such reductions should be paired with actions to improve survival in the Delta upstream of the facilities, to yield substantial increases in survival through the Delta.

- Despite implementing RPAs intended to reduce mortality at the export facilities, through-Delta survival remains low (Appendix E, Section E.2, Figure E.2-3, Tables E.2-2 and E.2-3).
- Hydrodynamic monitoring and simulation modeling indicate that exports have the greatest effect on flow and velocity in the region of the Delta nearest the export facilities (Appendix B).
- Results of studies show that route selection is generally proportional to the flow split at channel junctions, and the effect of exports on route selection is strongest at the junction leading directly to the export facilities (i.e., head of Old River). Results of juvenile Chinook salmon survival studies using CWT and more recently (2008, 2010, 2011, and 2012) ATs have not shown a strong or consistent relationship with SWP and CVP export rates. Steelhead data are limited to only 2011 and 2012; additional data through 2016 are being analyzed for both salmon and steelhead. Survival rates for juvenile salmon since 2002 have been consistently low independent of variation in both export rates and Delta inflows.

<u>Gaps in Information</u>

- Additional analyses are needed to investigate the expected change in salmonid route selection and subsequent survival from changes in export rates (Appendix D, Section D.8).
- The evidence of a relationship between exports and through-Delta survival is inconclusive; the key findings presented in this table are supported by medium or high basis of knowledge, but our basis of knowledge on the relationship between exports and through-Delta survival is low (Appendix E, Section E.6.2.1). Since 2002, juvenile fall-run Chinook salmon survival in the south Delta has been consistently low despite restriction of export rates. Survival rates for acoustic-tagged juvenile steelhead are currently available only for two years (2011 and 2012), which are insufficient to support an analysis of the potential relationship between export rate and survival. Analysis of additional AT data for 2013 through 2016 will help further assess potential relationships for both salmon and steelhead.
- Estimates of entrainment mortality at the export facilities from salvage counts depend on pre-screen mortality, but data on the magnitude and variability of pre-screen mortality are unavailable at the CVP (Appendix E, Section E.3.2.1).
- There is uncertainty in the spatial and temporal variability in predation pressure and how predation pressure responds to changes in water project operations and associated habitat changes (Appendix E, Sections E.3.2, E.3.3, E.4.2.5, and E.4.3). Based on current AT technology, it is difficult to determine when, where, and if a juvenile salmonid has been preyed on within a reach of the Delta. How water project operations affect Delta flows and velocities, physical structures, and habitat conditions that in turn affect both predators and prey warrants further investigation.

PROJECT EFFECTS

Water export operations contribute to salmonid mortality in the Delta via direct mortality at the facilities, but direct mortality does not account for the majority of the mortality experienced in the Delta; the mechanism and magnitude of indirect effects of water project operations on Delta mortality outside the facilities is uncertain.

- The contribution of water project operations to the total mortality of juvenile salmonids has not been quantified. Many of the mechanisms through which changes in Delta hydrodynamics and other factors related to water project operations may contribute to salmonid mortality (e.g., change in vulnerability to predation in Delta channels or change in migration routing as a result of water project operations) are uncertain.
- Estimates of direct mortality (e.g., mortality resulting from pre-screen losses and losses at the louver and salvage facilities, which are directly related to water project export operations) have been developed from CWT data by several authors and show, in general, that the magnitude of direct loss (e.g., percentage of a marked release group observed in fish salvage) is typically low for juvenile Chinook salmon (typically less than approximately 1%). However, such estimates do not include export-induced mortality prior to entering the facilities that is indirectly related to water project operations (e.g., mortality resulting from project related changes in habitat). Estimates of direct facility mortality as a proportion of total migration mortality have been as high as 5.5% for winter-run Chinook salmon and 17.5% for Chinook salmon released in the San Joaquin River (Zeug and Cavallo 2014).
- It is unknown whether equivocal findings regarding the existence and nature of a relationship between exports and through-Delta survival is due to the lack of a relationship, the concurrent and confounding influence of other variables, or the effect of low overall survival in recent years. These data gaps support a recommendation for further analysis of available data, as well as additional investigations to test hypotheses regarding export effects on migration and survival of Sacramento and San Joaquin River origin salmonids migrating through the Delta.

PHYSICAL CONDITIONS

The Delta is a complex and dynamic environment, and the relative influence of tides, inflow, and exports on hydrodynamic conditions (flow and velocity) varies temporally and spatially throughout the Delta. Project operations affect physical conditions in the Delta through various ways including Delta inflows, exports, and gate and barrier operations.

<u>Findings</u>

- The major rivers in the South Delta (San Joaquin, Old, and Middle) transition from a riverine environment to a tidally dominated environment in the Delta (Appendix B, Figure B.1-2).
- The hydrodynamic effect of increases in Delta inflow on flow and velocity in the South Delta is greatest at the upstream reaches of the major rivers, diminishes with distance downstream through the Delta or away from the mainstem rivers (i.e., into the interior Delta), and is affected by barriers, tidal phase, and exports (Appendix B, Figures B.5-1 through B.5-7 and B.5-13 through B.5-17).

PHYSICAL CONDITIONS

The Delta is a complex and dynamic environment, and the relative influence of tides, inflow, and exports on hydrodynamic conditions (flow and velocity) varies temporally and spatially throughout the Delta. Project operations affect physical conditions in the Delta through various ways including Delta inflows, exports, and gate and barrier operations.

- The hydrodynamic effect of exports on flow and velocity in the South Delta is strongest in Old River at the export facilities, in Middle River at Victoria Canal and the downstream end of Railroad Cut, and at Columbia Cut, and is affected by tidal phase, Delta inflow, and barriers (Appendix B, Figures B.5-1 through B.5-8 and B.5-13 through B.5-17).
- The effect of tides decreases with distance up mainstem rivers, and the tidally dominated region varies with Delta inflow, exports, and tidal phase (Appendix B, Figures B.5-1 through B.5-7).
- Hydrodynamic models were developed for water project planning and have typically been used for long time scales (e.g., daily) and large geographic areas (e.g., San Joaquin River flow routing).
- The application of current hydrodynamic simulation models to predictions of flow and velocity at South Delta channel junctions when encountered by migrating salmonids at specific times (i.e., on short time scales and small geographic areas) may not be reliable (Appendix B, Section B.3; Appendix C, Pages C-14 through C-163).
- DSM2 may be useful for assessing how exports from the South Delta, river inflows, barriers, and tides can influence the magnitude, duration, and direction of water velocities and flows within channels, depending on its accuracy relative to validation for specific areas and time scales. However, 15-minute velocities and flows estimated from DSM2 have been found to vary substantially from measured conditions and timing related to tidal conditions (Appendix C, Pages C-14 through C-231) and were not found to be accurate for assessing fish fates and behaviors at specific times and locations which would require direct measurement of flows in the field, or the application of simulation models depending on the temporal and spatial resolution needed to support analyses of specific hypotheses or management questions.
- Model validation analysis conducted for this report concluded that: 1) some locations of the South Delta validate better than others; 2) validation quality at Turner Cut varied over a period of several years; 3) validation at high inflows was poorer than at lower inflows; 4) validation was better at the daily average time step compared to the 15-minute instantaneous time step; and 5) validation using RMA 2-D was better than DSM2 on average (Appendix B, Sections B.3.1.5 and B.3.1.6; Appendix C, Pages C-14 through C-163).
- The application of hydrodynamic models to fish behavior requires calibration and validation at appropriate temporal and spatial scales (Appendix B, Section B.3; Appendix C, Pages C-14 through C-163).
- Results of limited analysis of AT data indicate that juvenile Chinook salmon migration rate slowed in areas of the Delta with bi-directional tidal velocity compared to upstream riverine reaches with uni-directional flows (Appendix D, Section D.6). No analyses were found on a potential relationship between water project exports and juvenile salmonid migration rates within the Delta, although data are available from recent AT studies that could be used to test hypotheses related to effects of riverine flow and export rates on reach-specific migration rates.

PHYSICAL CONDITIONS

The Delta is a complex and dynamic environment, and the relative influence of tides, inflow, and exports on hydrodynamic conditions (flow and velocity) varies temporally and spatially throughout the Delta. Project operations affect physical conditions in the Delta through various ways including Delta inflows, exports, and gate and barrier operations.

Gaps in Information

- Model calibration and validation can be limited by insufficient data on factors such as: 1) Delta Consumptive Use; 2) South Delta bathymetry; 3) Clifton Court inflow; and 4) monitoring station calibration.
- Further model refinements and validation are needed at temporal and spatial scales appropriate for use in analysis of salmonid migration.
- The magnitude of change in flow, water velocity, or water quality needed to elicit a behavioral or survival response by migrating juvenile salmonids has not been determined.
- The specific behavioral mechanisms underlying the slowing of migration rates in tidally influenced areas are uncertain. Selective tidal surfing behavior has been hypothesized as a mechanism supporting juvenile salmonid migration through the tidal region of the Delta, but requires further analysis and investigation (Appendix D, Section D.6).

MANAGEMENT ACTIONS

- Gates and barriers influence fish routing away from specific migration corridors.
- The relationship between San Joaquin River inflow and survival is variable, and depends on barrier status and region of the Delta.
- The extent to which management actions such as reduced negative Old and Middle River (OMR) reverse flows, ratio of San Joaquin River inflow to exports (I:E), and ratio of exports to Delta inflow (E:I) affect through-Delta survival is uncertain.

FINDINGS

General

- Spatial variability in the relative influence of Delta inflow and exports on hydrodynamic conditions means that high inflow or I:E, and low exports or E:I, may differentially affect fish routing and survival in different Delta regions (Appendix B, Section B.5; Appendix E, Sections E.6 and E.2.3).
- Uncertainty in the relationships between I:E, E:I, and OMR reverse flows and through-Delta survival may be caused by the concurrent and confounding influence of correlated variables, overall low survival, and low power to detect differences (Appendix E, Section E.2.3).

- Juvenile salmonid migration rates tend to be higher in the riverine reaches and lower in the tidal reaches (Appendix D, Sections D.3. and D.6; Appendix E, Section E.5, Figure E.5-1).

San Joaquin River

- Barriers: A barrier at the head of Old River reduces steelhead and Chinook salmon entrainment into the heads of OMR migration corridors. Historically, through-Delta survival of CWT juvenile fall-run Chinook salmon was estimated to be higher for those salmon using the San

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- The relationship between San Joaquin River inflow and survival is variable, and depends on barrier status and region of the Delta.
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Joaquin River migration corridor, indicating, on average, a survival benefit associated with the spring installation of the HORB; however, data from recent (2010 through 2012) AT studies have shown that survival has been equally low through all routes for Chinook salmon (Appendix D, Section D.11; Appendix E, Section E.4.2.1). The mechanisms affecting changes in juvenile survival among south Delta migration routes and factors that may have changed that earlier relationship in recent years remain uncertain and warrant further investigation.

- Inflow: Higher Delta inflow from the San Joaquin River is associated with increased survival in the San Joaquin River to Jersey Point when the HORB is in place; however, under low-flow conditions survival can be low even with the barrier in place (Appendix E, Section E.8, Figure E.8-2).
- Inflow: Higher San Joaquin River flow is associated with higher Chinook salmon survival to the Turner Cut junction but the effect does not always result in higher through-Delta survival because of mortality in downstream reaches (Appendix E, Section E.8, Figure E.8-1).
- I:E: The relationship between Delta survival of San Joaquin River Chinook salmon and I:E is variable but generally positive for lower I:E values (e.g., I:E < 3) (Appendix E, Section E.11, Figure E.11-1). Results of these studies are confounded by the use of flow ratios since the same I:E ratio can represent different absolute flow and export rates. These results are further confounded by installation and operations of various South Delta barriers. Data are available from only two years of AT studies using steelhead (Appendix E, Section E.11-4).
- Exports: There was a weak positive association between the through-Delta survival of San Joaquin Chinook salmon and combined exports using the CWT data set, but comparisons are complicated by the correlation between exports and San Joaquin River inflow (Appendix E, Section E.6.2.1).

Sacramento River

- Gates: Closure of the DCC gates can increase through-Delta survival by reducing the risk of juvenile salmonids migrating into the interior Delta from the Sacramento River; however, on flood tides at low flows, similar numbers of salmon can be diverted into the interior Delta through Georgiana Slough alone (Appendix D, Section D.12).
- Inflow: Increased Delta inflow from the Sacramento River is associated with increased through-Delta survival for Chinook salmon migrating from the Sacramento River (Appendix E, Section E.9.2.1).
- E:I: Statistical analyses suggest a weak but generally negative effect of increased E:I on survival of Sacramento River fall-run Chinook salmon, but not for late-fall-run Chinook salmon (Appendix E, Section E.10). Survival data are not available to assess potential relationships between E:I and survival for winter-run or spring-run Chinook salmon or steelhead. Uncertainty in the relationship between E:I and survival may be caused by the confounding

MANAGEMENT ACTIONS

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- The relationship between San Joaquin River inflow and survival is variable, and depends on barrier status and region of the Delta.
- The extent to which management actions such as reduced negative Old and Middle River (OMR) reverse flows, ratio of San Joaquin River inflow to exports (I:E), and ratio of exports to Delta inflow (E:I) affect through-Delta survival is uncertain.

influence of correlated variables and low power to detect differences (Appendix E, Section E.2.3).

GAPS IN INFORMATION

General

- The effects of OMR reverse flows on salmonid survival and route selection in the Delta (outside of the facilities) have had limited analysis. Data are available from the AT migration and survival studies, as well as earlier CWT data, that might be used in analyses of potential relationships between OMR reverse flows and juvenile salmonid survival. Relationships between OMR reverse flows and migration route and migration rate, as well as reach-specific and regional survival, could be tested using acoustic tag data from both Chinook salmon and steelhead.
- The relationships between water project operations and survival on various spatial and temporal scales are poorly understood. The detailed information generated from the recent salmon and steelhead AT, in combination with refinements in the application of hydrodynamic simulation models to fishery analyses in the Delta, offers the opportunity to conduct additional analyses at a finer spatial and temporal resolution than before; however, more data will be needed to understand patterns over a variety of conditions.

San Joaquin River

- Results of early CWT survival studies conducted using juvenile fall-run Chinook salmon released into the lower San Joaquin River downstream of Old River, and into Old River, showed evidence of higher survival to Jersey Point for those fish that migrated downstream in the San Joaquin River mainstem compared to fish migrating through Old River. Results of limited AT data from 2010 to 2012 showed evidence of equally low survival independent of route selection at the head of Old River. Reach-specific survival estimates with the HORB in place are available only for one year (2012) for both fall-run Chinook salmon and steelhead, although more recent data from 2014 to 2016 (all with the HORB in place for Chinook salmon and some of the steelhead releases) have yet to be analyzed. Further analysis of the available AT data and additional experimental studies to examine the mechanisms affecting juvenile salmon and steelhead survival for those fish migrating downstream in the San Joaquin River mainstem and those entering Old River are needed to assess the potential biological benefits of influencing migration route selection through installation of the HORB in South Delta channels.
- Because few observations of salmon migration survival are available for higher I:E values (e.g., I:E > 5), higher San Joaquin River inflow levels (e.g., Vernalis inflow > 10,000 cfs), and higher export levels (e.g., combined export rate > 5,000 cfs), the variability in survival under these higher levels of I:E, inflow, and exports is not well-characterized (Appendix E, Sections E.2.3 and E.11).

MANAGEMENT ACTIONS

- Gates and barriers influence fish routing away from specific migration corridors.
- The relationship between San Joaquin River inflow and survival is variable, and depends on barrier status and region of the Delta.
- The extent to which management actions such as reduced negative Old and Middle River (OMR) reverse flows, ratio of San Joaquin River inflow to exports (I:E), and ratio of exports to Delta inflow (E:I) affect through-Delta survival is uncertain.

- <u>Exports</u>: Data on potential relationships between San Joaquin River inflow and exports on migration and survival of acoustically tagged juvenile salmon and steelhead are limited to just a few years and environmental conditions; therefore, firm conclusions cannot be made from the AT data sets for San Joaquin Chinook salmon or steelhead (Appendix E, Section E.6.2.1).

CONSTRAINTS ON UNDERSTANDING

Current understanding of juvenile salmon and steelhead survival in the Delta is constrained by a variety of factors (as listed below).

<u>Findings</u>

- The nature of the I:E and E:I metrics as ratios makes it challenging to test their effects, since different sets of physical conditions may be represented with the same I:E or E:I value (e.g., both high and low inflow conditions may be associated with the same I:E value, depending on exports).
- Determining the effectiveness of management operations such as I:E, E:I, and OMR reverse flow restrictions is difficult when all observations are in the presence of those restrictions (i.e., there is no control condition to compare to the experimental condition) (Appendix E, Section E.13). Development of future experimental designs would need to consider increased operational flexibility and/or alternative approaches to the experimental design to test a range of prescribed water project operational conditions.
- There has been low variability and little replication in conditions during recent tagging studies, in particular San Joaquin River inflow and exports. Most observations of smolt survival have been at low levels of both inflow and exports, in part as a result of recent drought conditions. Furthermore, it is not possible to test the effects of changes in conditions in the absence of variability in those conditions (Appendix E, Section E.2.3). Developing the future experimental design for salmonid monitoring would need to consider prescribing flow and export conditions extending over a wide enough range to detect biological responses if such relationships exist.
- Low overall survival makes it difficult to detect changes in survival, both in general and in response to changes in management operations (Appendix E, Section E.13).
- Hydrodynamic models are developed and calibrated for specific locations, time periods and time scales, and study questions; application of simulation models for other uses (e.g., using the reviewed models in the South Delta or on the scale of fish response) is dependent, in part, on the specific hypotheses and management questions being evaluated and the resolution and accuracy needed in model predictions to support the analysis (Appendix B, Section B.3).
- Disparity between current hydrodynamic models and measurements of hydrodynamics data (flow and velocity) at key locations in the Delta (e.g., Turner Cut, Frank's Tract) limits our ability to detect patterns between changes in velocities and flows and changes in salmon

CONSTRAINTS ON UNDERSTANDING

Current understanding of juvenile salmon and steelhead survival in the Delta is constrained by a variety of factors (as listed below).

survival and behavior from AT observations (Appendix C, Figures 18 through 20 and 24 through 29). Further model calibration and validation and refinements to model parameters is expected to advance the application of these models in support of fishery analyses; and

- Salmon likely respond to changes in water velocities rather than to changes in flow, but hydrodynamic modeling results show larger disparities between modeled and measured conditions for velocity than for flow (Appendix C, Pages C-14 through C-163).

Gaps in Information

- Understanding the effects of water project operations on route selection and through-Delta survival of juvenile salmonids may require additional statistical analysis of route-specific survival, hydrodynamics, habitat complexity, and environmental variability. Completing the analysis of AT data through 2016 will provide the foundation for more statistical analyses using multivariate approaches involving a number of physical and biological covariates for hypothesis testing.
- Modeling of the potential biological response of particular water project operation actions has not been done (hypothetical examples of measurable objectives include: reduce migration into the Interior Delta through Turner Cut by 50%, increase juvenile survival in the South Delta to an average of 30%, etc.), which limits our ability to make short-term action recommendations that are predicted to achieve a specific biological objective and to evaluate the performance of the action in achieving the desired effect.
- Further analysis is needed to assess which hydrodynamic models best represent observed hydrodynamic or water quality changes caused by water operation decisions or other management actions, on the scale of fish perception and response; the calibration and validation of the appropriate spatial and temporal scales for biological application needs additional refinement.
- Several potential problems (gaps) have been identified in the literature relative to hydrodynamic model calibration in the South Delta, including representation of the CCF operations, South Delta bathymetry data, Delta Island Consumptive Use data, high inflow conditions, and challenges associated with estimating Delta outflow. Further refinement of hydrodynamic simulation models and their application to assessing salmonid migration and survival will improve the technical foundation for evaluation of the performance of management actions.

3.19 TECHNICAL DISAGREEMENTS

SST members agree with the key findings and gaps presented in the tables above. Technical disagreements about the characterization of information are identified in Volumes 1 and 2 and are summarized below.

3.19.1 Volume 1

- There was not consensus in the SST regarding the definition and application of the basis of knowledge. The basis of knowledge review rated peer-reviewed publications higher than agency or contract reports. While the assumption was made that peer-reviewed articles have more robust information, it was noted that agency reports and peer-reviewed articles can have varying degrees of robustness, the assumption is not likely true for all peer reviewed articles, and agency reports can also be peer reviewed. Furthermore, agency reports may provide better and more specific information relative to the questions we are asking and this is not reflected in the basis of knowledge definition or applications. At least one SST member felt that similar results from multiple agency reports should be rated higher than a medium basis of knowledge. Despite differences in the interpretation of weighting to be given to various sources of information among the SST, the body of scientific information available, including agency reports, peer-reviewed journal publications, discussions with technical experts, and data analyses prepared by the SST as part of preparing the gap analysis, were all used in developing findings and recommendations presented in this report.
- There was a disagreement within the SST about whether the analysis of ocean recovery rates of CWT fish (i.e., the Zeug and Cavallo [2013] analysis) is informative for Delta survival because ocean recovery rates combine Delta survival with ocean survival and incorporate assumptions about fishing effort between years. Some SST members believe that the joint probability of Delta survival and ocean survival is pertinent, although not conclusive, to Delta survival (Appendix E, Section E.6.2).
- There was disagreement within the SST about whether there is a relationship between exports and the relative survival associated with the Interior Delta route compared to the Sacramento River mainstem route, based on modeling by Newman and Brandes (2010). Some SST members believe that, despite the indeterminacy in model selection, a potential effect of exports was demonstrated (Appendix E, Section E.6.2.1). The disagreement was based, in part, on model selection that identified that relative Interior Delta survival was similarly predicted with models that did not include exports, based on the low samples sizes available.
- There was a disagreement within the SST about providing short-term recommendations for actions to improve salmonid survival at this time, nothing that no modeling or analysis has been conducted to assess potential benefits to salmon or steelhead from these actions and that a more systematic process of evaluation of alternatives and priorities should precede any recommendations for actions. Some on the SST felt that the prolonged low levels of juvenile salmon survival in the South Delta warrant immediate action

3.19.2 Volume 2

- There was a disagreement within the SST over whether the data provided in Volume 2 support the conclusion that improved protection of Sacramento River salmonid populations would result if the onset date of OMR reverse flow management were triggered by detection of migrants at monitoring stations located on the Sacramento River upstream of distributary junctions leading toward the San Joaquin River. Results of salmonid monitoring in the Sacramento River and San Joaquin River have shown that the seasonal timing of Delta entry for juvenile Endangered Species Act (ESA)-listed salmonids varies among years. The January 1 onset of OMR flow management coincides with the presence of winter-run Chinook salmon in most years, spring-run Chinook salmon in many years, and steelhead in some years. Some SST members conclude that although not capturing all of the seasonal variation in juvenile movement, the January 1 trigger date provides a general approximation of the migration timing during the winter months, and, based on its simplicity for triggering management actions, has utility (Management Question 3).
- In Volume 2, there is a statement that limiting OMR reverse flow to -5,000 cfs is effective at preventing increased routing into the Interior Delta, presumably resulting in increased survival. There was a disagreement over whether the data provided in Volumes 1 or 2 supported such a statement. Some felt the discussion and conclusion was based primarily on conceptual model predictions and reasoning, not on factual analysis (Management Question 3).
- There was a disagreement within the SST about the statement that short-term restrictions of exports resulting in OMR reverse flows more positive than the -5,000 cfs may do little to improve through-Delta survival for Chinook salmon due to low overall survival. The disagreement was that, since we have no evidence of the effects of OMR reverse flow restrictions on survival, we have no evidence that the continued OMR reverse flow restrictions will affect survival (Management Question 4).
- There was a disagreement within the SST about presenting the hypothesis that the influence of exports on habitat may have a stronger effect on survival than that of short-term hydrodynamic changes related to exports, since the argument is based on reasoning and not data analysis (Management Question 4).
- There was a disagreement within the SST about whether Passive Integrated Transponder (PIT) tags, which have been used extensively in salmonid studies in river systems such as the Columbia River, could expand the available evaluation methodologies; some members believe that, as a result of difficulties in PIT tag detection in larger channels (the PIT tag needs to be in close proximity to the detector to be read), the technology will not provide any better information than is currently available through existing methodologies. Therefore, there was disagreement over whether to recommend that PIT tag technologies be applied to the Delta to facilitate monitoring of biological metrics. The selection and application of specific technologies in future investigations will need to be based, in part,

on the nature of the investigation, specific data needs, detection ability, and other factors (Management Question 6).

- There were no areas of formal scientific disagreement among SST members regarding the use of surrogates; however, there is disagreement among scientists in general about the usefulness of performing surrogacy comparisons in situations where only some of the pertinent types of surrogacy can be evaluated. Seven common positions on the use of surrogates are identified (Management Question 8).

4.0 RECOMMENDATIONS FOR NEXT STEPS

The SST has identified the following recommendations for CAMT to consider. The recommendations provide guidance on how future investigation and research efforts could be focused to build on the existing knowledge base and address key data gaps. They were developed to advance our understanding of the role of factors influencing salmonid survival through the Delta, the role of Delta conditions in salmonid fitness at the individual and population level, and opportunities to improve salmonid population abundance and status through changes to Delta conditions and water project operations.

The recommendations are informed by the following overarching observations:

- The Delta is a very complicated environment in which to study and measure juvenile salmonid survival.
- While much information has been gained using the current approach, numerous key questions remain unresolved and will require new analyses and experimental approaches.
- The Delta should be perceived not as a singular region, but a suite of regions defined by different physical forcing factors. The regions are areas dominated by natural and water project inflow (upper San Joaquin River mainstem), tidal conditions (lower San Joaquin River mainstem and Delta), and exports (South Delta). Results of South Delta survival studies using juvenile Chinook salmon have shown consistently low survival over the past decade. Resolving the low observed juvenile salmonid survival may require different approaches for each region that would be integrated into a single program.
- Resolving the low survival should shift from questions developed by researchers to ones that simultaneously integrate three components: science (what can be tested), management (what needs to be tested), and operations (what can be put into place for testing). This shift in approach would support both observational studies and needed controlled experiments.
- Answering key survival and water project operation questions in the Delta is challenging, and future decisions will have to be made in the face of scientific uncertainty. Therefore, decision-support tools also need to be developed that help characterize risk and uncertainty for managers.

4.1 CONTINUE EXISTING SURVIVAL STUDIES, MONITORING, AND ANALYSIS OF DATA

Discussion: The purpose of this recommendation is to continue and complete the existing analyses of route entrainment, reach survival, predation investigations, and salvage that are under way. Ongoing studies might be adapted as a long-term monitoring and adaptive management plan is developed and implemented. They are needed to provide a foundation for an expanded research program, generate information, and inform near-term management decisions, and complete ongoing research studies to maintain time series information.

Schedule: Ongoing

Management Application: Current studies provide information about through-Delta survival of Chinook salmon and steelhead, and some estimates of reach-specific survival and junction-specific routing under potentially different (but usually not controlled) inflow and export conditions. Continuing to estimate through-Delta survival will provide continuity for time series data needed to assess current status, interannual variability, and long-term trends. Ongoing research on predation is critical to identifying relationships between predator and juvenile behavior, and predator concentrations.

4.2 INVESTIGATE SHORT-TERM ACTIONS TO IMPROVE SALVAGE FACILITY OPERATIONS

Discussion: The purpose of this recommendation is to determine whether current operations and salvage facilities at the SWP and CVP could be improved to reduce losses to listed and non-listed salmonids entrained into the facilities. The SST understands that a great deal of effort has been directed toward improving the facilities, and facility experts would need to be involved in any future discussions. Suggestions for actions to reduce direct facility mortality based on findings in Appendix E, Section E.3.2.2 include:

- Control predator populations in CCF and behind the CVP trash racks.
- Control secondary louver efficiency by control of bypass water velocities.
- Keep primary and secondary louvers free from debris, but also reduce time when they are inoperable for cleaning.
- Improve salmon passage within the CVP, and decrease predator passage within the CVP.
- Consider alternate truck release locations of salvaged fish to prevent large predator assemblages.
- Verify the assumption that pre-screen losses at the CVP intake are 15% and substantially lower than losses at the SWP.
- Test using the CVP for export instead of the SWP to reduce losses of salmonids in CFF.

Additional suggestions include:

- Test how different CCF radial gate openings affect water inlet velocities and fish entrainment; determine whether water velocity thresholds for entrainment at the gate entrances can be identified based on literature reviews, model studies, and empirical testing; and, if new operations are identified, evaluate whether survival is increased.
- Evaluate filling the scour hole inside the CCF radial gates to reduce predator habitat and predation.
- Review the fish facilities design criteria and compare them to current state and federal design criteria; adjust facility operations or modify facilities to meet the current state and federal criteria if possible. For example, install flow control structures behind CVP louvers to improve efficiency during low export volume operations.
- Review past studies and evaluate whether new fish truck transport release operations, such as the use of net pens and barges, would be effective in reducing post-release mortality.

Schedule: Ongoing

Management Application: The goal of these actions is to reduce the proportion of fish entrained into water project facilities, reduce losses to fish that are entrained within the facilities, and enhance the survival of fish salvaged by improving truck transport and release operations. To the extent possible, responses (e.g., entrainment, mortality) should be measured before and after any modification is implemented to document the effectiveness of the modification.

4.3 DEVELOP A LONG-TERM MONITORING, RESEARCH, AND ADAPTIVE MANAGEMENT PLAN

Discussion: A long-term monitoring, research, and adaptive management plan with stable and reliable funding for implementation is needed to fully assess the effects of water project operations and other Delta management actions. It is envisioned that this plan would need to be implemented for a period of at least 15 years. It should be based on monitoring, modeling, and direct manipulation of factors of interest. It will require a policy commitment to a range of management actions to be tested, agreement among managers and scientists of the level of precision needed to determine study success, and agreement that operations needed for the experimental conditions being tested can be achieved. The plan should augment and expand the scope of current studies in terms of the breadth, depth and number of analyses, monitoring studies, and experiments conducted.

The SST believes that studies that focus on causal mechanisms at appropriate time and space scales are an important approach, especially regarding understanding how fish behavior responds to local conditions.

Development of a long-term plan as envisioned here would require a number of discussions among research scientists and managers and may require a multi-pronged focus on water project operations, Delta habitat conditions, predation, and other stressors thought to contribute to the low survival observed over the past decade. Although there are a number of potential approaches to developing the long-term plan, one approach to consider would be an integrated (physical and biological) approach to monitoring and modeling, and the manipulation of treatment conditions (e.g., flow, exports, I:E ratios) within certain reaches and over specific time scales. Integration across technical disciplines (biologists, hydrodynamics experts, physical and biological modelers, and biometricians) and methods (fish tagging and modeling) would continue and expand. The plan would incorporate new information in an adaptive manner, where information gathered at one stage of the process is incorporated into the following action (i.e., data gathering or analysis, model development, or system manipulation), and the action is then adjusted based on the new information. Consideration should also be given to integrating the long-term plan with other smelt, salmon, and water management programs in the Delta and Central Valley.

Schedule: 3 to 5 years

Management Application: The long-term monitoring, research, and adaptive management plan would be used to assess the RPA actions and underlying mechanisms related to the influence of water project operations on salmonid population viability. Results of monitoring would also be applied to better understand the importance of other potential limiting factors on migration and survival of juvenile salmonids in the Delta. It would also be used to inform a broader suite of actions intended to improve juvenile salmon survival in the Delta and population productivity.

4.4 IMPLEMENT THE LONG-TERM MONITORING, RESEARCH, AND ADAPTIVE MANAGEMENT PLAN

Discussion: Implementing the long-term plan will involve conducting the analyses, monitoring, and research identified during plan development (and thereafter) to evaluate key questions and hypotheses in a methodical manner, adaptively applying the information to management actions, and developing decision-support tools for managers that help characterize uncertainty and risk. Plan implementation should emphasize timely synthesis of research and monitoring, and publishing in peer-reviewed journals. Implementing the long-term plan is needed to develop the information necessary to assess how existing water project operations directly and indirectly affect the survival of listed and non-listed salmonids in the Delta. In addition, a statistically robust, long-term program designed to investigate the underlying mechanisms affecting salmonid survival will improve the scientific basis for identifying new water project operations. It is envisioned that this plan would need to be implemented for a period of at least 15 years.

Schedule: 15+ years

Management Application: Implementation of the long-term monitoring, research, and adaptive management plan will allow water project operations to be assessed. It will reduce uncertainty, potentially identify the incremental role water projects operations have on salmonid survival through the Delta, and potentially lead to adjustments to water project operations that improve survival beyond the current levels. Information gained through implementing the long-term plan could be integrated with, and incorporated into, decision support tools used to better manage the system. It is envisioned that the long-term plan will be integrated with other major monitoring programs in the Central Valley.

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Appendix A
Water Project Facilities and Operations

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A.1 WATER PROJECT FACILITIES AND OPERATIONS

The State Water Project (SWP) and Central Valley Project (CVP) include upstream reservoirs (Shasta and Keswick dams on the Sacramento River, Oroville Dam on the Feather River, Folsom and Nimbus dams on the American River, New Melones Dam on the Stanislaus River), several water conveyance canals, water export and fish salvage facilities located in the South Delta, and various operable and temporary barriers located in the Delta. Depending on seasonal hydrometeorology, the operation of upstream dams frequently influence river flow and inflow from the Sacramento and San Joaquin rivers into the Delta. As drier conditions prevail, these operations play an increasingly significant role in controlling river flows and Delta inflow. For purposes of this assessment, operation of the upstream dams and reservoirs is not included in the gap analysis; however, freshwater inflow from the San Joaquin River into the Delta is included as part of water project operations. Elements of SWP and CVP operations considered in the gap analysis are briefly discussed below.

A.1.1 TEMPORARY, OPERABLE, AND NON-PHYSICAL BARRIERS

As part of SWP and CVP operations, both temporary rock barriers (e.g., agricultural barriers in the south Delta, the Head of Old River Barrier [HORB]) and operable barriers (Delta Cross Channel [DCC] radial gates) are used to regulate and manage water flows through Delta channels, reduce the effects of South Delta export operations on water elevation in Delta channels that impact agricultural irrigation diversions and improve water quality, and reduce the risk of juvenile salmon entrainment in the export facilities. In addition, in recent years, non-physical barriers for guiding downstream migrating Chinook salmon and steelhead have been tested in the Sacramento River at Georgiana Slough and San Joaquin River at the head of Old River.

The Temporary Barrier Project has been in place since 1991 and has included the seasonal installation and subsequent removal of rock barriers at several locations in the South Delta (DWR 2011a, 2011b). These barriers are used to increase water levels in South Delta channels and reduce the effects of exports on water levels, improve water circulation and water quality, improve flows and increase dissolved oxygen concentrations for adult fall-run Chinook migration, and reduce the migration of juvenile salmon and steelhead into Old River in the spring. Temporary barriers have been installed at various locations including Middle River, the HORB during both the spring and fall, Grant Line Canal, and Old River at Tracy barrier. Monitoring and analysis of barrier effects conducted by the California Department of Water Resources (DWR) and others have included salmon smolt survival studies, barrier effects on fish entrainment at the SWP and CVP, Swainson's Hawk surveys, water elevations, South Delta water quality, and hydrodynamic modeling of barrier effects (DWR 2011a, 2011b).

There are two primary operable barriers (radial gates) used as part of SWP and CVP operations in the Delta including the radial gates at the SWP Clifton Court Forebay (CCF) discussed below, and the CVP DCC. The DCC, located on the Sacramento River near Walnut Grove, was constructed in 195. The DCC is a constructed conveyance channel that includes two radial gates (each 60 by 30 feet) that can be opened and closed to manage Sacramento River water flowing into the interior Delta. Sacramento River water enters the Delta via Snodgrass Slough and a branch of the lower Mokelumne River, where it subsequently enters the San Joaquin River and the Old and Middle rivers (OMR) channels, and potentially the South Delta export facilities. The fresh Sacramento River water is used to improve South Delta water quality and convey Sacramento River water that is available for export to the SWP and CVP.

Seasonal radial gate operation of the DCC is controlled by the State Water Resources Control Board Decision 1641 (D-1641) and the National Marine Fisheries Service (NMFS) Biological Opinion (NMFS 2009). Based on NMFS (2009), closure of the gates is managed based on fish presence and water quality between October 1 and November 30. Between December 1 and January 31, the gates are closed for up to 45 days per D-1641, but per NMFS (2009), the gates are required to be closed except if D-1641 water quality standards are exceeded. In accordance with D-1641, the gates are closed for juvenile salmonid protection from February 1 through May 20. From May 21 through June 15, the gates are closed for 14 days for fishery protection at the request of NMFS and the California Department of Fish and Wildlife (CDFW). The gates are typically open between June 16 and October 31. Also, the gates are typically closed for flood protection when Sacramento River flows reach 20,000 to 25,000 cubic feet per second (cfs). The gates have also been closed on an intermittent basis to conduct hydrodynamic or fishery experiments. The number of days during October to December 2000 through 2011 when the DCC gates have been closed is summarized in Table A.1-1.

Table A.1-1. Number of Days During the Fall When the DCC Has Been Closed

				Experimental Purpose for Closure		
Year	**October**	**November**	**December**	**October**	**November**	**December**
2000	31	8	4	Yes	Yes	No
2001	21	8	27	Yes	No	No
2002	3	1	22	Yes	No	No
2003	0	0	31	No	No	No
2004	0	0	25	No	No	Yes
2005	0	4	28	No	No	No
2006	1	0	16	No	No	No
2007	0	0	17	No	No	No
2008	0	17	18	No	Yes	Yes
2009	4	11	18	Yes	No	No
2010	3	4	31	Yes	No	No
2011	10	0	31	Yes	No	No
Average	6	4	22			

A.1.2 CLIFTON COURT FOREBAY GATES

CCF is operated as a regulating reservoir within the tidal region of the south Delta to improve SWP water export operations (Clark et al. 2009). CCF was constructed in 1969 with a surface area of 2,200 acres. Water is diverted from Old River through five radial gates (each 20 by 20 feet) as the flooding tide reaches CCF and through the early part of the ebb tidal cycle. The frequency that the radial gates are opened to flood CCF depends on the SWP export rate, the volume of water storage in CCF, and tidal conditions. When the difference in water surface elevation between Old River and CCF is greatest, water velocities entering CCF typically exceed 15 feet per second at flow rates that typically range between 10,000 and 15,000 cfs (Clark et al. 2009). After CCF has been filled, the radial gates are closed and water exports are made from storage within CCF. Fish are entrained into CCF when the radial gates are open and are subject to very high pre-screen losses. The losses can occur from predation within CCF, salvage at the SWP Skinner Fish Facility, or entrainment through the louver guidance system into the water distribution canal the pumped water discharges to (Clark et al. 2009; Kano 1990; Gingras and McGee 1997; Gingras 1997). NMFS (2004) included a requirement to assess pre-screen losses within CCF on juvenile steelhead (Clark et al. 2009), and NMFS (2009) included a requirement to identify and implement actions that would reduce pre-screen losses resulting from radial gate and CCF operations.

A.1.3 SWP AND CVP EXPORTS

The SWP and CVP export water from the South Delta using pumps and conveyance canals at the Harvey O. Banks Pumping Plant (SWP) and the C.W. “Bill” Jones Pumping Plant (CVP). Both export facilities are equipped with louver fish guidance systems and include fish salvage facilities designed to collect, transport, and release fish that enter the facilities back into the Delta. The CVP export facility draws water directly from Old River while the SWP diverts water from Old River into CCF (see description above). The rate that water can be exported from the Delta varies in response to several factors that include seasonal restrictions imposed by D-1641, which limits exports during the late winter and spring to no more than 35% of total Delta inflow and during the summer and fall to no more than 65% of total Delta inflow. Constraints on the maximum rate of exports also exist to avoid channel erosion that is independent of Delta inflow. USFWS (2008) and NMFS (2009), in addition to the CDFW incidental take permit, include additional seasonal limits on exports through regulation of the OMR reverse flows to reduce the risk of entrainment losses of protected fish in the Delta. Export rates are also adjusted based on consideration of water quality conditions (e.g., electrical conductivity, and more recently turbidity to reduce the risk of delta smelt entrainment), water storage and demand, conveyance in distribution canals, and other factors.

A.1.4 OMR FLOW

Old River and Middle River are the two primary channels in the central and southern regions of the Delta that convey water to the SWP and CVP export facilities. Hydrodynamic conditions in the OMR channels are influenced by tidal conditions, DCC operations, SWP and CVP export rates, CCF radial gate operations, installation of the HORB, and Delta inflows from the San Joaquin River. Depending on these conditions, the daily flow of water in the channels typically is positive (flowing downstream to the west into the Delta) and then becomes reversed (negative; flowing upstream toward the SWP and CVP export facilities), and the proportion of time flow is positive or negative, which varies depending on the hydrodynamic conditions listed above. Results of a series of analyses have identified relationships between the magnitude of reverse flow in OMR and the risk of juvenile Chinook salmon and delta smelt to entrainment and salvage at the SWP and CVP export facilities (USFWS 2008; NMFS 2009). Results of these analyses showed a general pattern of a substantial increase in salmon and smelt salvage when reverse flows are more negative than -5,000 cfs. Both USFWS (2008) and NMFS (2009) use seasonal restrictions on OMR reverse flows as a method to reduce the risk of smelt and salmon entrainment losses.

A.1.5 VERNALIS INFLOW:EXPORT RATIO

NMFS (2009) included a restriction on SWP and CVP export rates during April and May to a proportion of the S inflow to the Delta from the San Joaquin River at Vernalis. The most restrictive operations limit combined SWP and CVP exports to 25% of the flow in the San Joaquin River when wet conditions prevail. The April-to-May export restriction was intended to improve downstream flow from the San Joaquin River and through the Delta during the spring outmigration period for juvenile steelhead produced in the San Joaquin River watershed, as well as reduce the risk of entrainment mortality of steelhead at the SWP and CVP export facilities. The April-to-May export operations restrictions were challenged in Federal District court by the public water agencies and DWR and were the subject of the NMFS Biological Opinion (NMFS 2009) remand by Judge Wanger. The remand of the NMFS Biological Opinion was subsequently overturned on appeal.

A.1.6 SAN JOAQUIN RIVER INFLOW

San Joaquin River flow at Vernalis originates from several upstream tributaries including the Merced, Tuolumne, and Stanislaus rivers, as well as the upper San Joaquin River and local runoff. Among these upstream tributaries, the Stanislaus River and operation of New Melones Reservoir is the only water-project-related operation identified in NMFS (2009). For purposes of the analysis conducted by the SST, the combined San Joaquin River flow measured at Vernalis was assessed, not the contribution of flow from individual tributaries.

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Appendix B
Effects of Water Project Operations on Delta Hydrodynamics

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B.1 INTRODUCTION AND BACKGROUND

This appendix is an assessment of the effect of water project operations on hydrodynamics in the South Delta, at the Delta Cross Channel (DCC), and in the Georgiana Slough area in the North Delta. The assessment is based on empirical data from monitoring programs and hydrodynamic model results from historical and synthetic scenarios. Comparing a historical scenario to empirical data provides a means to evaluate the accuracy of the models. Synthetic scenarios also provide information on a range of possible conditions allowing individual variables to be evaluated independently. The water project variables assessed were State Water Project (SWP) and Central Valley Project (CVP) exports, river inflow to the Delta, diversions and barriers.

Hydrodynamic conditions in the Delta, including the distribution of flows through the Delta, are influenced by a variety of factors including freshwater inflows, tides, channel geometry and channel bed characteristics, configuration of channels, water diversions, and operation of barriers and tidal gates. Under periods of low inflow, most of the system is strongly tidal with reversing flows. As inflows increase, channels become riverine, where flows do not reverse.

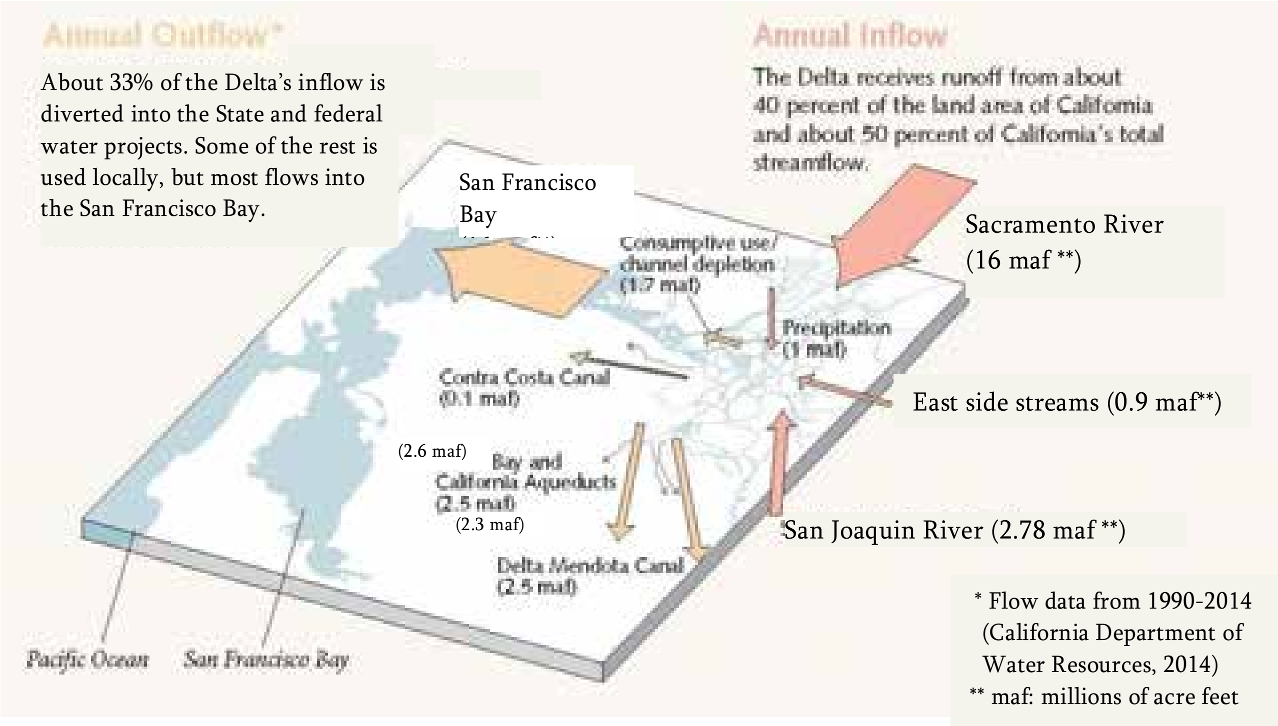
As described in more detail below, exports can influence the direction of daily (or tidally) averaged flow in the South Delta, with high exports causing more negative daily average flows in Old and Middle rivers (OMR) (see Section B.5.3). Operation of the DCC affects the balance of flow between the western and eastern/southern sides of the Delta. Opening the DCC allows flow to transfer from the Sacramento River channel to the Mokelumne River and then on to the lower San Joaquin River and Interior Delta (DeGeorge 2013). The flow patterns in the South Delta tend to be more complex than the North Delta due to the influence of the Clifton Court radial gate operations and export pumps on OMR, the more complex interconnected channels, the presence of South Delta temporary barriers, and greater tidal excursion along the mainstem of the San Joaquin River. Flow splits at critical junctions may be affected by the conveyance characteristics of the connecting channels, tidal phasing, and installation and operation of barriers and gates (DWR 2011a, 2011b).

Table B.1-1 provides annual average inflows and diversions from the Delta from 1990 to 2014. The location and relative magnitude of the major inflows and diversions are shown graphically in Figure B.1-1.

Table B.1-1. Major Sacramento-San Joaquin River Delta Inflows and Diversions, 1990-2014 (DWR 2014a)

Inflow/Diversion	Annual Average (maf)	Annual Minimum (maf)	Annual Maximum (maf)
Sacramento River	16	6.5	29
San Joaquin River	2.8	.6	8.5
Eastside Tributaries	3.7	.9	11
Delta Outflow	16	3.9	43
In-Delta Average Diversions	1.7	1.7	1.7
Precipitation	.9	.5	1.4
SWP Exports	2.6	.9	7
CVP Exports	2.3	1.0	2.7

Note: maf = million acre feet



About 33% of the Delta's inflow is diverted into the State and federal water projects. Some of the rest is used locally, but most flows into the San Francisco Bay.

The Delta receives runoff from about 40 percent of the land area of California and about 50 percent of California's total streamflow.

* Flow data from 1990-2014 (California Department of Water Resources, 2014)
** maf: millions of acre feet

Figure B.1-1. Major Annual Inflows to and Diversions from the Sacramento-San Joaquin Delta

Source: Illustration from USGS (2000); data updated from Dayflow (DWR 2014a)

Tides are a significant factor affecting hydrodynamics in parts of the Delta, depending on inflow. DSM2 model scenarios from Kimmerer and Nobriga (2008) indicate that maximum and minimum flows range from +150,000 to -155,000 cubic feet per second (cfs) in the western Delta at Chipps Island; from +29,000 to -29,000 cfs in the lower San Joaquin River at the mouth of Middle River; and from +2,500 to -2,900 cfs in the San Joaquin River between Upper and Lower Roberts Island (Figure B.1-2) (Cavallo et al. 2013).

Under the same scenarios, maximum and minimum velocities ranged from + 1.9 to -1.8 feet per second (ft/sec) in the western Delta near Jersey Point; from +1.3 to -1.2 ft/sec in the lower San Joaquin River at the mouth of Middle River; and from +1.4 to -1.8 ft/sec between Middle and Lower Roberts Island.

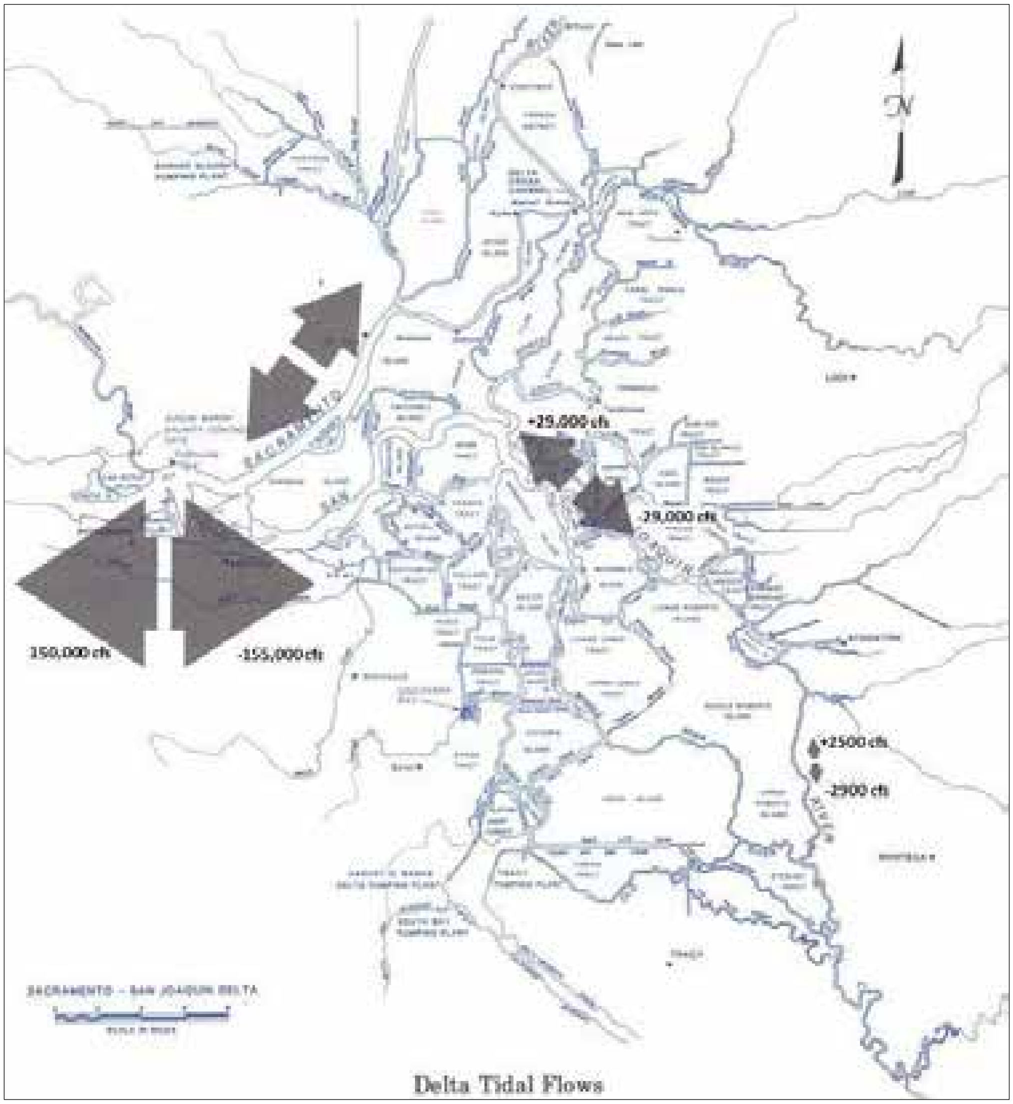


Figure B.1-2. Modeled Maximum Flows at Four Locations in the Sacramento-San Joaquin Delta using DSM2 at Low Inflows of 12,000 cfs, High Exports of 10,000 cfs, and Head of Old River Out

Note: Flows are dominated by large tidal oscillation in the western Delta, which diminishes as you move upstream. Source: Graphic from DWR (1995) Delta Atlas; model results from DSM2 scenarios from Kimmerer and Nobriga (2008).

The SWP and CVP pumping facilities in the South Delta divert Sacramento River and San Joaquin River water. Sacramento River water is diverted through the open DCC, which was built to combat saltwater intrusion in the Delta, dilute local pollution, and improve the quality of irrigation supplies in the Central Valley. The Sacramento River water flows through the Interior Delta for agricultural use and export at the South Delta export facilities. Sacramento River water also regularly flows into Georgiana and Three Mile sloughs, and moves through OMR to reach the South Delta and the SWP and CVP export facilities.

B.2 WATER FLOW AND VELOCITY MONITORING

There is a large network of hydrologic monitoring stations in the Delta operated by the U.S. Geological Survey (USGS), California Department of Water Resources (DWR), and U.S. Bureau of Reclamation (USBR). Much of the data from these stations is telemetered to data repositories managed by DWR in the California Data Exchange Center (CDEC) (DWR 2014b). Most stations record flow in cubic feet per second, while some also record velocity and water quality parameters. The data on CDEC is sometimes preliminary and not quality assured or controlled. Stations record at a time frequency of at least one hour. Many stations record at a frequency of every 15 minutes. Figure B.2-1 shows the location of CDEC surface water stations in the Delta. The USGS also manages a data repository referred to as the National Water Information System (NWIS). In addition to flow and water quality parameters, the USGS records turbidity at some stations. Figure B.2-2 shows the location of NWIS surface water stations in the Delta.

Figure B.2-1. Surface Water Stations in the Sacramento-San Joaquin Delta in the DWR CDEC Data Repository

Source: DWR (2014a)

Figure B.2-2. Surface Water Monitoring Stations in the Sacramento-San Joaquin Delta in the USGS NWIS

Source: USGS (2014)

B.3 HYDRODYNAMIC SIMULATION MODELS

Hydrodynamic simulation models are useful for forecasting and planning. Forecast guidance means that predictions of flow and velocity (and temperature and salinity for instance) conditions in the future are available to water project operators and water users. For planning purposes, simulation models are useful to compare different scenarios and isolating and evaluating individual model variables.

There are several platforms commonly used for modeling hydrodynamics in the Delta. These include one-dimensional (1-D) models such as DSM2, two-dimensional (2-D) models such as RMA2, and three-dimensional (3-D) models such as UnTRIM. A more detailed description of available hydrodynamic models is provided in Appendix C. Hydrodynamic models are typically developed based on a spatial computational mesh, a bathymetric dataset, boundary conditions, initial conditions and several model parameters. The accuracy of the model application depends on the accuracy of these inputs, including site-specific parameters, and reduction of numerical error by choosing appropriate time step, grid size, and orientation for the solution. Various modeling approaches and types of model grids are shown in Figure B.3-1 and discussed by Moffat & Nichol Engineers (2003).

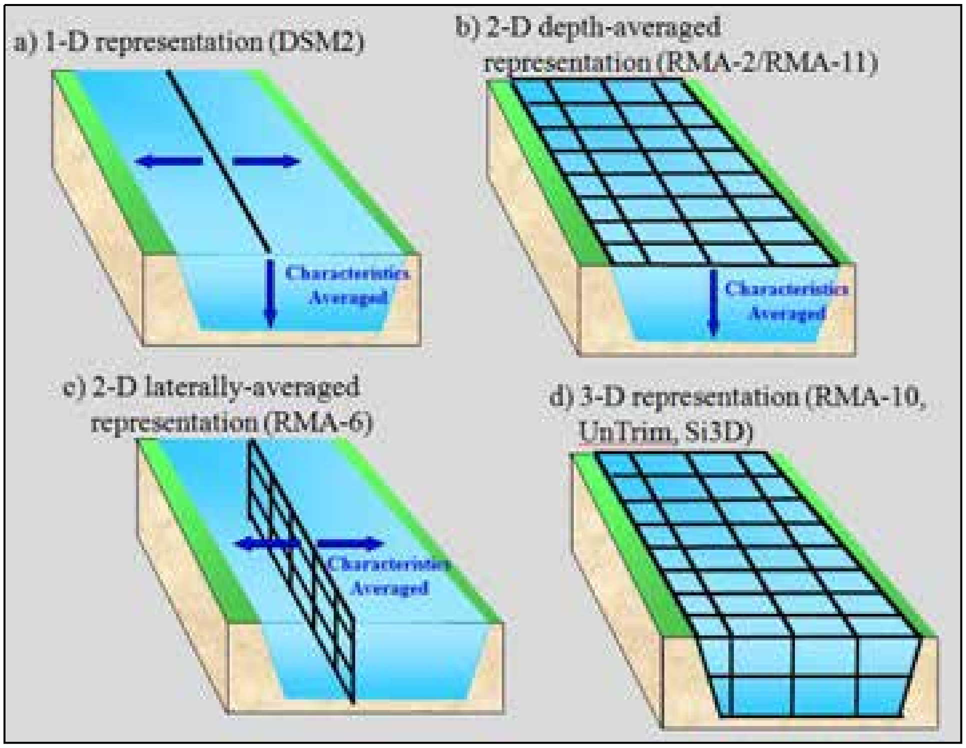


Figure B.3-1. Model Dimensionality

Note: Though not shown on the figure, the RMA2 model also supports a 1-D representation.
Source: Bombardelli et al. (2011)

All numerical modeling approaches have limitations. 3-D models generally provide more information about the spatial distribution of velocity, salinity, and other variables than lower dimensional models. Perhaps more critically, as described below, 3-D models are more mechanistic and, therefore, rely on fewer empirical parameters.

B.3.1 MODEL DESCRIPTION, CALIBRATION AND VALIDATION

B.3.1.1 Three-Dimensional Models

3-D models estimate flow characteristics in three dimensions and through the tidal cycle, providing a detailed approximation of hydrodynamics. In actuality, flows in the Delta are turbulent, involving chaotic and unsteady velocities, changing on the time scale of seconds. Simulation of turbulent motion for a system the size of the Delta is not computationally feasible because it would require prohibitively small grid cells and time steps. Therefore, large-scale models average over the turbulent time scales to describe tidal motions. The limitations of 3-D models include:

- Spatial resolution/computational cost – the spatial resolution of the bathymetry of the model domain, and velocity, is typically limited by the large computational expense associated with high-resolution models. However, recently the resolution of bathymetry has been decoupled from the resolution of the computational mesh allowing high-resolution bathymetry to be represented on a coarse computational mesh (Casulli and Stelling 2010).

- Site-specific parameters – at minimum, 3-D models require bottom friction coefficients to parameterize the resistance to flow at solid boundaries. These parameters are specified in model calibration either from standard reference manuals (e.g., Brater et al. 1996) or by tuning to improve calibration and may be specified globally or in map form[1].
- Turbulence closure – the effect of turbulent motions on the tidal time scale motions is estimated by a turbulence closure. While many turbulence closures are available (e.g., Umlauf and Burchard 2003), this is an ongoing area of research and, particularly in stratified settings, the effect of turbulence on tidal flows is not easy to estimate accurately and different turbulence closures may give significantly different results (Wang et al. 2011).
- Numerical errors – a numerical method approximates the governing equations to some level of accuracy. The predictions of the model can vary substantially among different numerical methods (e.g., Gross et al. 1999) and refinement of numerical methods is an ongoing area of research. Even numerical methods that are theoretically accurate often have unfavorable stability properties that require use of unrealistic diffusion coefficients or diffusive filters to maintain stability. Some models may have additional limitations, for example, not allowing wetting and drying of computational cells.

B.3.1.2 Vertically Averaged Two-Dimensional Models

Vertically averaged 2-D models average the 3-D (turbulent averaged) equations of motion over the vertical dimension and discretize the resulting equations. This typically provides an order of magnitude reduction in the total number of grid cells, and computational expense, associated with these models relative to 3-D models. The vertical distributions of velocity are not represented by 2-D models; therefore, they have a limited ability to represent density-driven and wind-driven flow. The effect of the unresolved vertical distributions of velocity on mixing and transport is parameterized by dispersion coefficients. These dispersion coefficients represent “three-dimensional processes” and are typically several orders of magnitude larger than eddy diffusivity (the effect of turbulence), indicating substantial reliance of 2-D models on these empirical parameters. The limitations of vertically averaged models are:

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[1] Map form: 1. A geographic map on which meteorological conditions or elements are represented by figures, symbols, or isopleths. 2. Data values that are projected relative to a precise latitude–longitude grid in any specified projection, such as Mercator or polar stereographic.

- No characterization of vertical variation in velocity or salinity.
- Heavy reliance on dispersion coefficients. These site-specific parameters vary spatially and should theoretically be varied with flow conditions and tidal conditions (Monismith et al. 2002). In practice, a constant set of dispersion coefficients, often in map form, are applied for all flow and tidal conditions. For this reason, 2-D models are likely to be less accurate than well-calibrated 3-D models for unusual flow and/or tidal conditions.

B.3.1.3 One-Dimensional Models

1-D models average the 3-D (turbulent averaged) equations of motion over the vertical and lateral directions and discretize the resulting equations. Therefore, salinity in regards to transport, is assumed to be fully mixed over the cross-section. 1-D models have minimal computational expense, relative to 3-D models, but also provide quite limited information about velocity and salinity distribution. The limitations of 1-D models include:

- No characterization of lateral variability in velocity or salinity.
- Heavy reliance on dispersion coefficients.

B.3.1.4 Model Calibration and Validation

Model calibration efforts are highly specific and depend on the project to which the model is being applied and the geographic focus and relevant time periods of model application. Well-calibrated 1- or 2-D models may perform better for many applications than poorly calibrated 3-D models.

Several potential problems have been identified in the literature relative to hydrodynamic model calibration and validation in the South Delta (MacWilliams et al. 2008). One is the representation of the Clifton Court Forebay (CCF) operation. Inflow at CCF radial gates is not measured continuously; it is estimated. There are two estimation methods used by DWR. The first method involves calculating the difference between expected storage and actual storage in CCF, with expected storage estimated from the export pump's rating. The second method involves using stage data measured inside and outside of the forebay gates and gate heights. The two methods provide similar results, but neither is an actual measurement of inflow within the channel into CCF.

Another factor affecting validation is the time phase difference between modeled results and measured data. During the 2012 Stipulation Study, modeled flow data were compared to measured data at Turner Cut (Delaney et al. 2014). The time was out of phase by about two hours, and the flow magnitude during the high-low tide was different by about 1,500 cfs (Figure B.3-2). At the time of the writing of the 2012 Stipulation Study, the source of the error (modeled or empirical) was unknown.

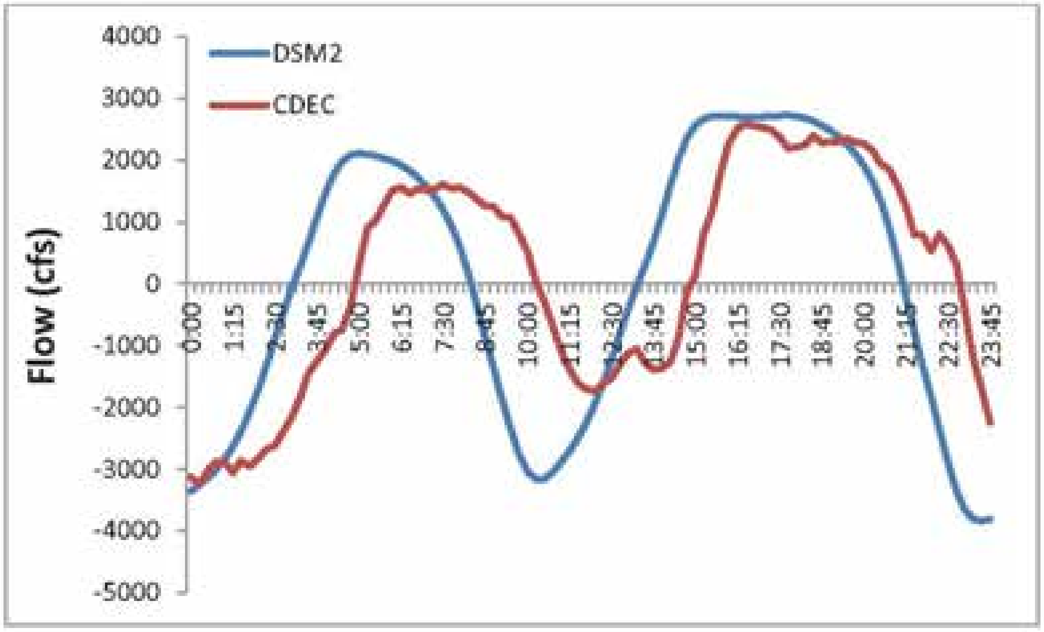

Figure B.3-2. Fifteen-minute Flow Data over 24 Hours at Turner Cut Represented by Both DSM2 Model Results and Measured Data

Source: Delaney et al. (2014)

Other factors identified as adversely affecting hydrodynamic model calibration and validation in the South Delta are inadequate bathymetry data in the South Delta, and inadequate Delta Consumptive Use data. Channel configuration has a major effect on the influence of inflow and exports on the magnitude, direction, and proportion of flow entering downstream channels through the interior, central, and South Delta. Current, high-resolution channel bathymetry is necessary to better determine the combined hydrologic effects of exports, tides, and river inflows on salmonid movement and survival through the Delta. Delta Consumptive Use becomes extremely important at low net Delta outflows. DWR has an ongoing program to develop better Delta Consumptive Use estimates called DETAW. There is also work ongoing at UC Davis on this topic (baydeltaoffice.water.ca.gov/modeling/deltamodeling/delta/reports/annrpt/2006/2006Ch7.pdf and www.cwemf.org/Activities/DETAWWorkshop/IDCPres.pdf).

B.3.1.5 Comparison of Modeled to Measured Water Flow and Velocity

To assess the accuracy of DSM2 hydrologic model simulations in the South Delta, we compared results from a historical hydrodynamic simulation to field-measured hydrologic data from four monitoring stations in the South Delta: the head of Turner Cut, Old River at Highway 4, Old River near the intake to Clifton Court, and West Canal near the intake to Clifton Court (Figure B.3-3).

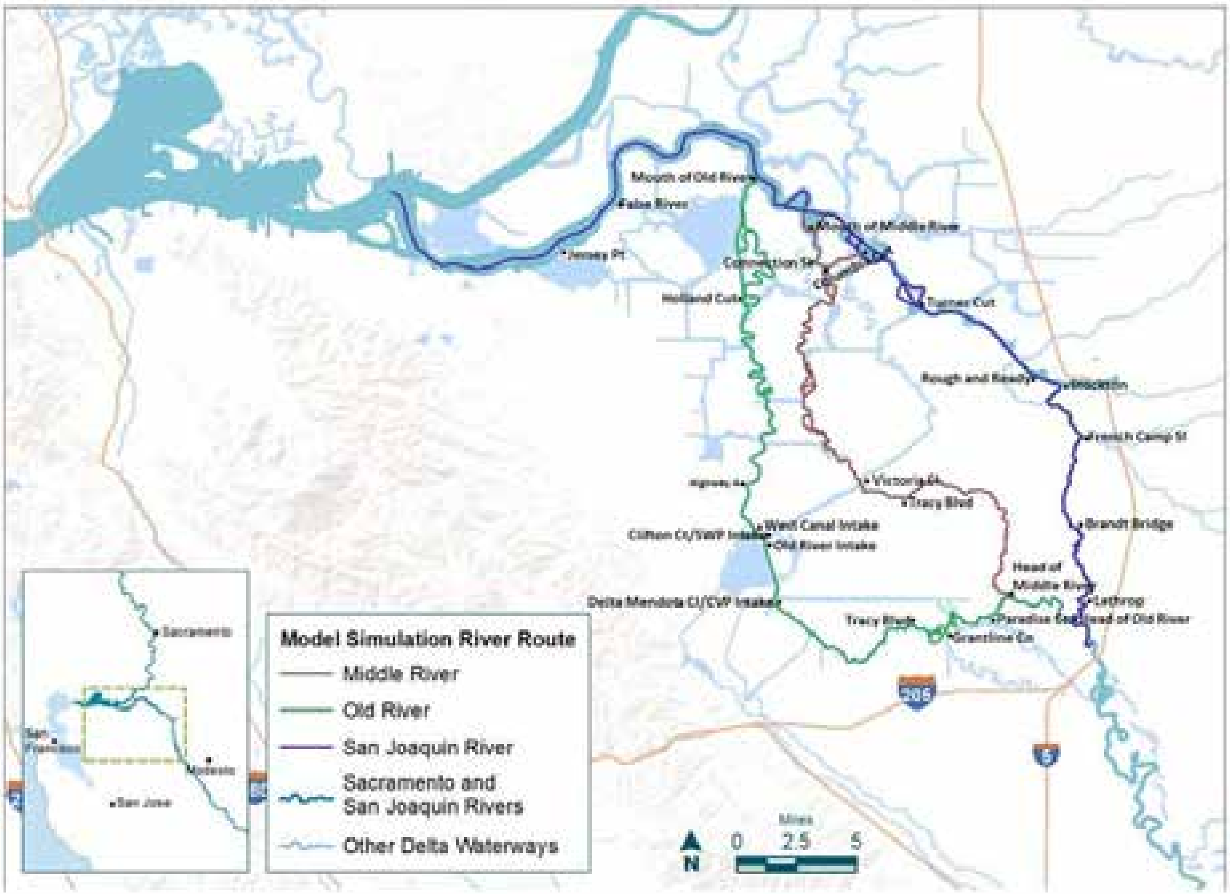

Figure B.3-3. Location of Monitoring Stations used for Comparing Historical DSM2 Simulations with Field-measured Data and for Evaluating DSM2 Model Comparisons

We compared historical measured 15-minute flow and velocity data over a one-month period, immediately upstream and downstream of the CCF intake to simulated model results for similar locations (Figure B.3-4 and Figure B.3-5). The model results and empirical data were obtained from RMA. The tidal phase shift (or lag) was removed for the comparison. The monitoring stations examined were West Canal Intake and Old River at Clifton Court Intake. The corresponding DSM2 channels were 132 and 82, respectively. The cyclic effect of tidal action on flows and velocities in South Delta channels are clear both in the observed field measurements and in the model simulations. In addition to showing the 15-minute time step, Figure B.3-4 and Figure B.3-5 show tidally filtered flows and velocities to remove the tidal effects from the data.

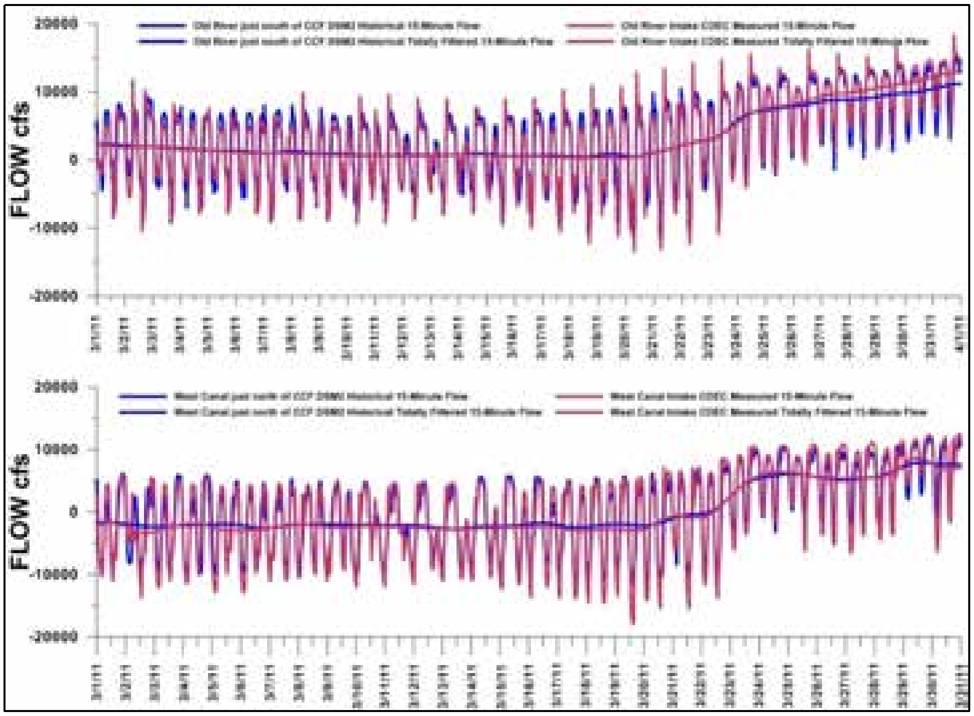

Figure B.3-4. Comparison of Field Measurements and DSM2 Simulation Results for 15-minute and Tidally Filtered 15-minute Flow Immediately Upstream and Downstream of the CCF Intake

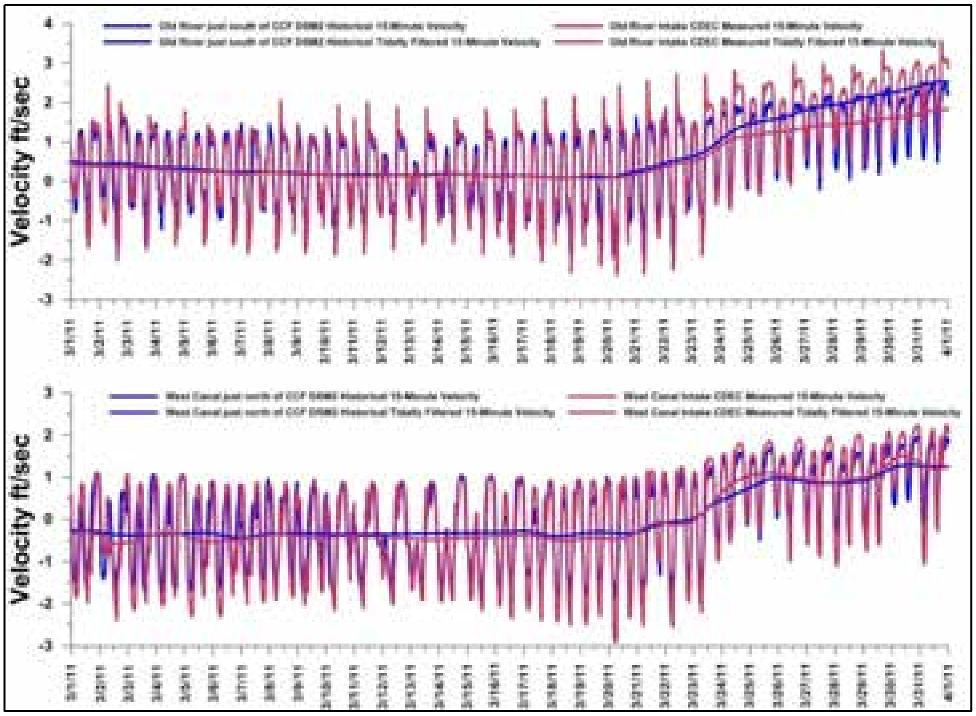

Figure B.3-5. Comparison of Field Measurements and DSM2 Simulation Results for 15-minute and Tidally Filtered 15-minute Velocity Immediately Upstream and Downstream of the CCF Intake

We also examined X:Y scatter plots of the measured and simulated flow and velocity data (Figure B.3-6 through Figure B.3-9). If the model predictions and field observations are in perfect agreement, a regression fit to the data would have a slope of 1.0 and a correlation coefficient (r^2) equal to 1.0. Regression coefficients for each of the South Delta locations included in the comparative analysis are summarized in Table B.3-1.

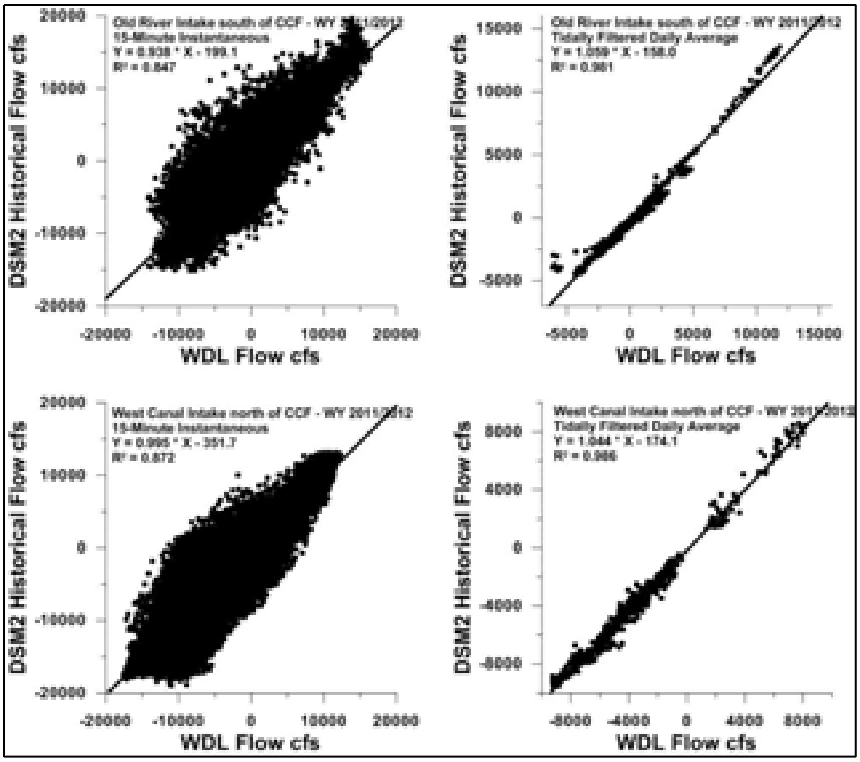

Figure B.3-6. Comparison of Field Measurements and DSM2 Simulation Results for 15-minute and Tidally Filtered Daily Average Flow at the Old River and West Canal Intakes

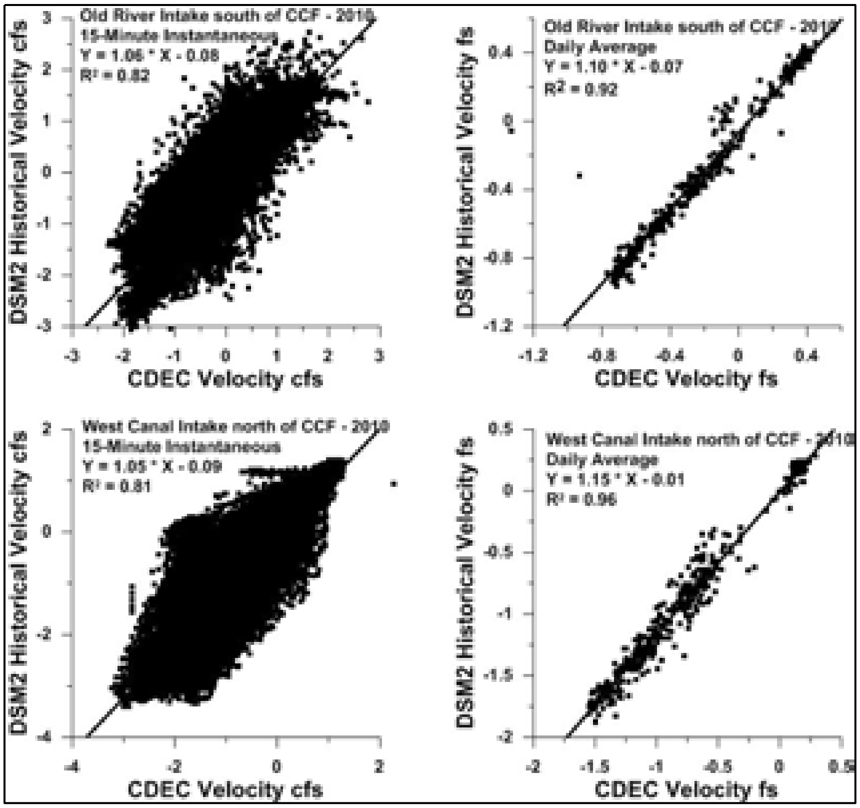

Figure B.3-7. Comparison of Field Measurements and DSM2 Simulation Results for 15-minute and Tidally Filtered Daily Average Velocity at the Old River and West Canal Intakes

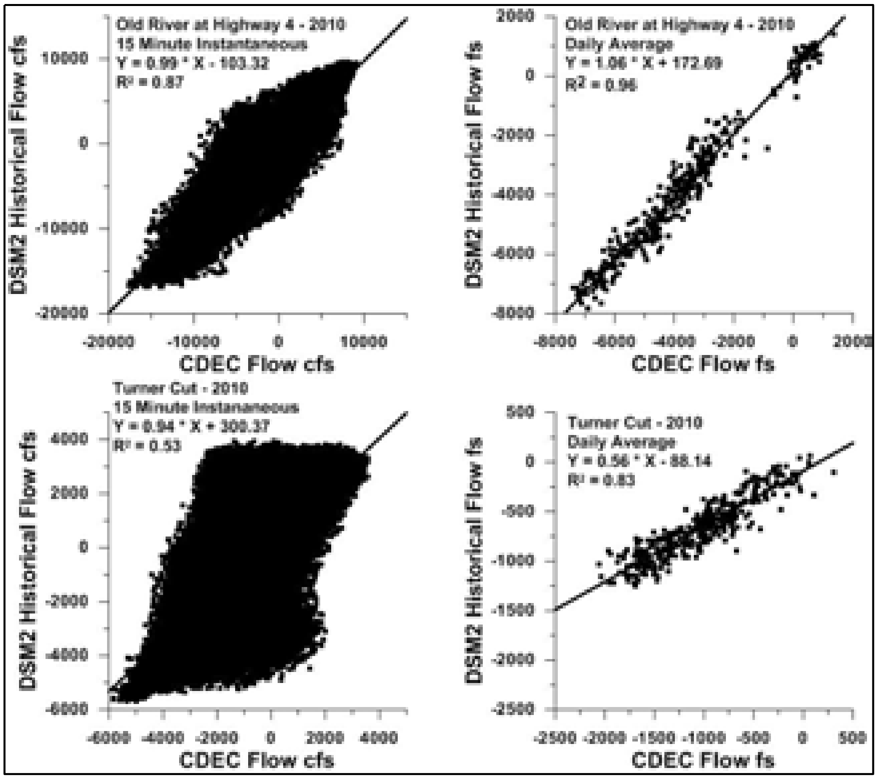

Figure B.3-8. Comparison of Field Measurements and DSM2 Simulation Results for 15-minute and Tidally Filtered Daily Average Flow at the Old River at Highway 4 and Turner Cut

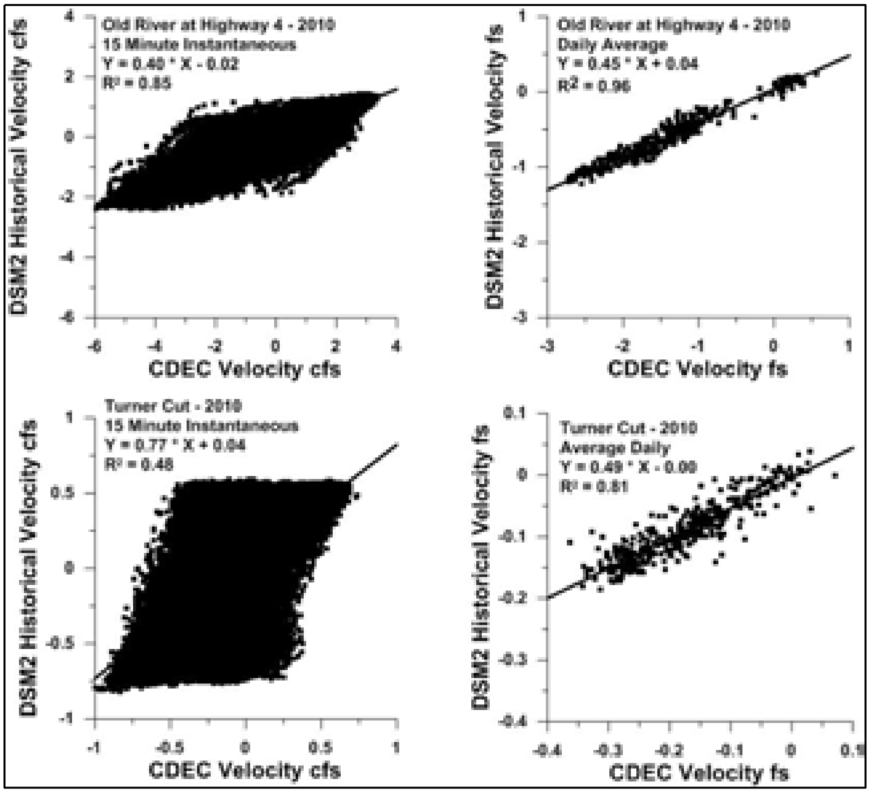

Figure B.3-9. Comparison of Field Measurements and DSM2 Simulation Results for 15-minute and Tidally Filtered Daily Average Velocity at the Old River at Highway 4 and Turner Cut

Table B.3-1. Regression Slope and Coefficients for a Comparison Between Empirical Flow and Velocity Data and Corresponding Modeled Results for Four Stations in the South Delta

Location	15-minute Flow Slope, r^2	15-minute Velocity Slope, r^2
West Canal near Clifton Court	0.995, 0.872	1.018, 0.829
Old River near Clifton Court	0.938, 0.847	1.137, 0.841
Old River at Highway 4	0.985, 0.888	0.340, 0.889
Turner Cut	0.754, 0.451	0.614, 0.451
Location	Tidally Filtered Average Daily Flow Slope, r^2	Tidally Filtered Average Daily Velocity Slope, r^2
West Canal near Clifton Court	1.044, 0.986	1.103, 0.990
Old River near Clifton Court	1.059, 0.981	1.317, 0.990
Old River at Highway 4	1.081, 0.986	0.447, 0.987
Turner Cut	0.504, 0.711	0.412, 0.716

Based on results of these analyses, we concluded that the agreement between DSM2 model predictions and measured flow and velocity is better at some locations than others in the South Delta. Results also show that the model predictions and measured values are in better agreement when using average daily values than when using 15-minute values. Furthermore, the agreement at one location can change over months and years such as the case of Turner Cut (Figure B.3-10). The variation between modeled and measured values at a location could be the result of model input inaccuracies and over-simplified assumptions, consumptive use, bathymetry or inaccuracies, and drift in the meters used to measure velocities in the Delta.

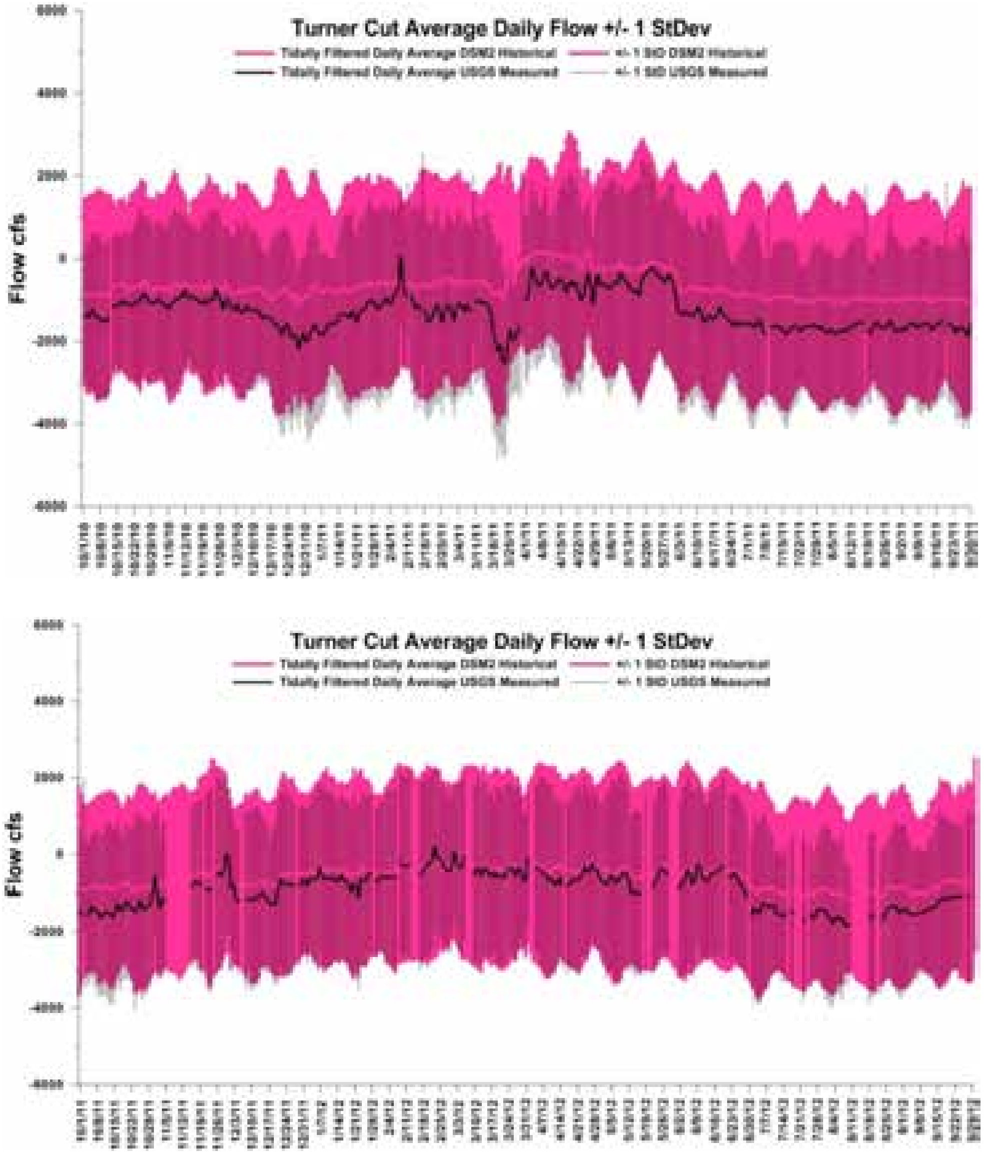

Figure B.3-10. Comparison of Field Measurements and DSM2 Simulation Results for 15-minute and Tidally Filtered Daily Average Flow at Turner Cut for Water Years 2011 and 2012

Numerous studies have been conducted in the last couple of decades to better document the hydrodynamics at complex locations in the Delta (Dinehart and Burau 2005a, 2005b; Paulsen and Chiang 2008; Brunell et al. 2010; DWR 2012, 2013). The purposes of these studies are to calibrate the hydrodynamic models at those locations, and to expand the results to other areas in the Delta. The USGS also regularly collects velocity transects at many locations in the Delta for the calibration of their flow stations.

B.3.2 COMPARISON OF ONE-DIMENSIONAL AND TWO-DIMENSIONAL MODEL RESULTS

While many hydrodynamic models have been applied in the Delta, the hydrodynamic models most extensively used in studies that have both hydrodynamic and particle tracking components are DSM2, RMA2, and UnTRIM. For this reason, available model comparisons performed to date have largely applied to these models.

The DSM2 and RMA2 hydrodynamic model performance in the Delta are compared by Bombardelli et al. (2011). The report concludes that while one model may perform better than the other at individual locations, both models performed well for a range of conditions including high and low tributary flow and high and low exports.

The Salmon Scoping Team (SST) requested a comparison between DSM2-1D and RMA-2D model simulations and measured flow and velocity data at 18 locations in the South Delta to help determine if there is a model that can be used at a short time scale and small geographic scale to complement the fine-scale acoustic tag fish data that have been collected. The complete report is included as Appendix C.

DSM2 is a 1-D longitudinal model with depth and cross section averaged. RMA-2D adds a second dimension, cross section, at the wider channels in the Delta. The depth dimension is still averaged, and one dimension is used in most of the South Delta where the channels are narrower. Model simulations of historical conditions were performed for the period from October 1, 2010 through September 30, 2012. Water year 2011 was a wet year and 2012 a below normal/dry year.

RMA compared three scenarios, DSM2-1D with their boundary conditions, RMA-2D with DSM2 boundary conditions, and RMA-2D with their own boundary conditions to the measured data. Most boundary conditions between DSM2 and RMA were similar, with the exception of Cache Slough/Yolo Bypass area (Appendix C, Pages 3 and 8 for a complete description).

The quality of fit between model results and measured data is presented in the form of time series of both 15-minute instantaneous and tidally averaged time scales in Appendix C. In addition, RMA used several model error metric statistics and model skill[2] to quantify the differences between model results and measured data. The error metrics were mean, lag, linear regression, and amplitude ratio. A summary of flow and velocity error metrics and

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2 Model skill is a measure of hydrodynamic model performance that captures the degree to which deviations in the observed data about the observed data average correlate with deviations in the modeled data about the observed data average (Willmott 1981).

model skill are presented in Table B.3-2 and Table B.3-3 with colored cells for a quick assessment of goodness of fit with observed data. The colors range from green for better fit to red for worse fit.

The DSM2 and RMA models both compared favorably with measured data throughout much of the South Delta. The RMA model compared better with measured data than DMS2 with regard to mean difference from measured data (17.2% versus 54.2%, respectively) and lag (22 versus 28 minutes, respectively), while DSM2 model compared slightly better than RMA with regard to linear regression (0.941 versus 0.937 r^2, respectively) and amplitude ratio (0.940 versus 0.939, respectively). The two models were very close in terms of model skill (RMA=0.967 versus DSM2=0.957), both near the cusp of accurate and acceptable (0.95). There was little difference between the results of RMA in the South Delta using the DSM2 boundary conditions compared to their own RMA boundary conditions (see Table B.3-2 and Table B.3-3).

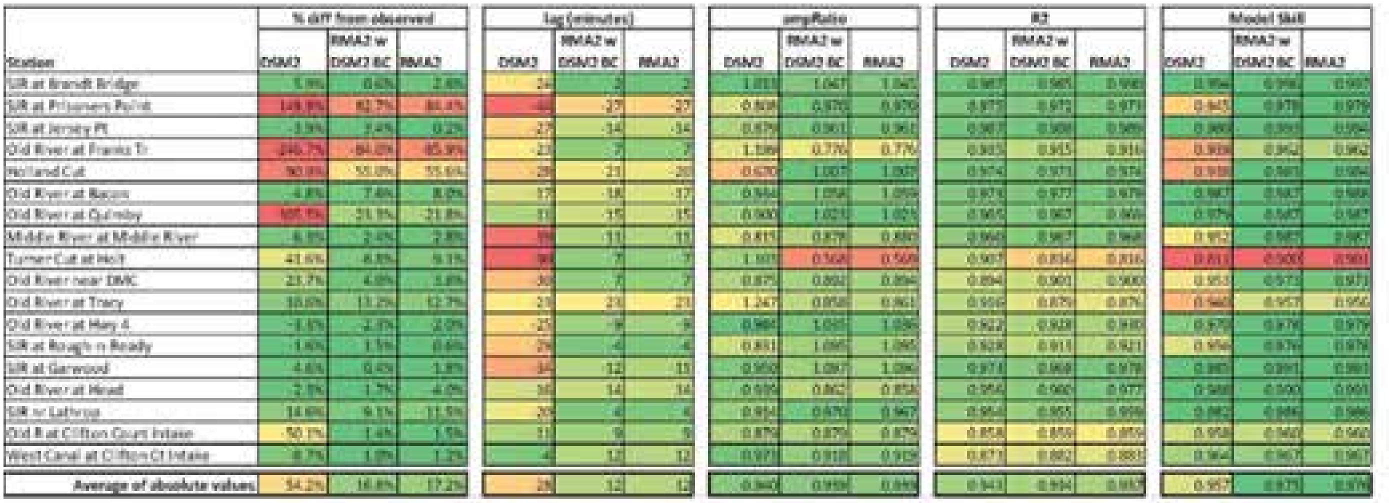
For the RMA model, the mean percent flow difference from measured data is about 10% or less at most locations analyzed with an average absolute difference of 17%. For DSM2, the mean percent difference from measured data was about 10% for the majority of stations as well, but there were a few more locations that did not validate well resulting in an average absolute difference of 54%. These stations are described in more detail below.

DSM2 flow lagged measured data at all locations, with an average lag of 28 minutes. The RMA model had a mix of positive and negative lags with an average of the absolute lag values of 12 minutes.

At most locations, r^2 values for flow exceeded 0.9 for both models and averaged about 0.94 for both models. Amplitude ratios and slopes ranged from 0.8 to 1.1 at most locations for both models and averaged 0.94.

During the lower flow periods within water year 2011 and 2012, DSM2 and RMA produced similar flow results at many locations. In comparison, there tended to be more disparity among the models and between the models and measured data during the high flow period in April 2011. Two contributing factors could be: 1) geometry in either model may not be as accurate at higher water levels; and 2) measured data gauges may not be as accurate at high flows for some locations.

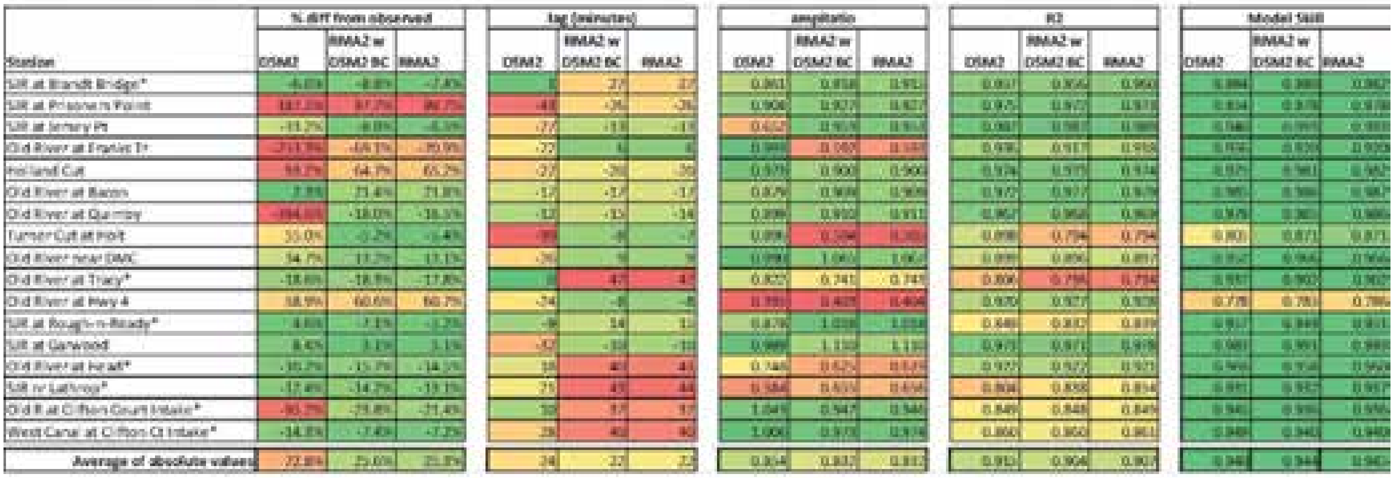
Table B.3-2. Summary of Flow Error Metrics and Model Skill



Station	% diff from observed			lag (minutes)			ampRatio			R2			Model Skill		
	DSM2	RMA2 w DSM2 BC	RMA2	DSM2	RMA2 w DSM2 BC	RMA2	DSM2	RMA2 w DSM2 BC	RMA2	DSM2	RMA2 w DSM2 BC	RMA2	DSM2	RMA2 w DSM2 BC	RMA2
SJR at Brandt Bridge	5.9%	0.6%	2.6%	24	2	2	1.033	1.067	1.062	0.987	0.985	0.990	0.994	0.998	0.997
SJR at Prisoners Point	149.9%	82.7%	84.4%	-46	-27	-27	0.808	0.970	0.970	0.975	0.971	0.971	0.945	0.979	0.979
SJR at Jersey Pt	-3.9%	3.4%	0.2%	-27	-14	-14	0.879	0.961	0.961	0.987	0.989	0.989	0.990	0.993	0.994
Old River at Franks Tr	246.7%	-84.0%	-85.9%	-23	7	7	1.339	0.776	0.776	0.915	0.915	0.916	0.906	0.962	0.962
Holland Cut	90.8%	55.0%	55.6%	-28	-23	-20	0.670	1.007	1.007	0.974	0.971	0.974	0.918	0.985	0.984
Old River at Bacon	-4.8%	7.4%	8.0%	17	-18	-17	0.944	1.058	1.059	0.978	0.977	0.978	0.987	0.987	0.988
Old River at Quimby	105.7%	-21.9%	-21.8%	11	-15	15	0.900	1.021	1.021	0.965	0.967	0.966	0.976	0.987	0.987
Middle River at Middle River	6.9%	2.4%	2.8%	59	-11	11	0.815	0.879	0.880	0.960	0.967	0.968	0.952	0.985	0.987
Turner Cut at Holt	41.6%	-6.8%	-9.1%	96	7	7	1.107	0.568	0.569	0.907	0.834	0.816	0.851	0.900	0.901
Old River near DMC	23.7%	4.0%	3.6%	30	7	7	0.875	0.892	0.894	0.894	0.900	0.900	0.953	0.971	0.971
Old River at Tracy	10.6%	13.2%	12.7%	23	23	23	1.247	0.958	0.961	0.916	0.875	0.876	0.940	0.957	0.956
Old River at Hwy 4	-3.6%	2.3%	2.0%	-25	-9	-9	0.984	1.035	1.036	0.922	0.928	0.930	0.970	0.979	0.979
SJR at Rough n Ready	1.6%	1.5%	0.6%	29	4	4	0.851	1.095	1.095	0.928	0.913	0.921	0.956	0.976	0.976
SJR at Garwood	4.6%	0.4%	1.8%	34	12	15	0.950	1.087	1.086	0.974	0.968	0.978	0.985	0.991	0.991
Old River at Head	2.5%	1.7%	-4.0%	16	14	14	0.939	0.862	0.858	0.956	0.960	0.977	0.988	0.990	0.993
SJR nr Lathrop	14.6%	9.1%	-11.5%	20	4	4	0.914	0.970	0.967	0.964	0.955	0.959	0.982	0.986	0.986
Old R at Clifton Court Intake	-50.1%	1.4%	1.5%	11	9	9	0.879	0.879	0.879	0.858	0.859	0.859	0.958	0.960	0.960
West Canal at Clifton Ct Intake	8.7%	1.0%	1.2%	4	12	12	0.971	0.918	0.919	0.873	0.882	0.881	0.964	0.967	0.967
Average of absolute values	54.2%	16.8%	17.2%	28	12	12	0.940	0.959	0.959	0.943	0.934	0.937	0.957	0.975	0.976

Note: Shading ranges from green for better fit to red for worse fit.
Source: RMA (2015)

Table B.3-3. Summary of Velocity Error Metrics and Model Skill



	% diff from observed			lag (minutes)			ampratio			R2			Model Skill		
Station	DSM2	RMA2 w DSM2 BC	RMA2	DSM2	RMA2 w DSM2 BC	RMA2	DSM2	RMA2 w DSM2 BC	RMA2	DSM2	RMA2 w DSM2 BC	RMA2	DSM2	RMA2 w DSM2 BC	RMA2
SJR at Brandt Bridge*	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
SJR at Prisoners Point	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
SJR at Jersey Pt	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Old River at Franks Tr	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Holland Cut	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Old River at Bacon	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Old River at Quimby	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Turner Cut at Holt	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Old River near DMC	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Old River at Tracy*	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Old River at Hwy 4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
SJR at Rough-n-Ready*	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
SJR at Garwood	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Old River at Head*	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
SJR nr Lathrop*	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Old R at Clifton Court Intake*	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
West Canal at Clifton Ct Intake*	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Average of absolute values	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Notes: Asterisks after station names indicate that observed data are from CDEC, which can contain time shift errors. Shading ranges from green for better fit to red for worse fit.
Source: RMA (2015)

There were four locations in the South Delta where both models diverged from measured flow data: Old River at Franks Tract (Appendix C, Figures C24-C26), San Joaquin River at Prisoners Point (Appendix C, Figures 18-20), and Holland Cut (Appendix C, Figures 27-29). The largest differences between DSM2 and RMA and their divergence from measured data occurred at Old River at Franks Tract (-246.7 versus -85.9, respectively) (Table B.3-2), Old River at Quimby (-305.5 versus -21.8, respectively) (Table B.3-2; Appendix C, Figures 33-35), Turner Cut (+41.6 versus -9.1, respectively) (Table B.3-2; Appendix C, Figures 39-41), and Holland Cut (+90.9 versus +55.6, respectively) (Table B.3-2). At Turner Cut, both models were in the poor category for model skill (Table B.3-2). Refer to Appendix C (pages 14 through 16) for a detailed explanation of the difficulties at these locations.

There were larger disparities between modeled velocity and measured velocity relative to flow. For the RMA model, the average absolute difference was 25% (compared to 17% for flow), and for DSM2, the average absolute difference was 73% (compared to 54% for flow). The trend among the locations was mostly similar for both models with the exception of Old River at Highway 4. Old River at Highway 4 had a particularly higher percent difference between modeled velocity results and measured velocity (Appendix C, Figures 48-50 for flow and Figures 118-120 for velocity): about 60% for both models compared to about -3% for both models for flow.

B.4 TEMPORARY, OPERABLE, AND NON-PHYSICAL BARRIERS

As part of SWP and CVP operations, both temporary rock barriers (e.g., agricultural barriers in the South Delta, the Head of Old River Barrier [HORB]) and operable barriers (DCC radial gates) are used to regulate and manage water flows through Delta channels and reduce the effects of South Delta export operations on water elevation in South Delta channels. In recent years, use of non-physical barriers for guiding downstream migrating Chinook salmon and steelhead have been tested in the Sacramento River at Georgiana Slough and San Joaquin River at the head of Old River.

B.4.1 TEMPORARY BARRIERS

The South Delta Temporary Barriers Project has been in place since 1991 and has included the spring installation and subsequent fall removal of four rock barriers at a number of locations in the South Delta (DWR 2011a). The historical construction schedule can be found at http://baydeltaoffice.water.ca.gov/sdb/tbp/web_pg/tempbsch.cfm. The three agricultural barriers are used to increase water levels in South Delta channels (thereby reducing the effects of exports on water levels), and to improve water circulation and water quality for agricultural use. Temporary agricultural barriers are installed at Middle River, the head of Old River during the spring and fall, Grant Line Canal, and Old River at Tracy in the spring.

As part of the Delta Temporary Barriers Project evaluation (DWR 2011a, 2011b), the 1-D DSM2 model was used at a 15-minute time step to simulate changes in average daily flow in various Delta channels with and without the temporary barriers. The model was used to represent actual hydrologic boundary conditions during the period that the barriers were installed. Results of the model validation show that the model predictions and observed stage and flow generally agree at a majority of locations.

Results of the DSM2 simulations showed that installation of the temporary barriers resulted in 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 from the barrier. The barriers were also found to diminish tidal variation in flows with the effect most pronounced in OMR when the Grant Line Canal 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).

B.4.2 HEAD OF OLD RIVER BARRIER

The HORB is used to increase flows and dissolved oxygen concentrations for adult fall-run Chinook migration, and reduce the proportion of juvenile salmon and steelhead migrating into Old River in the spring. Results of DSM2 simulations show that installation of the HORB significantly reduces the flow of water that enters Old River and Grant Line Canal (DWR 2011a, 2011b) from the lower San Joaquin River. The HORB increases flow 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 (see section B.5.3 for details).

B.4.3 DELTA CROSS CHANNEL

The USGS conducted a fine-scale hydrodynamic study, in conjunction with fine-scale fish tracking, on the Sacramento River near the head of the DCC. Prior to the study, fisheries researchers thought that smolts feeding along the west bank of the main channel during a rising tide would not be diverted into the DCC entrance. The purpose of the study was to compare hydrodynamic results to fish tracking results. In addition to the streamwise velocity, USGS identified lateral and vertical secondary circulation velocity patterns within the stream cross sections (Dinehart and Burau 2005b). The lateral and vertical velocity patterns were influenced by the difference in water surface elevation between the Sacramento River mainstem and channels east of the DCC. For example, towards the end of an outgoing tide in the Sacramento River, velocities in the Sacramento River and open DCC were both downstream. When the tide shifted to incoming in the Sacramento River, the velocity in the Sacramento River deceased, but the velocity was directed downstream north of the DCC and upstream south of the DCC. At the same time, velocity in the DCC increased and was still directed downstream. At the start of the next outgoing tide on the Sacramento River, velocity in the Sacramento mainstem was downstream both north and south of the DCC, but the velocity north was slower than the velocity south, and the velocity in the DCC shifted to upstream and flowed into the Sacramento River (Figure B.4-1).

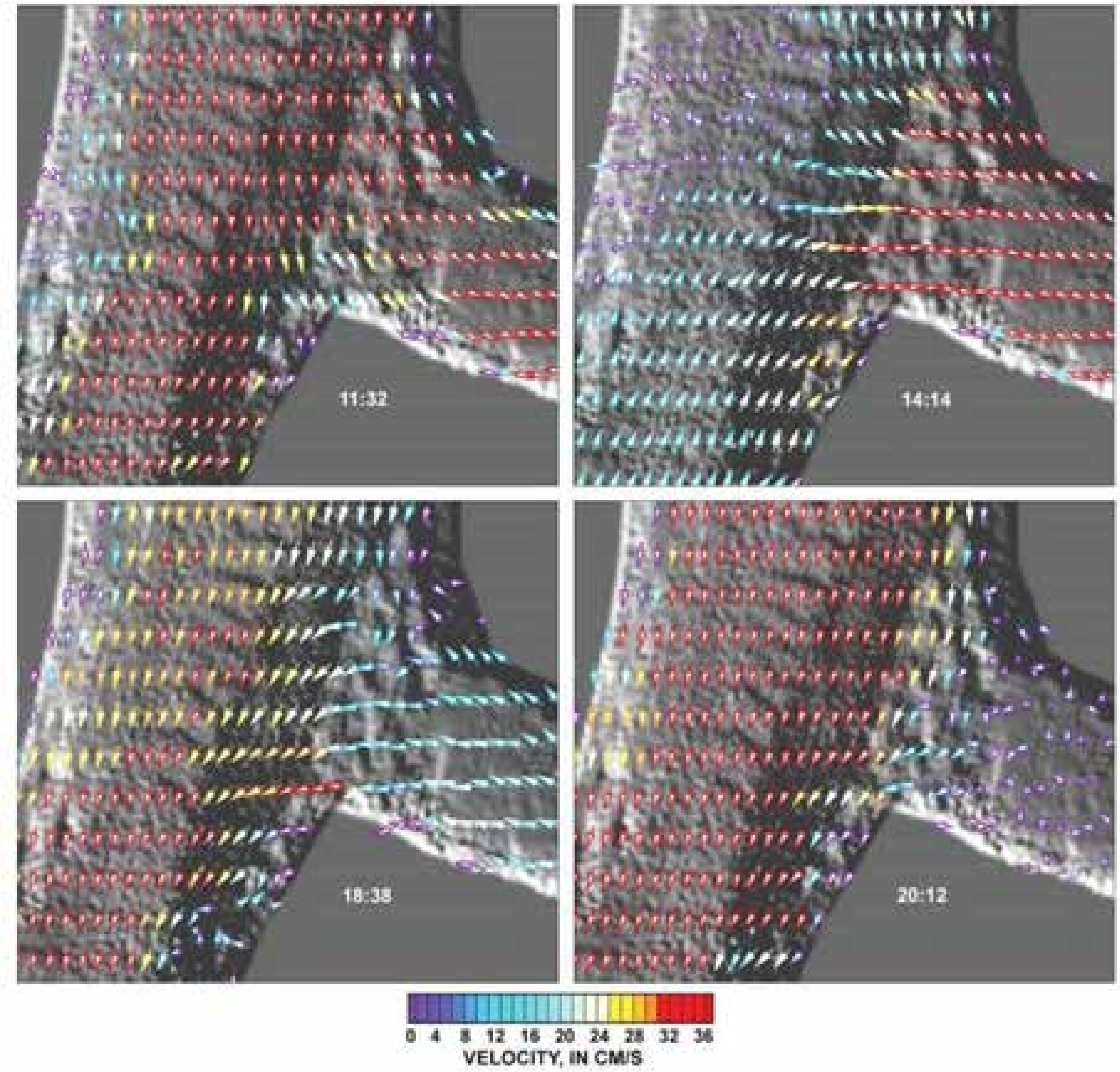


Figure B.4-1. Fine-scale Velocity Vectors in the Sacramento River at the Delta Cross Channel over a 9-hour Period

Note: Arrows illustrate the direction and color contours illustrate the magnitude.
Source: Dinehart and Burau (2005b)

Flow directions through time and space were illustrated with “streamtraces.” Streamtraces simulate the paths of massless particles that follow the flow. A rake of streamtrace origins was placed from bank to bank across the Sacramento River just upstream of the DCC, for a rising tide, to compare flow direction originating from the east versus west banks. The study results show that streamtraces originating near the west bank of the main channel entered the DCC for four hours during each diurnal tidal phase (Figure B.4-2(A)).

To examine the near-bed effects of flow toward the canal entrance, a rake of streamtrace origins was placed diagonally along the thalweg at a depth of 7 meters in the vector grid. The streamtraces indicated a vertical upward movement of 5 meters on paths from the thalweg into the DCC (Figure B.4-2(B)).

B.4.4 GEORGIANA SLOUGH NON-PHYSICAL BARRIER

The National Marine Fisheries Service (NMFS) 2009 Biological and Conference Opinion for the Long-Term Operations of the Central Valley Project and State Water Project (BiOp) included a reasonable and prudent alternative requiring DWR and the USBR to consider engineering solutions to reduce the diversion of juvenile salmonids from the Sacramento River into the interior and South Delta, Action IV.1.3 of the BiOp. After evaluating results of experimental tests using various alternative non-physical barrier technologies, DWR implemented the Georgiana Slough Non-Physical Barrier Studies in 2011, 2012, and 2014 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. As part of the studies, hydrodynamics and velocity were measured simultaneous to fine-scale fish movements in the study area Acoustic Doppler Current Profilers (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 (Figure B.4-3).

The purpose of the 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. A hydrodynamic model was developed and releases of drifters to validate particle transport streamtraces modeled with the temporally broader hydrodynamic model.

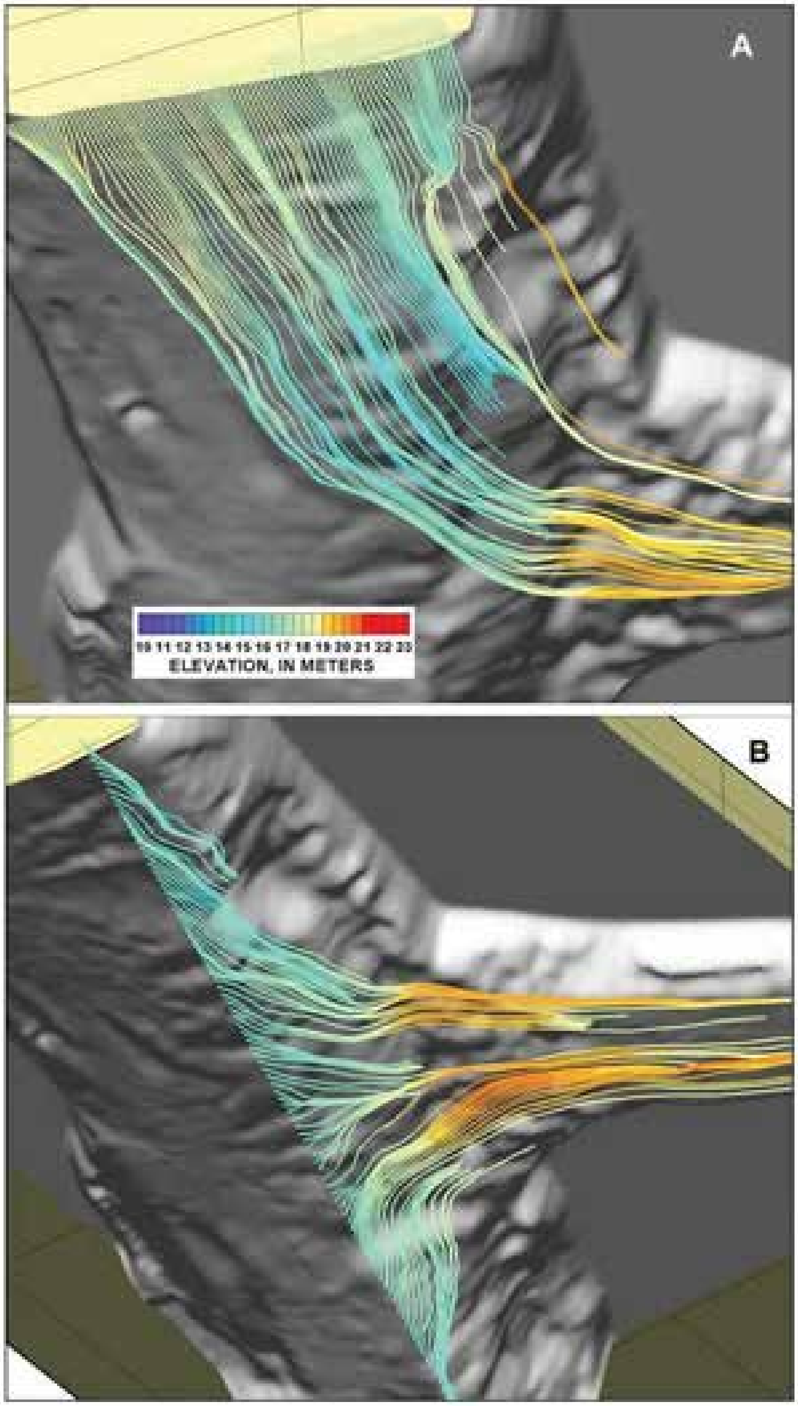


Figure B.4-2. Streamtraces in the Sacramento River at the Delta Cross Channel During a Rising Tide

Notes: Streamtraces are a visualization of flow direction through 3-D fields. The color contour represents the horizontal elevation.
Source: Dinehart and Burau (2005)

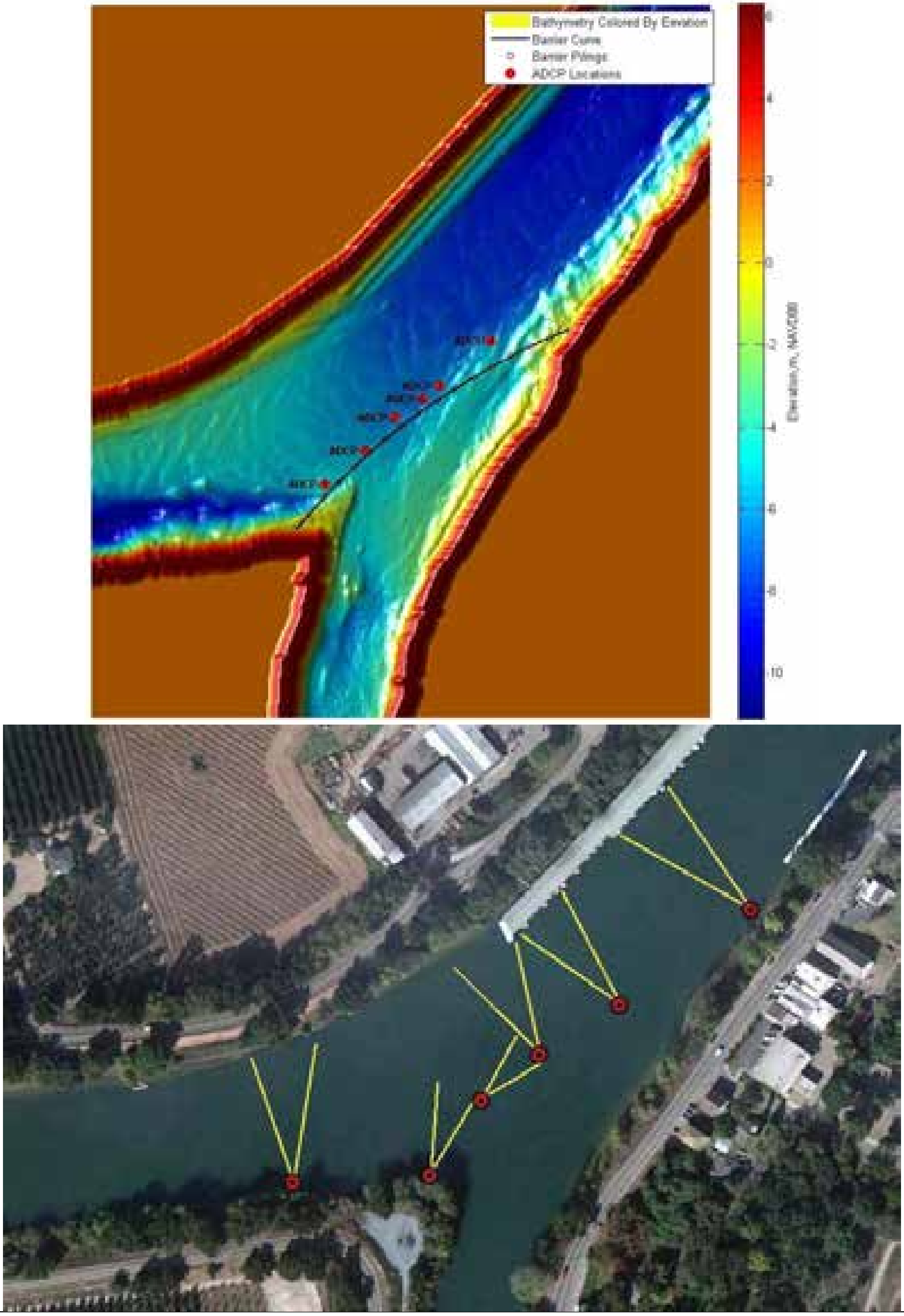


Figure B.4-3. ADCP Deployment Locations in the Sacramento River at Georgiana Slough for the 2011 (upper) and 2012 (lower) Non-physical Barrier Study

Source: DWR (2012)

Particles (or drifters) that enter the junction of the Sacramento River with Georgiana Slough are either transported into Georgiana Slough or bypass it during downstream flow conditions. Areas in 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. In Figure B.4-4, the critical streakline (red) separates the entrainment zone for modeled particles that enter the Georgiana Slough and the entrainment zone for particles that remain in the Sacramento River during downstream flow conditions. Figure B.4-5 is an illustration of the critical streakline for upstream flow conditions, and Figure B.4-6 shows the critical streakline for converging flow conditions.

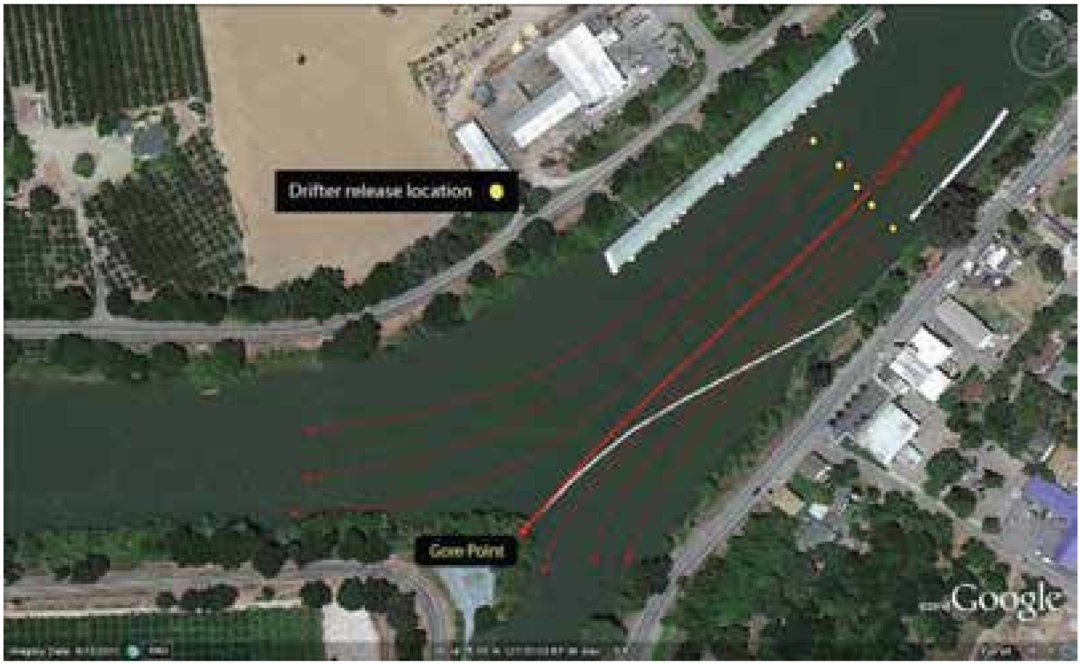


Figure B.4-4. Drifter Release Locations (yellow dots) During Ebb Tides and Modeled Particle Paths and Critical Streamline Under Downstream Conditions

Source: DWR (2013)

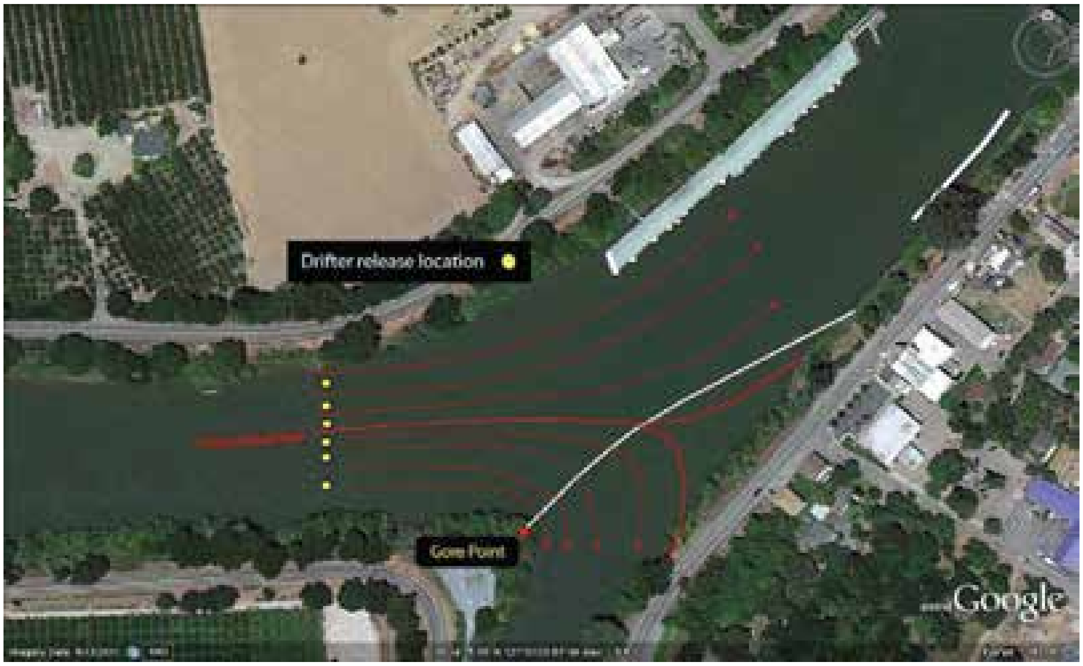


Figure B.4-5. Drifter Release Locations (yellow dots) During Flood Tides and Modeled Particle Paths and Critical Streamline Under Upstream Conditions

Source: DWR (2013)

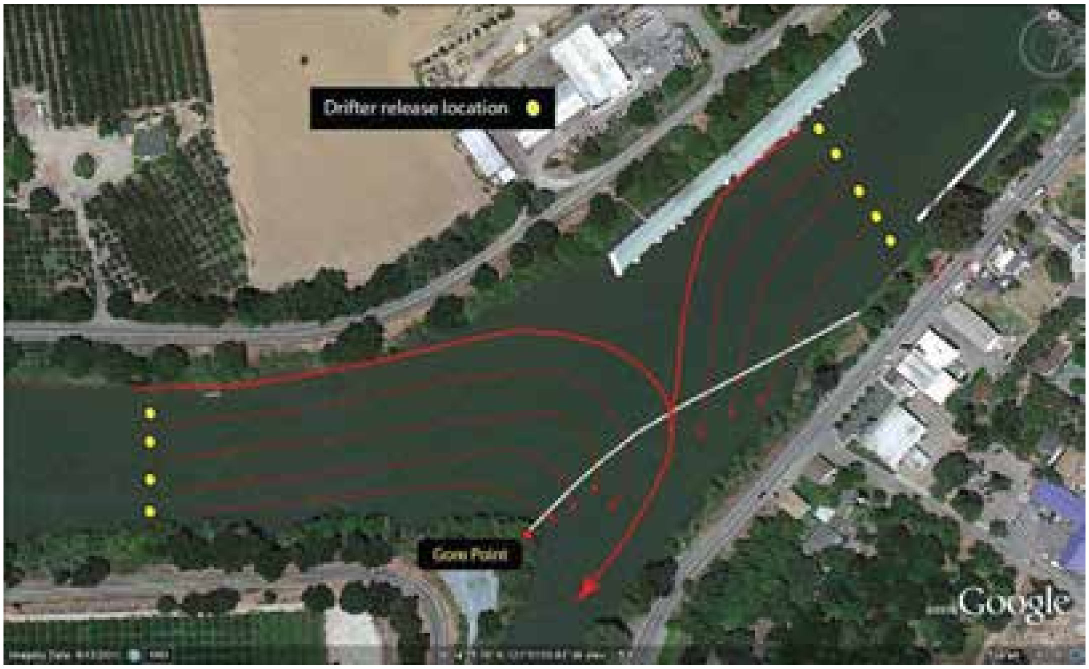


Figure B.4-6. Drifter Release Locations (yellow dots) During a Converging Stage and Modeled Particle Paths and Critical Streakline Under Converging Conditions

Source: DWR (2013)

The streakline positions are useful in understanding entrainment of particles. The streakline positions are 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: 1) upstream; 2) downstream; 3) converging flows when water is entering the side channel; 4) upstream; 5) downstream; and 6) 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 intended use and then averaged over the time scale of interest. Typically in the Delta, the average of the components of the ratio is calculated and then the ratio is calculated. This often results in incorrect results (DWR 2013).

B.4.5 CLIFTON COURT FOREBAY GATE OPERATIONS

CCF is operated as a regulating reservoir within the tidal region of the South Delta for SWP water export operations (Clark et al. 2009). CCF was constructed in 1969 with a surface area of 2,200 acres. Water is diverted from Old River and West Canal into the CCF intake through five radial gates (each 20 by 20 feet). Diversion (gate opening) is timed to occur as the flooding tide reaches the CCF intake and through the early part of the ebb tidal cycle. The frequency that the radial gates are opened to flood CCF depends on the SWP export rate, the volume of water storage in CCF, and tidal conditions. When the difference in water surface elevation between Old River and CCF is greatest, water velocities through Clifton Court Canal typically exceed 15 ft/sec at flow rates typically ranging between 10,000 and 15,000 cfs (Clark et al. 2009). After CCF has been filled, the radial gates are closed and water exports are made from storage within CCF.

B.5 HYDRODYNAMIC EFFECTS OF EXPORT OPERATIONS

B.5.1 METHODS

The SST characterized the extent of the effect of the SWP and CVP South Delta export operations on flow along channels and at selected junctions in the South Delta and Georgiana Slough over a range of Delta inflows and HORB installation with the DCC closed using results of DSM2 simulation modeling. As discussed above, the accuracy of DSM2 modeling is better at some locations than others in the South Delta, and is better for average daily values than for 15-minute values. Accuracy can also change over months and years as has been observed at Turner Cut.

The South Delta was partitioned into three routes: 1) mainstem of the San Joaquin River; 2) Old River; and 3) Middle River. DSM2 model runs were used to examine changes in daily average, minimum, and maximum water flow, and 15-minute instantaneous velocity, under three simulation scenarios, similar to Cavallo et al. (2013).

In assessing the effects of export rate on hydrodynamic conditions in the Delta, we evaluated the geographic area (i.e., footprint) where export-related changes in daily average, maximum, and minimum flow; and tidally averaged, maximum and minimum velocities associated with the low/low and high/high tides phases were detected based on the model results. The changes in flow within Delta channels were evaluated as a function of three levels of Delta inflow and three levels of SWP and CVP exports. Changes in velocity were evaluated as a function of two levels of Delta inflow and two levels of exports. The results were illustrated as both profile figures and color contour figures representing a “heat” map.

The model scenarios were developed by DWR for Kimmerer and Nobriga (2008) to evaluate particle transport over a wide range of exports and inflows, with the HORB in and out (the HORB was modeled as six culverts and water moving in both directions), and with the DCC gates closed and opened. We used the scenarios to isolate the effect of SWP and CVP export rate, Delta inflow, and HORB position on water flow and velocity and direction, over a range of Sacramento River and San Joaquin River basin inflow conditions. Thus, we were able to evaluate the effect of exports on flow and velocity over a range of inflow and barrier conditions and, alternatively, evaluate the effect of inflows over a range of exports and barrier conditions.

Cavallo et al. (2013) analyzed a subset of the DSM2 model scenarios originally developed by Kimmerer and Nobriga (2008) in order to examine changes in channel flow. These were the three lower inflow scenarios from Kimmerer and Nobriga (2008) with Delta inflow ranging from 12,000 cfs to 38,000 cfs; San Joaquin River flow ranging from 1,495 to 5,712; Sacramento River flow ranging from 10,595 to 32,288; and exports ranging from 2,000 cfs to 10,000 cfs. Conditions were compared when the HORB was in or out, the DCC was closed, and the agricultural barriers were not installed.

There were two limitations of the Cavallo et al. (2013) scenarios. First, the Sacramento River and San Joaquin River inflows were varied together proportionally; therefore, we were not able to independently evaluate the effect of Sacramento versus San Joaquin river inflow. Second, without the two higher inflow scenarios in Kimmerer and Nobriga (2008), we were not able to analyze a wide range of inflows.

B.5.2 CONCEPTUAL MODEL

The conceptual model that was developed for the hypothesized relationships between water project operations and Delta hydrodynamics is illustrated in Table B.5-1. The relationships shown in black text in the model were examined using available information and modeling results. The relationships shown in red text were not examined due to lack of resources.

Table B.5-1. Hydrodynamics Drivers, Linkages, and Outcomes [DLOs] Components for Analysis (DLOs not included in the analysis are shown in red italic text)

Drivers	Linkages	Outcomes
• Exports • River inflow; Sacramento and San Joaquin • Tide • *Channel morphology*	• Proximity to exports • Channel configuration/barrier deployment • *CCF operation radial gate operations (e.g., opening to fill CCF and then closing to isolate the pumping plant operations from the Delta)*	• Instantaneous velocities or flows • Net daily flow • Sub-daily velocity • *Percent positive flow* • *Water temperature* • *Salinity* • *Residence time* • *Source/origin of water*

Note: Red italicized text indicates Drivers, Linkages, and Outcomes that were not analyzed.

Results of the examinations were characterized as follows: 1) the results of studies and analyses are consistent and supportive of the relationship predicted based on the conceptual model; 2) the results of studies and analyses were not consistent or did not support the predicted relationships based on the conceptual model, suggesting that alternative hypotheses and relationships should be considered; or 3) the available information was inconsistent or inadequate to support or refute a predicted relationship, which was identified as a data or information gap that could be addressed in the future.

The following predictions were made based on the conceptual model:

- The effect of exports and inflows, within the context of tides, on average, maximum, and minimum daily flows, varies with proximity to the exports.
- The effect of exports and inflows, within the context of tides, on average, maximum, and minimum daily flows, varies with channel configuration.
- The effect of exports and inflows, within the context of tides, on average, maximum, and minimum daily flows, varies with barrier deployment.
- The effect of exports and inflows, within the context of tides, on average daily, maximum, and minimum flows, varies with Clifton Court radial gate operations.

B.5.3 EXPORT EFFECTS ON FLOW

Results of the modeling showing daily average, maximum, and minimum flows and differences between scenarios are presented as profile illustrations in Figure B.5-1 through Figure B.5-7, as a table in Table B.5-2, and as a “heat” map in Figure B.5-8. These are presented together and used to illustrate the subsequent narrative regarding the effects of SWP and CVP exports on hydrodynamic conditions in the mainstem San Joaquin River, Old River, Middle River, and Georgiana Slough in the sections below.

The basis of knowledge for the relationship between different routes’ hydrodynamic metrics and drivers such as exports, barriers or Clifton Court radial gate operations is low because it is based on non-peer reviewed agency reports. Understanding for the relationship between migration route and hydrodynamic metrics is based on non-peered reviewed agency reports and information presented in this report.

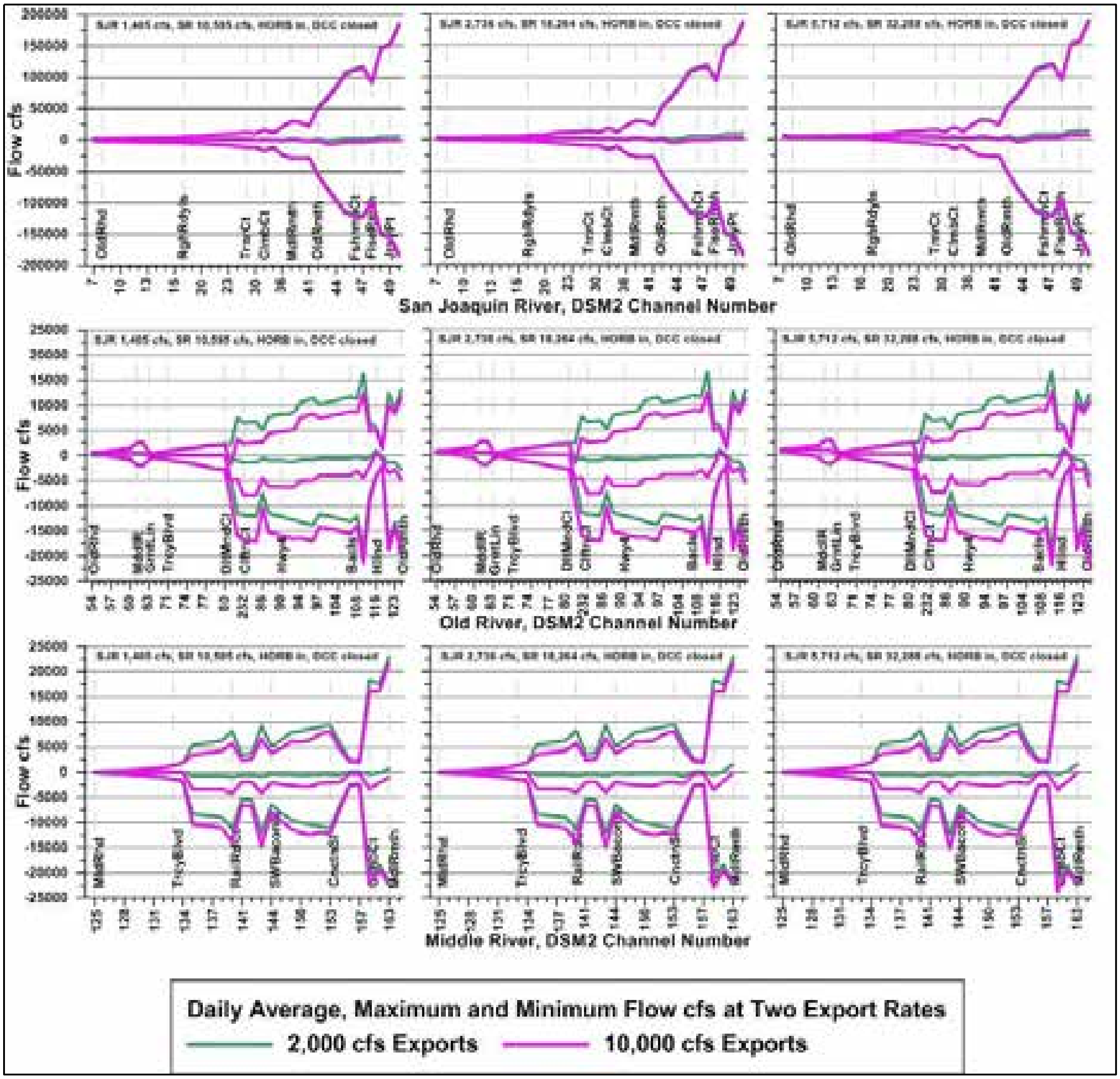


Figure B.5-1. DSM2 Modeled Daily Average, Maximum, and Minimum Flow in Each DSM2 Channel Reach for Each of Six Model Scenarios in Each of Three Routes in the South Delta With the HORB In

Notes: The six scenarios were low inflow/low exports, low inflow/high exports, medium inflow/low exports, medium inflow/high exports, high inflow/low exports, and high inflow/high exports. These exports represent the most extreme modeled scenarios and, therefore, capture the maximum difference in flow. The three routes were the San Joaquin River mainstem, Old River, and Middle River. The x axis is serial DSM2 channel reach number.

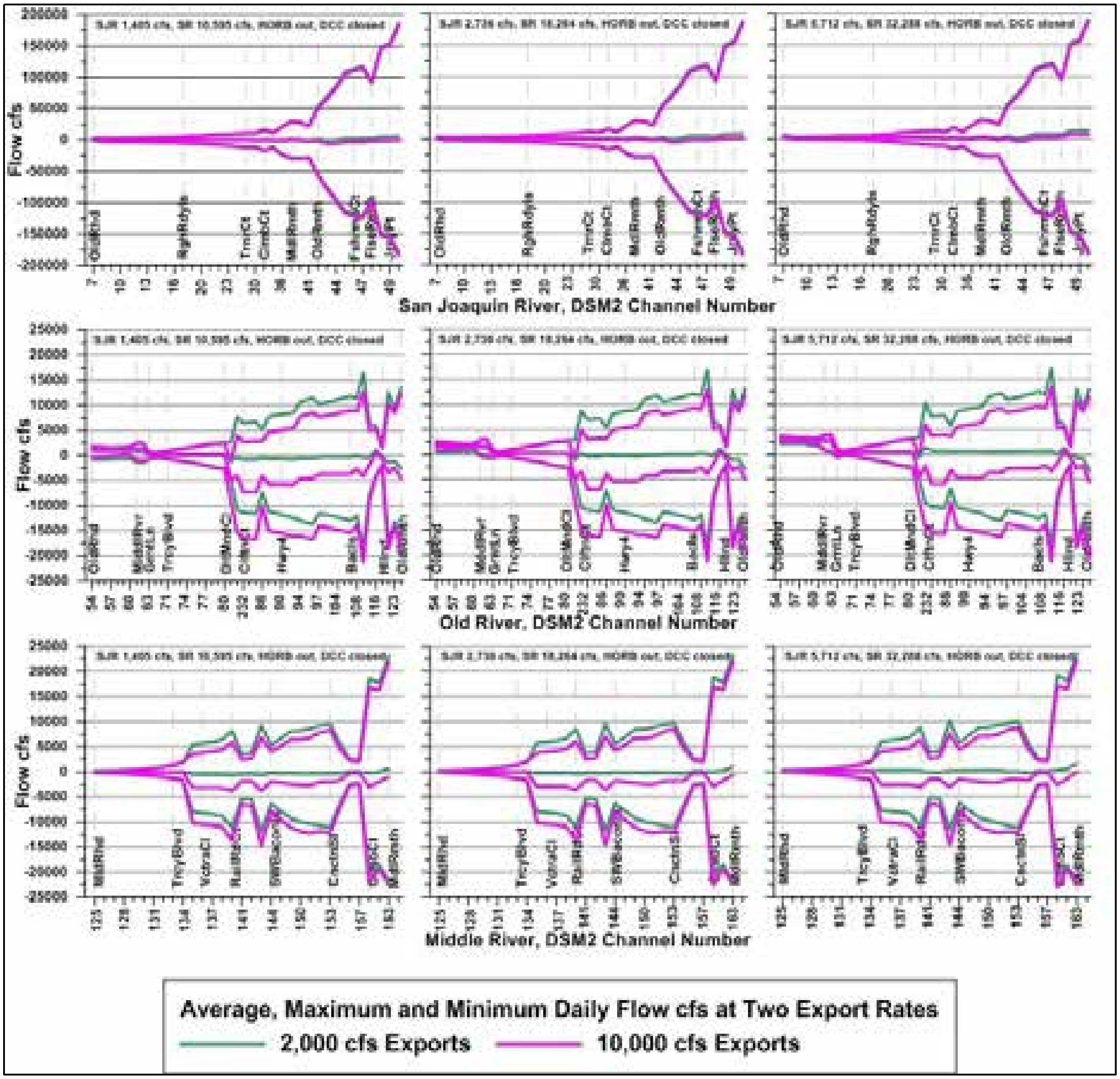


Figure B.5-2. DSM2 Modeled Daily Average, Maximum, and Minimum Flow in Each DSM2 Channel Reach for Each of Six Model Scenarios in Each of Three Routes in the South Delta With the HORB Out

Notes: The six scenarios were low inflow/low exports, low inflow/high exports, medium inflow/low exports, high inflow/medium exports, low inflow/high exports, and high inflow/high exports. These exports represent the most extreme modeled scenarios and, therefore, capture the maximum difference in flow. The three routes were the San Joaquin River mainstem, Old River, and Middle River. The x axis is serial DSM2 channel reach number.

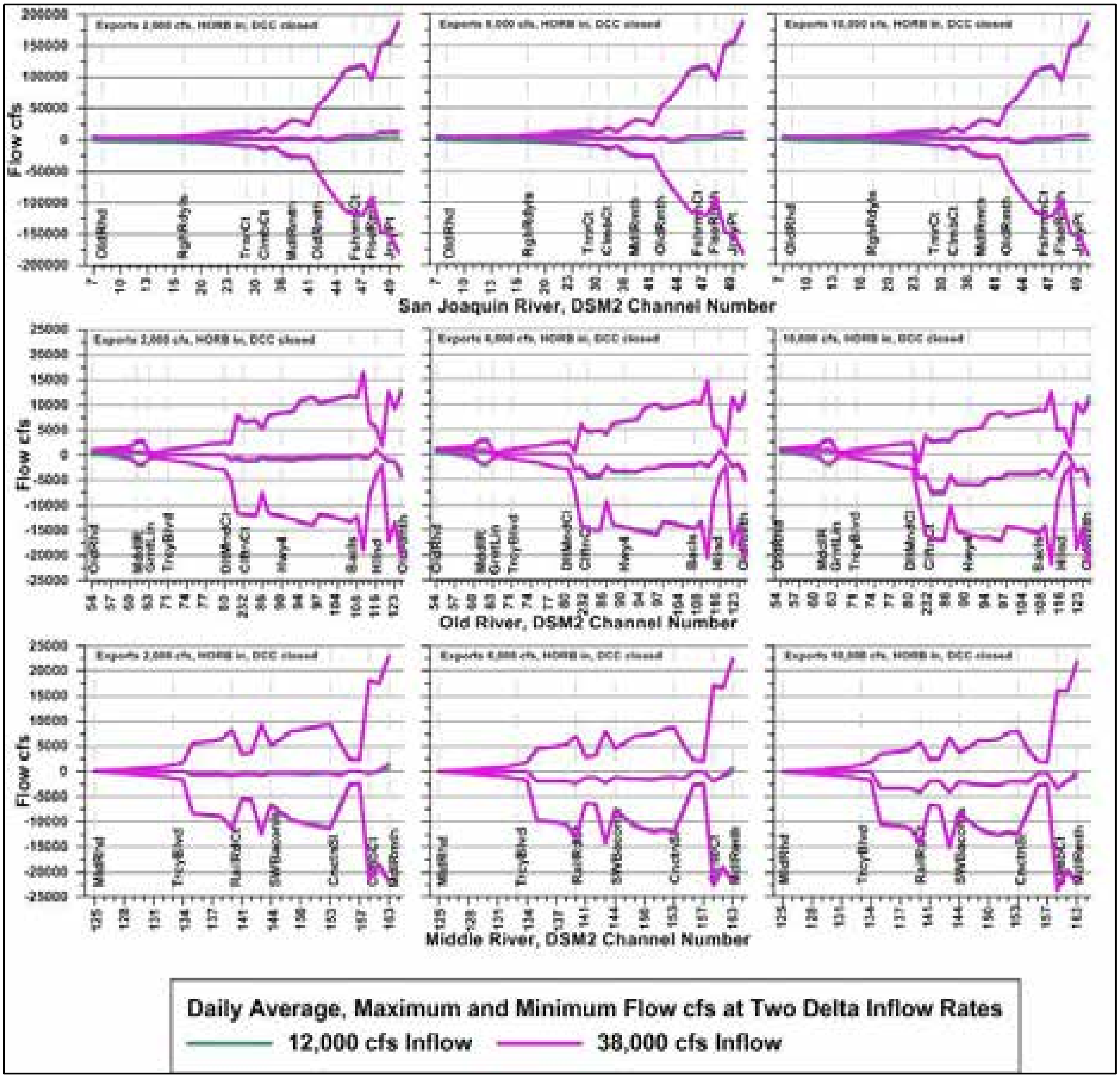


Figure B.5-3. DSM2 Modeled Daily Average, Maximum, and Minimum Flow in Each DSM2 Channel Reach, in Each of Six Scenarios, in Each of Three Routes in the South Delta

Notes: The six scenarios were low inflow/low exports, high inflow/low exports, low inflow/medium exports, high inflow/medium exports, low inflow/high exports, and high inflow/high exports. These inflows represent the most extreme modeled scenarios and, therefore, capture the maximum difference in flow. The three routes were the San Joaquin River mainstem, Old River, and Middle River. The x axis is serial DSM2 channel reach number.

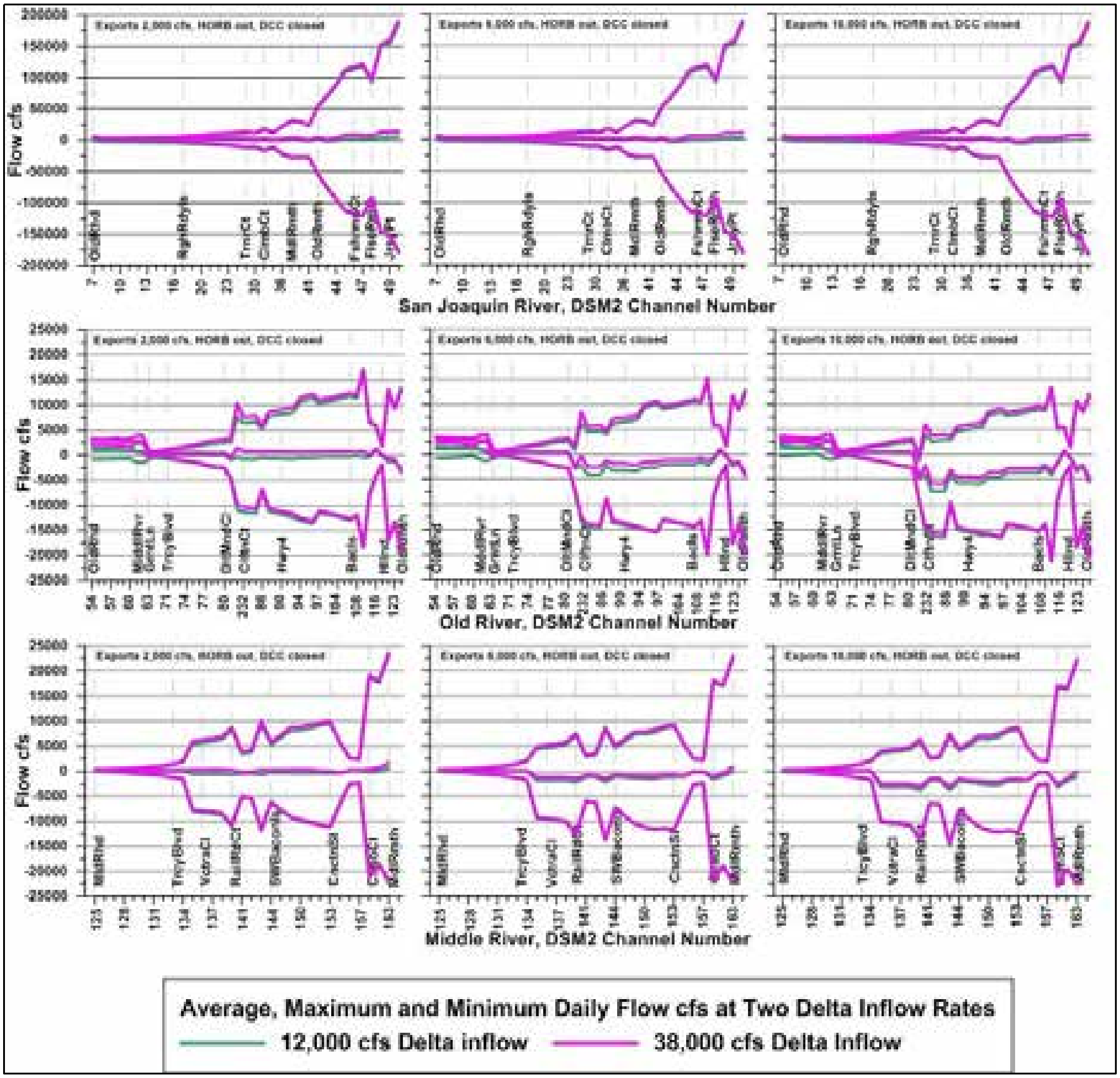


Figure B.5-4. DSM2 Modeled Daily Average, Maximum, and Minimum Flow in Each DSM2 Channel Reach, for Each of Six Model Scenarios, for Each of Three Routes in the South Delta With the HORB Out

Notes: The six scenarios were low inflow/low exports, high inflow/low exports, low inflow/medium exports, high inflow/medium exports, low inflow/high exports, and high inflow/high exports. These inflows represent the most extreme modeled scenarios and, therefore, represent the maximum difference in flow. The three routes were the San Joaquin River mainstem, Old River, and Middle River. The x axis was serial DSM2 channel reach number.

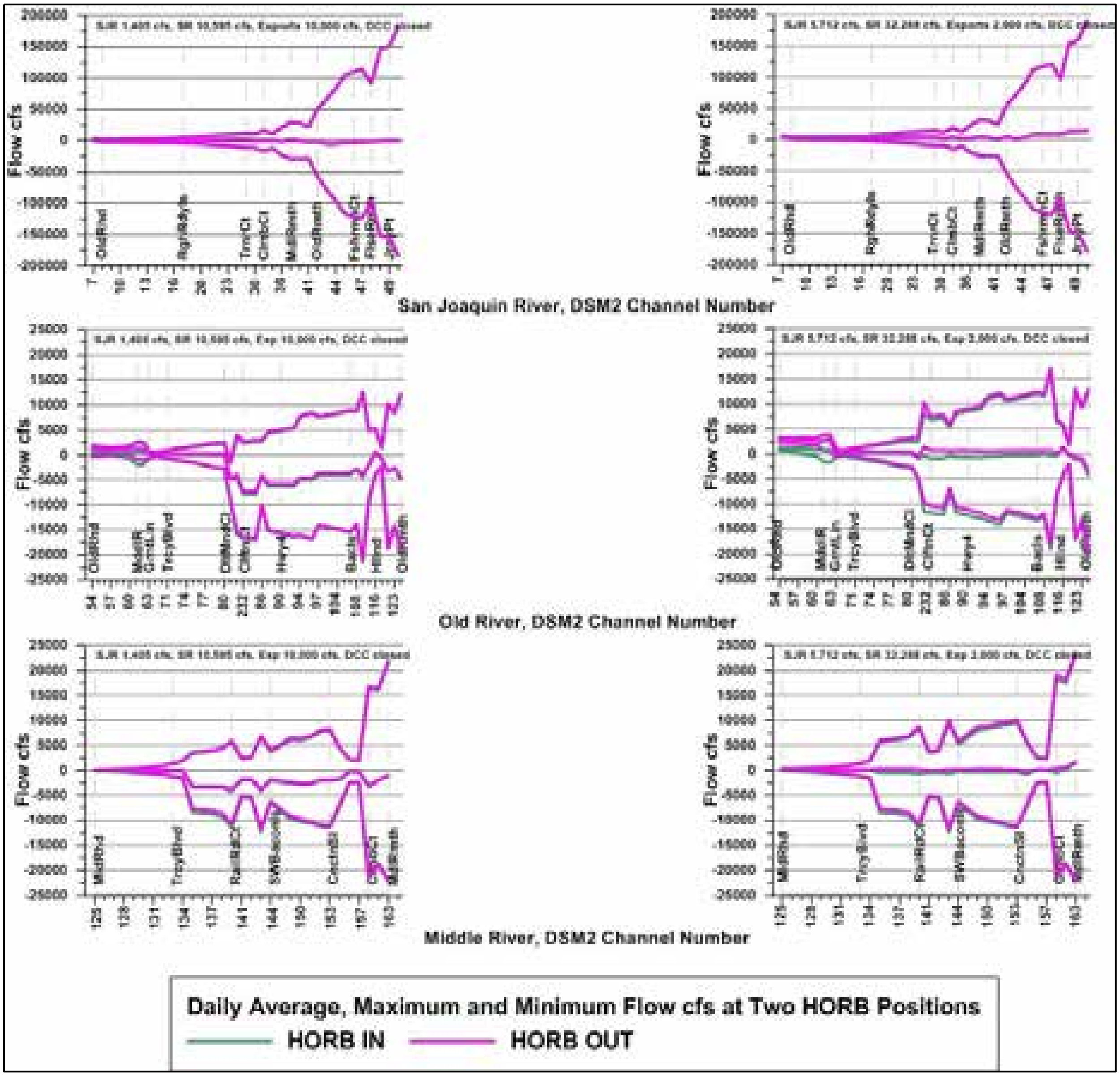


Figure B.5-5. DSM2 Modeled Daily Average, Maximum, and Minimum Flow in Each DSM2 Channel Reach, for Each of Four Scenarios, in Each of Three Routes in the South Delta, With and Without the HORB

Notes: The four scenarios were low inflow/high exports/HORB in, low inflow/high exports/HORB out, high inflow/low exports/HORB in, and high inflow/low exports/HORB out. These inflow, exports, and HORB positions represent the most extreme modeled scenarios and, therefore, the maximum difference in flow. The three routes were the San Joaquin River mainstem, Old River, and Middle River. The x axis is serial DSM2 channel reach number.

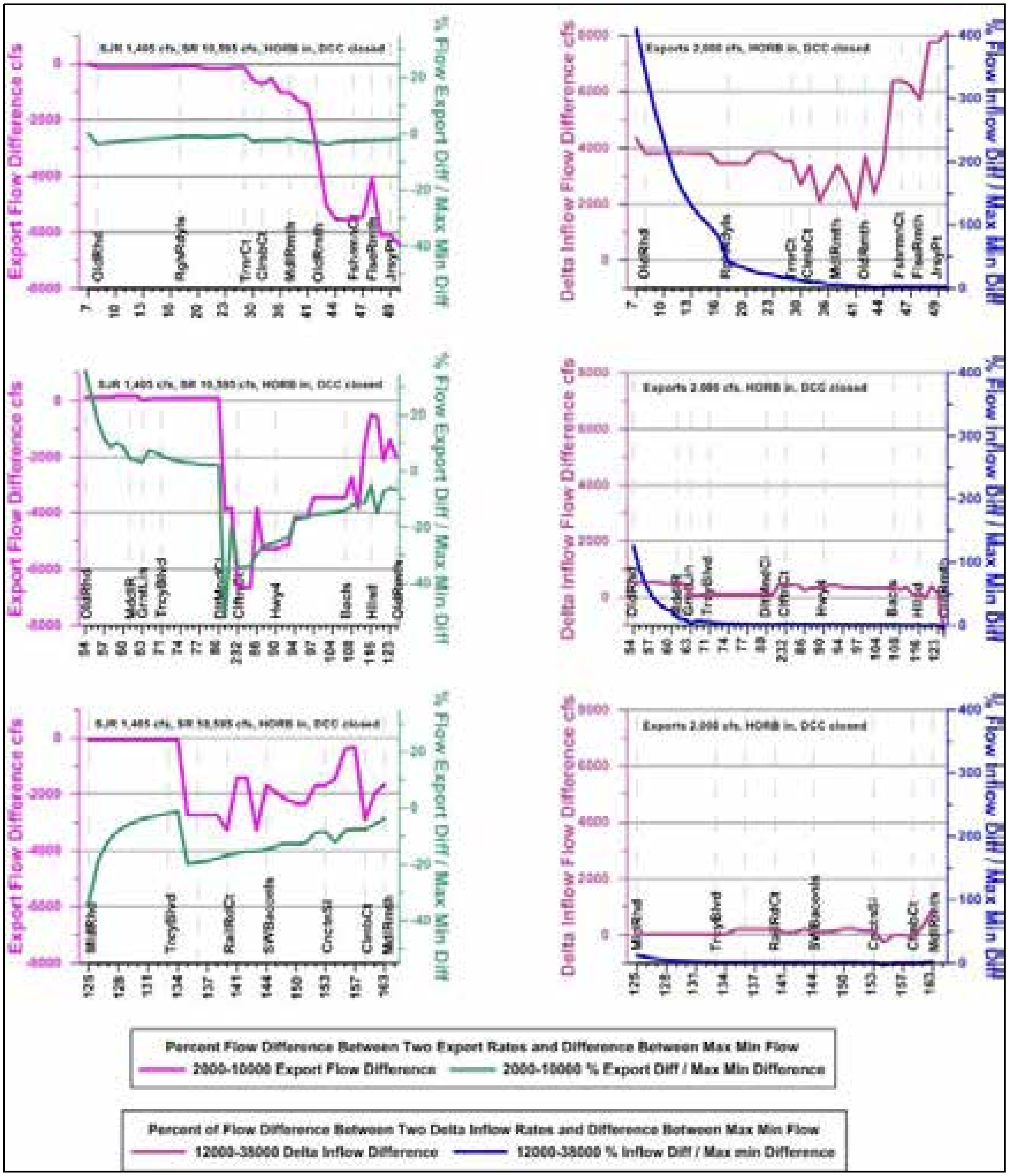


Figure B.5-6. Effect of Export Rate and Delta Inflow on Percent of Flow and Export Difference in the Lower San Joaquin River

Notes: All left panels represent the represent the high inflow scenario, the difference in daily average flow between low and high export rate (left y axis), and the difference in daily average flow between low and high export rate divided by the difference between daily minimum and maximum flow at the low export rate (right y axis) with the HORB installed. The right panels represent the difference in daily average flow between low and high inflow rate (left y axis) and the difference in daily average flow between low and high inflow rate divided by the difference between daily minimum and maximum flow at the low at the low inflow rate with the HORB installed. All right panels represent the low export scenario. The three routes were the San Joaquin River mainstem, Old River, and Middle River. The x axis is serial DSM2 channel reach number.

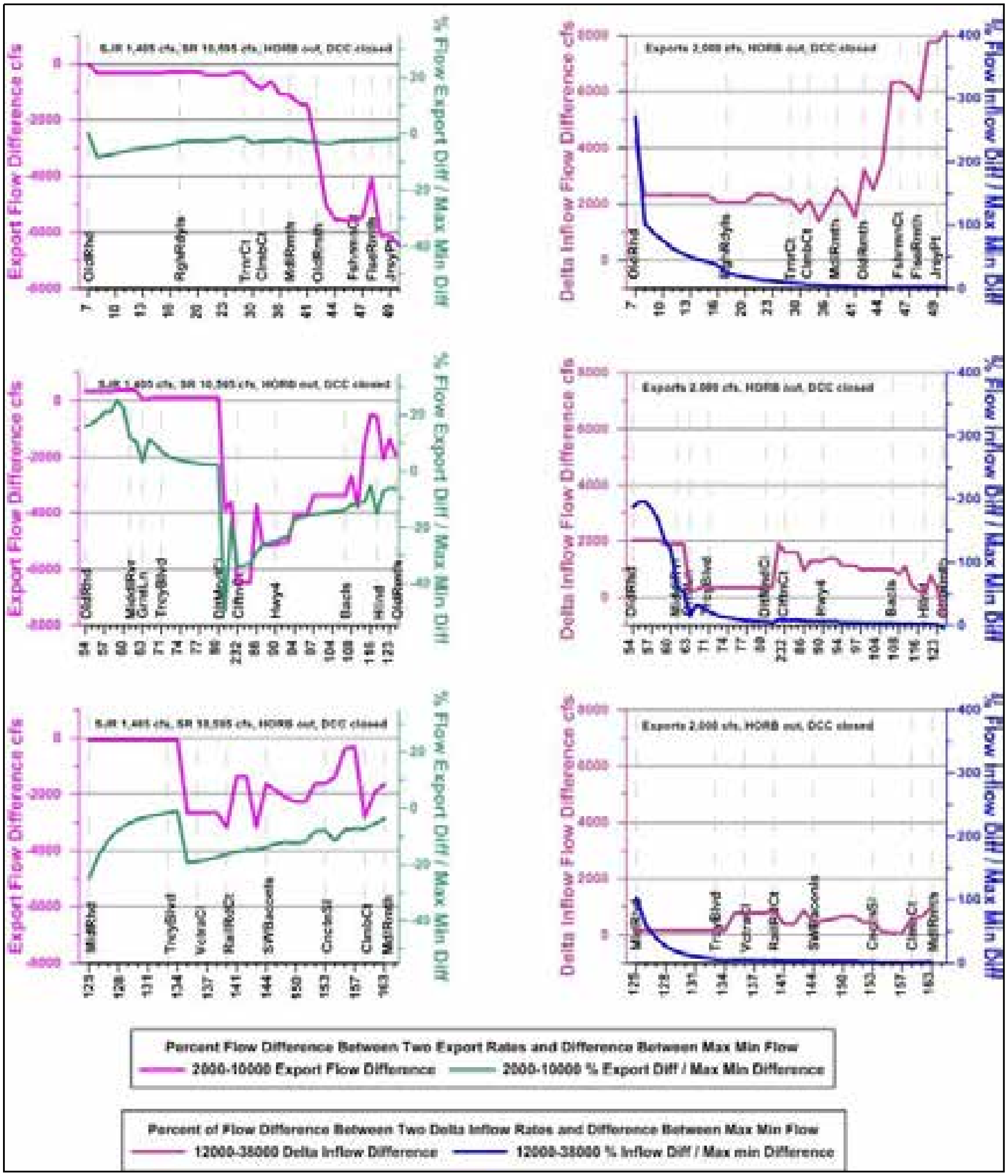


Figure B.5-7. Effect of Export Rate and Delta Inflow on Percent of Flow and Export Difference in the Lower San Joaquin River

Notes: All left panels represent the high inflow scenario, the difference in daily average flow between low and high export rate (left y axis), and the difference in daily average flow between low and high export rate divided by the difference between daily minimum and maximum flow at the low export rate (right y axis) without the HORB. The right panels represent the difference in daily average flow between low and high inflow rate (left y axis) and the difference in daily average flow between low and high inflow rate divided by the difference between daily minimum and maximum flow at the low inflow rate (right y axis) without the HORB. All right panels represent the low export rate scenario. The three routes were the San Joaquin River mainstem, Old River, and Middle River. The x axis is serial DSM2 channel reach number.

Table B.5-2. Summary of Hydrodynamic Simulation Model Results for Flows and Changes in Flow at Various Locations Within the South Delta With and Without the Head of Old River Barrier

Metric	San Joaquin River Route Head of Old River to Jersey Point		Middle River Route Head to Mouth of Middle River		Old River Route Head to Mouth of Old River	
Barrier Status	HORB In	HORB Out	HORB In	HORB Out	HORB In	HORB Out
Locations of high and low daily average flow in route at export of 10,000 cfs and Delta inflow of 12,000 cfs	+1,346 cfs upstream of head of Old River; -6,062 cfs between mouths of Middle and Old rivers	+1,341 cfs upstream of head of Old River; -6,004 cfs downstream of mouth of Old River	-29 cfs at head of Middle River; -4,153 cfs at Railroad Cut	+8.42 cfs at head of Middle River; -3,845 cfs at Railroad Cut	-7,905 cfs downstream of SWP intake; +557 cfs at Holland Cut	+1,241 cfs downstream of CVP intake; -7,330 cfs downstream of SWP intake
Locations of high and low daily maximum flow in route at export of 10,000 cfs and Delta inflow of 12,000 cfs	+2,118 cfs downstream of head of Old River; +182,393 cfs downstream of Jersey Point	+1,762 cfs downstream of head of Old River; +182,446 cfs downstream of Jersey Point	+35 cfs at head of Middle River; +21,718 cfs at mouth of Middle River	+78 cfs at head of Middle River; +21,814 cfs at mouth of Middle River	-1,702 cfs downstream of CVP intake; +12,437 cfs downstream of Bacon Island	-1,328 downstream of CVP intake; -12,671 cfs downstream of Bacon Island
Locations of high and low daily minimum flow in route at export of 10,000 cfs and Delta inflow of 12,000 cfs	-555 cfs upstream of head of Old River; -184,193 cfs downstream of Jersey Point	-337 cfs upstream of head of Old River; -183,975 cfs downstream of Jersey Point	-126 cfs at head of Middle River; -22,472 cfs at Columbia Cut	-114 cfs at head of Middle River; -22,389 cfs at mouth of Middle River	+276 cfs at head of Old River; -21,333 cfs downstream of Bacon Island	+133 cfs at head of Middle River; -21,100 cfs downstream of Bacon Island
Locations of high and low change in daily average flow in route due to increasing exports from 2,000 cfs to 10,000 cfs at Delta inflow of 12,000 cfs	+0.94 cfs upstream of head of Old River; -6,449 cfs downstream of Jersey Point	+0.78 cfs upstream of head of Old River; -6,461 cfs downstream of mouth of Old River	-47 cfs upstream of Victoria Canal; -3,270 cfs upstream of southwest Bacon Island	-42.2 cfs upstream of Victoria Canal; -3,175 cfs at Railroad Cut	+184 cfs upstream of Grant Line Canal; -6,642 cfs at SWP intake	+381 cfs at head of head of Middle River; -6,472 cfs at SWP intake
Locations of high and low difference between daily minimum and maximum flow in route at export of 10,000 cfs and Delta inflow of 12,000 cfs	+2,980 cfs upstream of head of Old River; +366,596 cfs downstream of Jersey Point	+3,004 cfs upstream of head of Old River; +369,752 cfs downstream of Jersey Point	+161 cfs at head of Middle River; +44,048 cfs at mouth of Middle River	+237 cfs at head of Middle River; +45,363 cfs at mouth of Middle River	+358 cfs at head of Old River; +33,770 cfs downstream of Bacon Island	+709 cfs upstream of Grant Line; +37,536 cfs downstream of Bacon Island
Locations of high and low change in daily average flow in route due to increasing Delta inflow from 12,000 to 38,000 cfs at export of 2,000 cfs	+1,777 cfs upstream of mouth of Old River; +8,130 cfs downstream of mouth of Old River	+1,381 cfs downstream of Columbia Cut; +8,145 cfs downstream of Jersey Point	-262 cfs downstream of Connection Slough; +928 cfs at mouth of Middle River	+67 cfs upstream of Columbia Cut; +1,001 cfs upstream of Columbia Cut	+540 cfs downstream of head of Old River; -1345 cfs at mouth of Old River	+2,050 cfs upstream of head of Middle River; -702 cfs at mouth of Old River
Locations of high and low difference between daily minimum and maximum flow in route at export of 2,000 cfs and Delta inflow of 38,000 cfs	+1,060 cfs upstream of head of Old River; +368,502 cfs downstream of Jersey Point	+1,600 cfs upstream of head of Old River; +368,767 cfs downstream of Jersey Point	+282 cfs at head of Middle River; +45,218 cfs at mouth of Middle River	+155 cfs at head of Middle River; +42,825 cfs at mouth of Middle River	+427 cfs at head of Old River; +35,753 cfs downstream of Bacon Island	+817 cfs upstream of Grant Line; +35,495 cfs downstream of Bacon Island

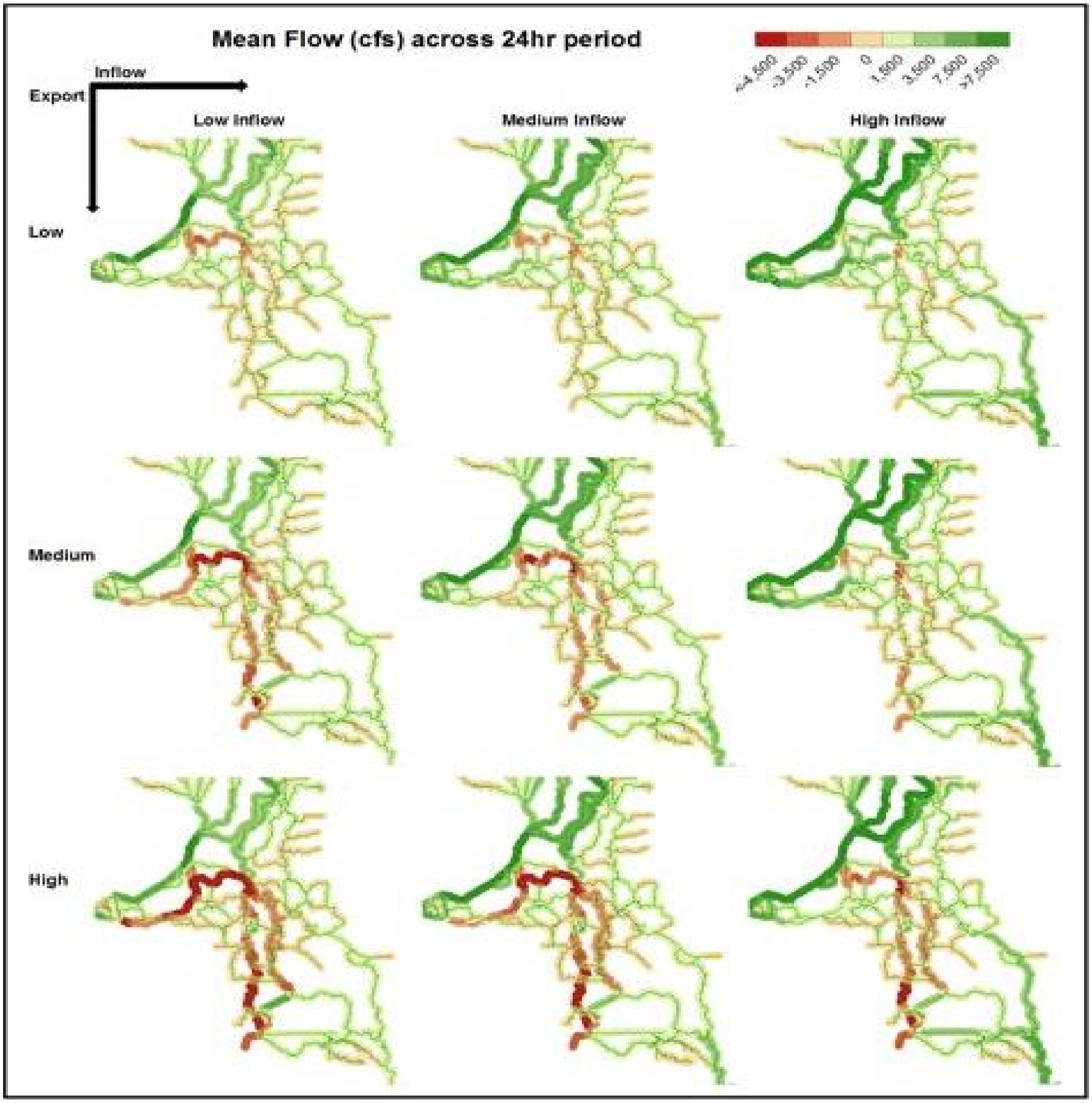


Figure B.5-8. DSM2 Modeled Daily Average Flow at Each DSM2 Channel Reach in the South Delta at Three Export Rates and Three Delta Inflow Rates. The Export Rates Were 2,000, 6,000 and 10,000 cfs, and the Delta Inflow Rates Were 12,000, 21,000, and 38,000 cfs.

Note: The magnitude of flow is illustrated as a color from red to green (see legend at top of figure).

B.5.3.1 San Joaquin River Mainstem

In the context of the three South Delta routes, the mainstem San Joaquin River, on average, had the least negative change in modeled flow due to exports with and without the HORB, and the most positive change in flow due to Delta inflow with the HORB installed under the scenarios modeled (Figures B.5-1 through B.5-4 and B.5-6 through B.5-8).

- The modeled tidal influence on flow in the lower half of the San Joaquin River was about eight times greater than in OMR (the y axis for the San Joaquin River is ±200,000 cfs, whereas the y axis for OMR is ±25,000 cfs) (Figure B.5-1). As an example, the difference in average daily flow on the San Joaquin River at the mouth of Old River was similar in magnitude to the Old River at Clifton Court, but the ratio of the change in average daily flow due to exports compared to the change in flow due to daily tide is an order of magnitude less in the San Joaquin River at the mouth of Old River (3.5% compared to 35%).
- At the head of Old River junction, the effect of increasing exports on flow within the junction was a decrease in flow downstream towards the riverine San Joaquin River and an increase in flow downstream in Old River (towards the exports) corridor. The change in daily average flow into Old River, due to increasing exports from 2,000 to 10,000 cfs, increased by 217 cfs, which was 10% of the difference between the daily minimum and maximum flow of 2,300 cfs at the lower export rate (Cavallo et al. 2013; Figure B.5-9).
- At the Turner Cut junction, the effect of increasing exports on flow within the junction was an increase in flow in Turner Cut towards the exports (or interior Delta) corridor. The change in daily average flow into the Turner Cut, due to an increase in exports from 2,000 to 10,000 cfs, increased by 589 cfs, which was 7.5% of the difference between the minimum and maximum flow of 7,800 cfs at the lower export rate (Cavallo et al. 2013; Figure B.5-10).
- At the Columbia Cut junction, the effect of increasing exports on flow within the junction was an increase in flow in Columbia Cut towards the exports (interior Delta). The change in average daily flow into Columbia Cut, due to an increase in exports from 2,000 to 10,000 cfs, increased by 1,360 cfs, which was 9% of the difference between the daily minimum and maximum flow of 14,640 cfs at the low export rate (Cavallo et al. 2013; Figure B.5-11). The modeled effect of Delta inflow on flow in the upper San Joaquin River route, with the HORB installed, was about four times greater than in upper Old River route (Figure B.5-7). As an example of the positive effect of inflow in the upper San Joaquin River route with the HORB installed (low exports), upstream of the head of Old River, the difference in average daily flow due to a change in inflow from 12,000 to 38,000 cfs was +1,777 cfs, and that was 165% of the difference between the maximum and minimum flow of 1,060 cfs. For comparison, in Old River near the head, the average daily flow difference due to a change in inflow from 12,000 to 38,000 cfs was +540 cfs, and that was 126% of the difference between the maximum and minimum flow of 427 cfs (Table B.5-7). Without the HORB, the difference between the San Joaquin River and Old River was much less (Figure B.5-7; Table B.5-7).

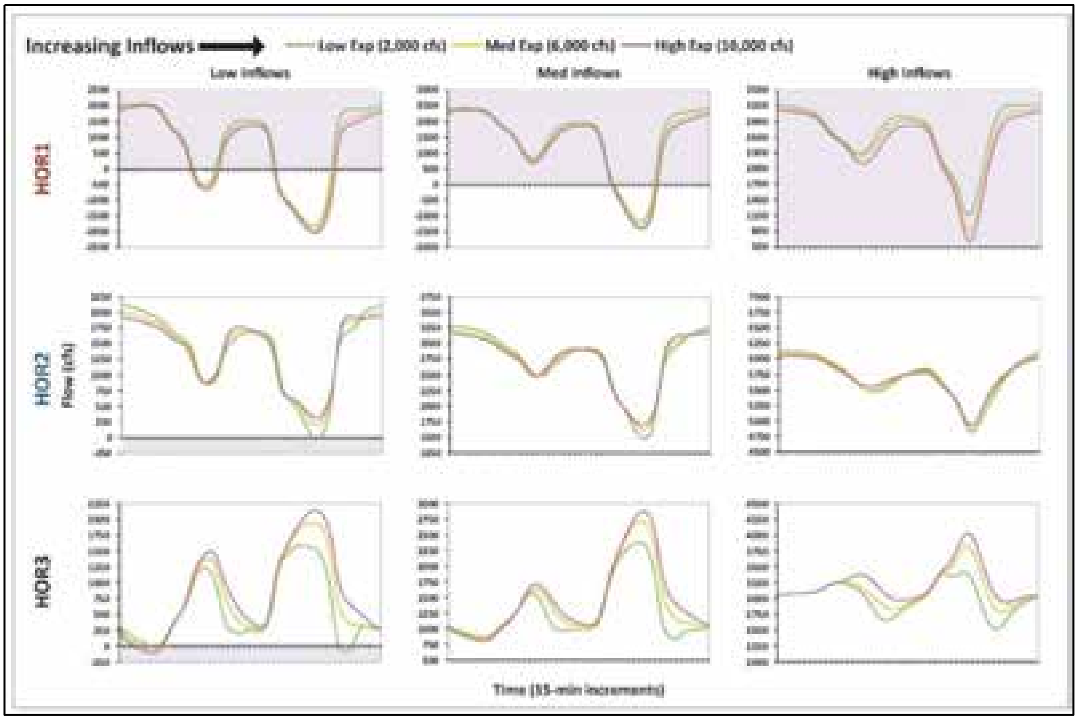


Figure B.5-9. DSM2 Modeled Instantaneous 15-minute Flow Versus Time Over 24 Hours at the Junction of the San Joaquin River and Head of Old Rivers in Three DSM2 Channel Reaches for Nine Model Scenarios

Notes: The three DSM2 channel reaches are in the vertical panel direction. The nine model scenarios include three Delta inflow rates in the horizontal panel direction (12,000, 21,000, and 38,000 cfs), and three export rates within each panel (2,000, 6,000, and 10,000 cfs). HOR1 is the San Joaquin River downstream of the junction, HOR2 is the San Joaquin River upstream of the junction, and HOR3 is Old River downstream of the junction (Cavallo et al. 2013).

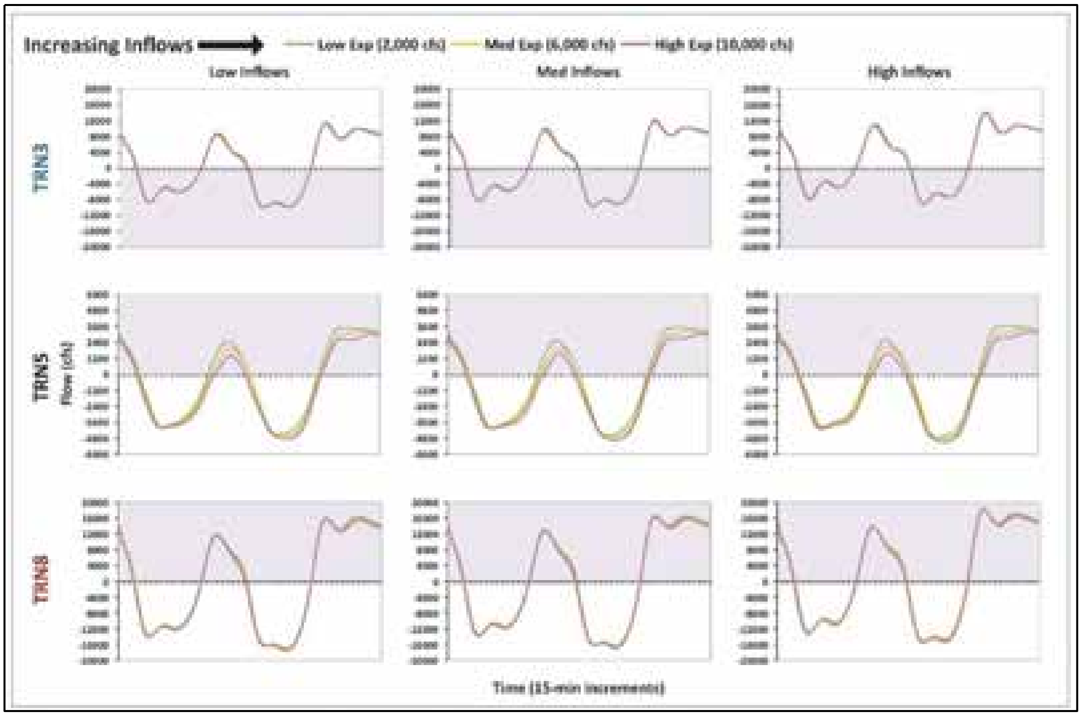


Figure B.5-10. DSM2 Modeled Instantaneous 15-minute Flow Versus Time Over 24 Hours at the Junction of San Joaquin River and Turner Cut in Three DSM2 Channel Reaches for Nine Model Scenarios

Notes: The three DSM2 channel reaches are in the vertical direction. The nine model scenarios include three Delta inflow rates in the horizontal direction (12,000, 21,000, and 38,000 cfs), and three export rates within each panel (2,000, 6,000, and 10,000 cfs). TRN3 is the San Joaquin River upstream of the junction, TRN5 is Turner Cut downstream of the junction, and TRN8 is the San Joaquin River downstream of the junction (Cavallo et al. 2013).

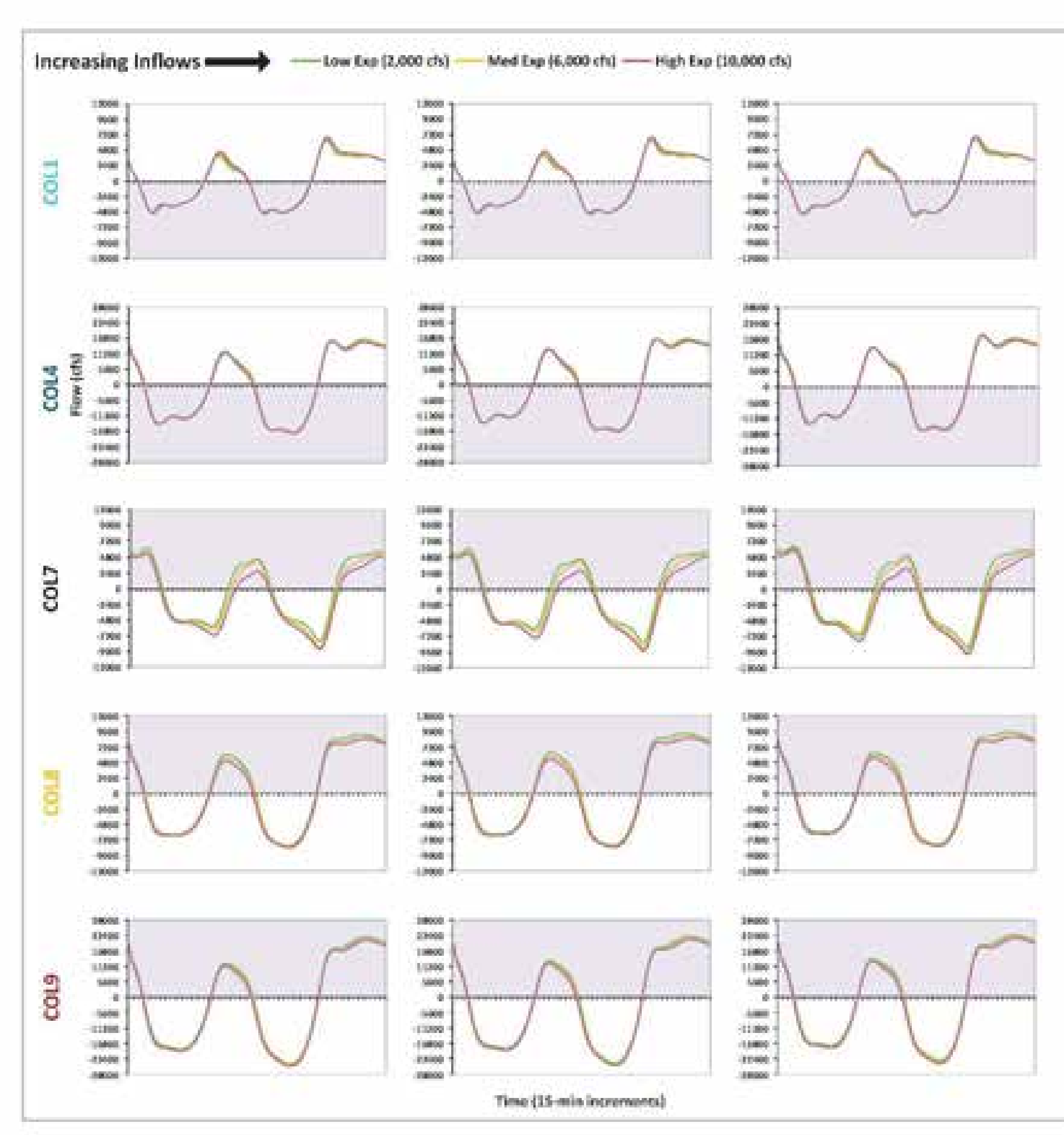


Figure B.5-11. DSM2 Modeled Instantaneous 15-minute Flow Versus Time Over 24 Hours at the Junction of San Joaquin River and Columbia Cut in Five DSM2 Channel Reaches for Nine Model Scenarios

Notes: The five DSM2 channel reaches are in the vertical direction. The nine model scenarios include three Delta inflow rates in the horizontal direction (12,000, 21,000, and 38,000 cfs), and three export rates within each panel (2,000, 6,000, and 10,000 cfs). COL1 is Disappointment Slough upstream of the junction, COL4 is the San Joaquin River upstream of the junction, COL7 is Columbia Cut downstream of the junction, COL8 is the San Joaquin River downstream of the junction, and COL9 is the San Joaquin River downstream of the junction (Cavallo et al. 2013).

B.5.3.2 Old River

In the context of the three South Delta routes, Old River, on average, had the greatest change in modeled flow due to exports with and without the HORB, under the scenarios modeled (Figures B.5-1 through B.5-4 and B.5-6 through B.5-8).

- Old River had the greatest negative change in daily average, minimum, and maximum modeled flow due to an increase in exports with or without the HORB, compared to the other two routes. The largest relative changes occurred downstream of the CVP and SWP export facilities and dissipated toward the mouth (Figures B.5-1, B.5-2, B.5-6, and B.5-7; Table B.5-2).
- Exports draw water toward the export facilities from upstream and downstream locations in Old River. The mid-route location of the export facilities in Old River causes exports to increase downstream flows in Old River upstream of the facilities (particularly with no HORB) and decrease downstream flows downstream of the facilities (Figures B.5-2 and B.5-7).
- Without the HORB, flow was more positive in Old River between the head of Old River and Grant Line Canal due to increasing exports. For instance, at exports of 2,000 cfs, Delta inflow of 12,000 cfs, and HORB in place, the daily average flow between the head of Old River up to Grant Line Canal ranged between 407 and 323 cfs, whereas without the HORB it ranged between 907 and 790 cfs (Figure B.5-5; Table B.5-2).
- At Clifton Court (low inflow and HORB in), the difference in average daily flow due to a change in exports from 2,000 to 10,000 cfs was -6,642 cfs, which was 35% of the difference between the minimum and maximum flow of 19,209 cfs (Table B.5-2). At the mouth of Old River, the average daily flow difference due to a change in exports from 2,000 to 10,000 cfs was -2,029 cfs, which was 7% of the difference between the daily minimum and maximum flow of 30,606 cfs (Table B.5-2).
- Upstream of CVP and SWP intakes, the effect of increasing exports is positive flows towards the export facilities. Just upstream of Grant Line Canal, the average daily flow difference due to increasing exports from 2,000 to 10,000 cfs was +184 cfs, which was 4% of the difference between minimum and maximum flow of 4,742 cfs (Table B.5-2).
- Increasing exports increases flow upstream of the CVP and SWP intakes and reduces flow downstream, but the negative effect just downstream was 36 times greater than the positive effect upstream (Figures B.5-1, B.5-2, and B.5-7; Table B.5-2).
- For comparison, in Middle River at Railroad Cut, the average daily flow difference due to a change in exports from 2,000 to 10,000 cfs was -3,270 cfs, and that was 16% of the difference between the minimum and maximum flow of 19,726 cfs. At the mouth of Middle River, the average daily flow difference due to a change in exports from 2,000 to 10,000 cfs was -1,657 cfs, and that was 4% of the difference between the minimum and maximum flow of 44,048 cfs (Table B.5-2).
- Exports decrease minimum flow more than maximum flow immediately downstream of the SWP export facility (Table B.5-2). For instance, at Delta inflow of 12,000 cfs and HORB in place, as exports increase from 2,000 to 10,000 cfs, the maximum flow decreases

by approximately 4,000 cfs whereas the minimum flow decreases by approximately 5,000 cfs (Table B.5-2).

B.5.3.3 Middle River

In the context of the three South Delta routes, Middle River, on average, had the least change in modeled flow due to inflow, and an intermediate change in flow due to exports, with and without the HORB installed, under the scenarios modeled (Figures B.5-1 through B.5-4 and B.5-6 through B.5-8).

- Increasing exports caused an increase in reverse daily average, minimum, and maximum flow while increasing inflow increased daily average, maximum, and minimum flow. Modeled relative daily changes in these metrics due to an increase in exports were intermediate between changes found in the San Joaquin River and Old River, and modeled relative daily changes due to an increase in Delta inflow were the least among the three rivers (Figure B.5-1 through B.5-8; Table B.5-2).
- Although the negative changes in flow due to exports were least among the three routes, the greatest changes within Middle River occurred at Victoria Canal, downstream of Railroad Cut, and again at Columbia Cut (Figures B.5-1 through B.5-8). The tidal influence at these locations increased between Victoria Canal and Columbia Cut.

B.5.3.4 Georgianna Slough

In Georgiana Slough, the effect of increasing exports on flow within the slough was an increase in flow towards the Interior Delta. The change in daily average flow into the Interior Delta was an increase of 124 cfs, which was 2% of the difference between minimum and maximum flow of 6,765 cfs (Figure B.5-12; Cavallo et al. 2013). Observed flow data on the Sacramento River, upstream and downstream of Georgiana Slough, indicate that there was no visible change in flow on the Sacramento River due to an increase in exports.

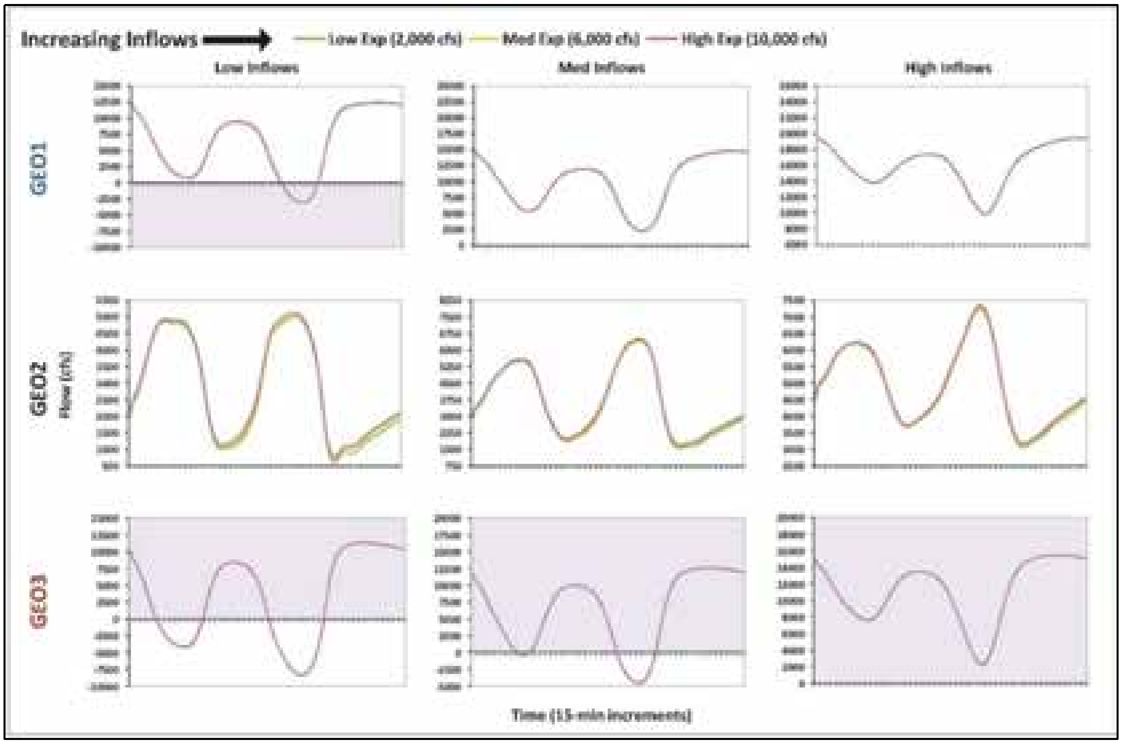


Figure B.5-12. Flow at Georgiana Slough Junction Channels Over 24 Hours

Notes: Time of day in 15-minute increments is on the x axis and magnitude of flow is on the y axis. Curve color indicates export level (Cavallo et al. 2013).

B.5.3.5 Conclusions

Hydrologic simulations provide a means for evaluating local and regional changes in Delta hydrodynamic conditions associated with alternative water project management; however, the Delta channels and channel junctions are characterized by complex and dynamic conditions, which complicate the development and interpretation of modeling results.

Model results support the conceptual model prediction that the effect of exports and inflows, within the context of tides, on average daily flows varies with proximity to the exports, channel configuration and barrier deployment, and CCF radial gate operations. Exports, within the context of tides, have the greatest effect on average daily flows in Old River immediately downstream of the exports and gradually dissipating towards the mouth. Exports have a positive effect upstream of the exports compared to a negative effect downstream. Upstream, the average daily flow increases towards the exports, whereas downstream average daily flow decreases, particularly immediately downstream of exports. If the HORB is deployed, exports have less of an effect on flow upstream (between the head of Old River and Grant Line Canal).

Exports, within the context of tides, have the least effect on average daily flows in the San Joaquin River mainstem. While it is accurate that near Jersey Point, if exports increase from 2,000 to 10,000 cfs, the change in average daily flow is about -6,500 cfs, the difference between the daily minimum and maximum flow is 360,000 cfs, which is due predominately to the tides. The -6,500 cfs change in average daily flow is 2% of the daily change between daily minimum and maximum flow.

Inflows, within the context of tides, have the greatest effect on average daily flows in the San Joaquin River mainstem between the head of Old River and Columbia Cut with the HORB deployed, and some effect on Old River between the head and Grant Line Canal if the HORB is not deployed. Inflows had the least effect on Middle River.

The positive effect of Delta inflows in the San Joaquin River mainstem, within the context of tides, had a greater effect on average daily flows than the negative effect of exports on Old River.

1-D DSM2, in particular, provides a tool for assessing changes in Delta hydrodynamic conditions and has been used extensively for water supply planning. Validation tests indicate that DSM2 is more accurate for predicting average daily metrics than 15-minute time step metrics. The model validates well at some locations with weaker agreement between observed and predicted flow and velocity at other locations. Factors such as simplifying assumptions for Delta consumptive water use, channel bathymetry, complex geometry, and dynamic tidal conditions contribute to variability in model validation. More complex 2-D or 3-D simulation models may be needed to represent more complex hydrodynamic conditions on a finer time scale experienced by juvenile salmonids migrating through the Delta (Section B.3; Appendix C).

Selection of the appropriate simulation modeling tool should be based on the specific goals and objectives of an analysis, the level of resolution needed in model results, the complexities of the areas being modeled in terms of dynamic tidal and flow conditions, and channel geometry. The selected modeling tool should be calibrated and independently validated at a temporal and spatial scale appropriate for the desired analysis.

B.5.3.6 Gaps in Information

Gaps associated with the hydrodynamic simulation modeling and monitoring stations are described below:

- The flow and velocity of water in Clifton Court channel are not measured directly—they are estimated.
- Delta Consumptive Use, diversions on to and returns from the Delta islands, is not estimated adequately. Delta Consumptive Use becomes extremely important at low net Delta outflows. There are ongoing efforts to improve the estimations.
- Channel bathymetry in the South Delta are inadequate. Channel configuration has a major effect on the influence of inflow and exports on the magnitude, direction, and

proportion of flow entering downstream channels through the Interior, Central, and South Delta.

B.5.4 EXPORT EFFECTS ON VELOCITIES

Similar to the analyses regarding flow, the SST characterized the extent of the effect of the SWP and CVP South Delta export operations on velocity along the channels in the South Delta over a range of Delta inflows with no HORB (Figure B.5-13 through Figure B.5-17; Table B.5-3). Due to limited resources, we evaluated fewer scenario options. The scenarios were limited to low Sacramento River and San Joaquin River inflow (10,595 and 1,405 cfs, respectively) and low export (2,000 cfs), high inflow (32,288 and 5,712 cfs respectively) and low export, and high inflow/high export (10,000 cfs). The low inflow/high export scenarios were not examined because they are not realistic from an operations perspective.

The availability of the 15-minute output demonstrates the complexity of the hydrodynamics in the South Delta. Figure B.5-13 is an illustration of the complete tidal cycle for each DSM2 channel reach in each route. The multiple lines in each graph are the individual channel reaches in the route and represent the 15-minute instantaneous velocity over the tidal cycle. The graphs show how the tide phase reaches the upstream channels several hours later than the downstream channels (up to 7 hours later in the San Joaquin River mainstem). They also show that, within a route, there are groups of channel reaches that are similar, in terms of curve shape and tide phase timing, compared to other channel reaches. Old River demonstrates the most complex characteristics. Two channels in Old River actually run in the opposite direction compared to the majority of channels: near Grant Line Canal and at the north boundary of Bacon Island. This level of complexity makes it difficult to develop metrics for assessment, particularly in the Old River route.

Similar to the flow section above, Figures B.5-14 and B.5-15 present profiles for each route. For velocity, we graphed the minimum and maximum velocity associated with the flood and ebb high/high and low/low tide phase, respectively. For the two channels in Old River that flow in the opposite direction, the minimum and maximum of the low/low and high/high tide phases were selected.

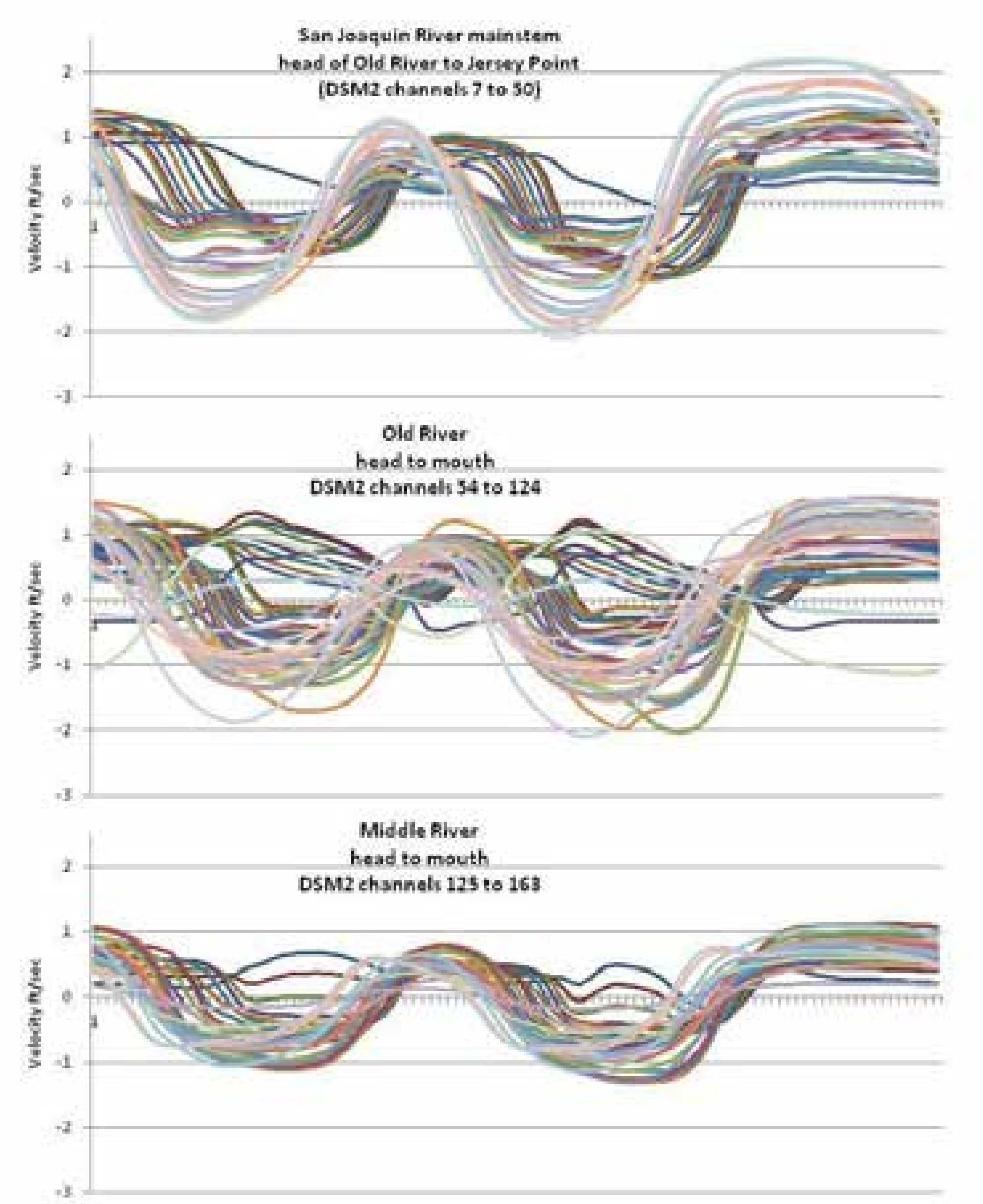


Figure B.5-13. DSM2 Modeled Instantaneous 15-minute Interval Velocity Versus Time Over One Tidal Cycle (~25 Hours) in DSM2 Channel Reaches in Three Routes of the South Delta.

Notes: The DSM2 channel reaches are reaches of river as defined in the DSM2 model grid. The routes are San Joaquin River mainstem, Old River, and Middle River. Each line represents one DSM2 channel reach within the route at the low inflow/low export model scenario.

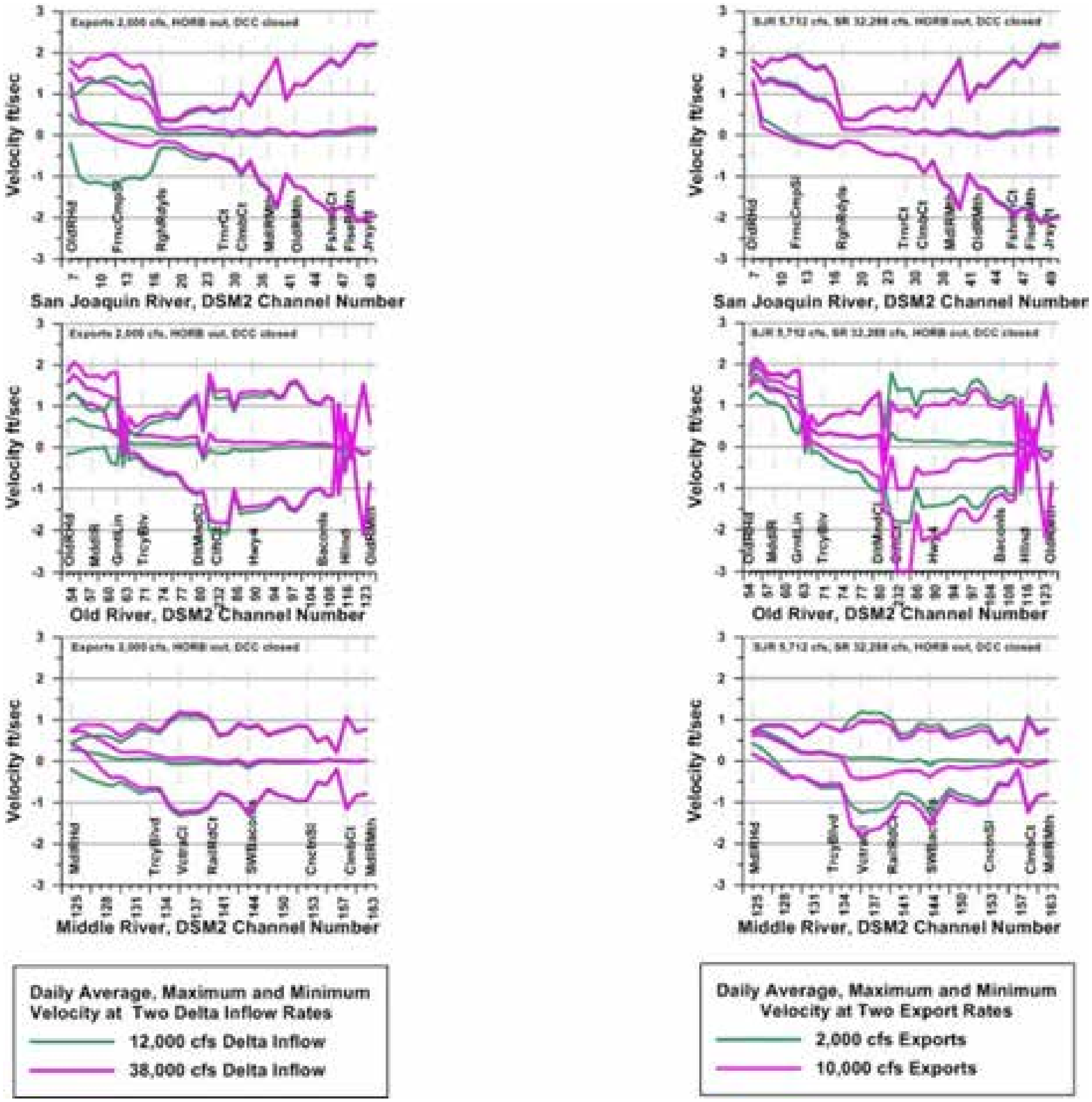


Figure B.5-14. DSM2 modeled average daily velocity and instantaneous maximum velocity associated in each channel reach, in each of two routes in the south Delta. The two model scenarios were, left panels - low exports at low and high inflows, and right panels - high inflows at low and high exports. We limited the export scenarios to low exports and the inflow scenario to high inflows because high exports are not permitted at low inflows. In each graph, the upper set of lines represents the maximum velocities for the scenario, and middle set on lines represents the daily average velocities for the scenario and the lower set of lines represents the minimum velocities for the scenario. The minimum and maximum velocities are associated with the flood and ebb tides, respectively.

Note: The three routes are San Joaquin mainstem, Old River and Middle River. The x axis is the serial DSM2 model channel number.

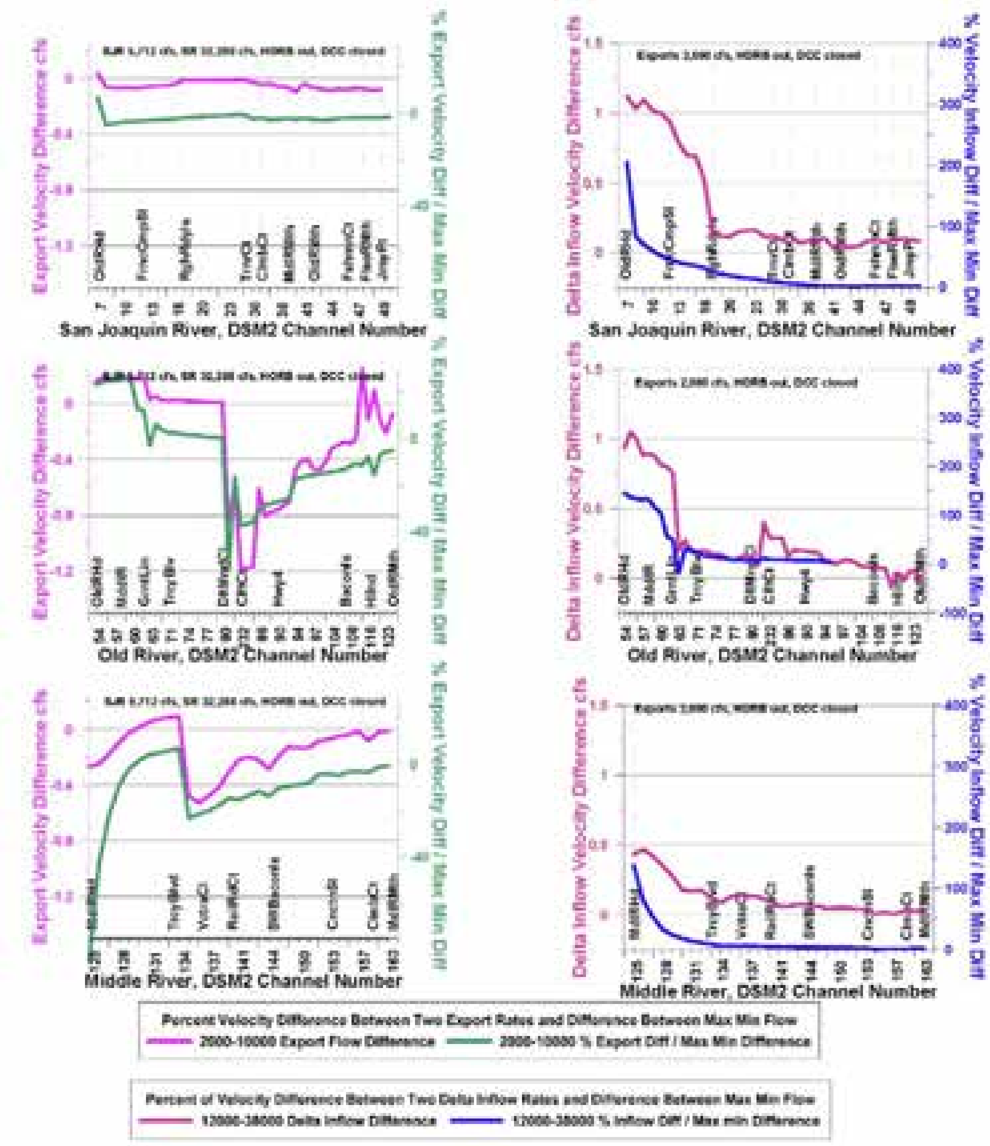


Figure B.5-15. Effect of Export Rate and Delta Inflow on Percent of Flow and Export Difference in the Lower San Joaquin River

Notes: The three routes are San Joaquin River mainstem, Old River, and Middle River. The x axis is the serial DSM2 model channel number. The left panels represent the high inflow scenario, the difference in average tidal velocity between low and high export rate (left y axis), and the difference in daily average velocity between low and high export rate divided by the difference between instantaneous maximum and minimum velocity at the low export rate (right y axis) without the HORB. The right panels represent the difference in daily average velocity between low and high inflow rate (left y axis) and the difference in daily average velocity between low and high inflow rate divided by the difference between daily maximum and minimum velocity at the low at the low inflow rate without the HORB. All right panels represent the low export scenario.

Similar to the flow section above, Figure B.5-16 is a "heat" map of the minimum and maximum velocity associated with the flood and ebb tides, respectively. The upper three panels are the minimum velocities associated with the flood tide phase throughout the South Delta for the three scenarios: low inflow/low export, high inflow/low export, and high inflow/high export. The lower three panels are the maximum velocities associated with the ebb tide phase throughout the South Delta for the three scenarios.

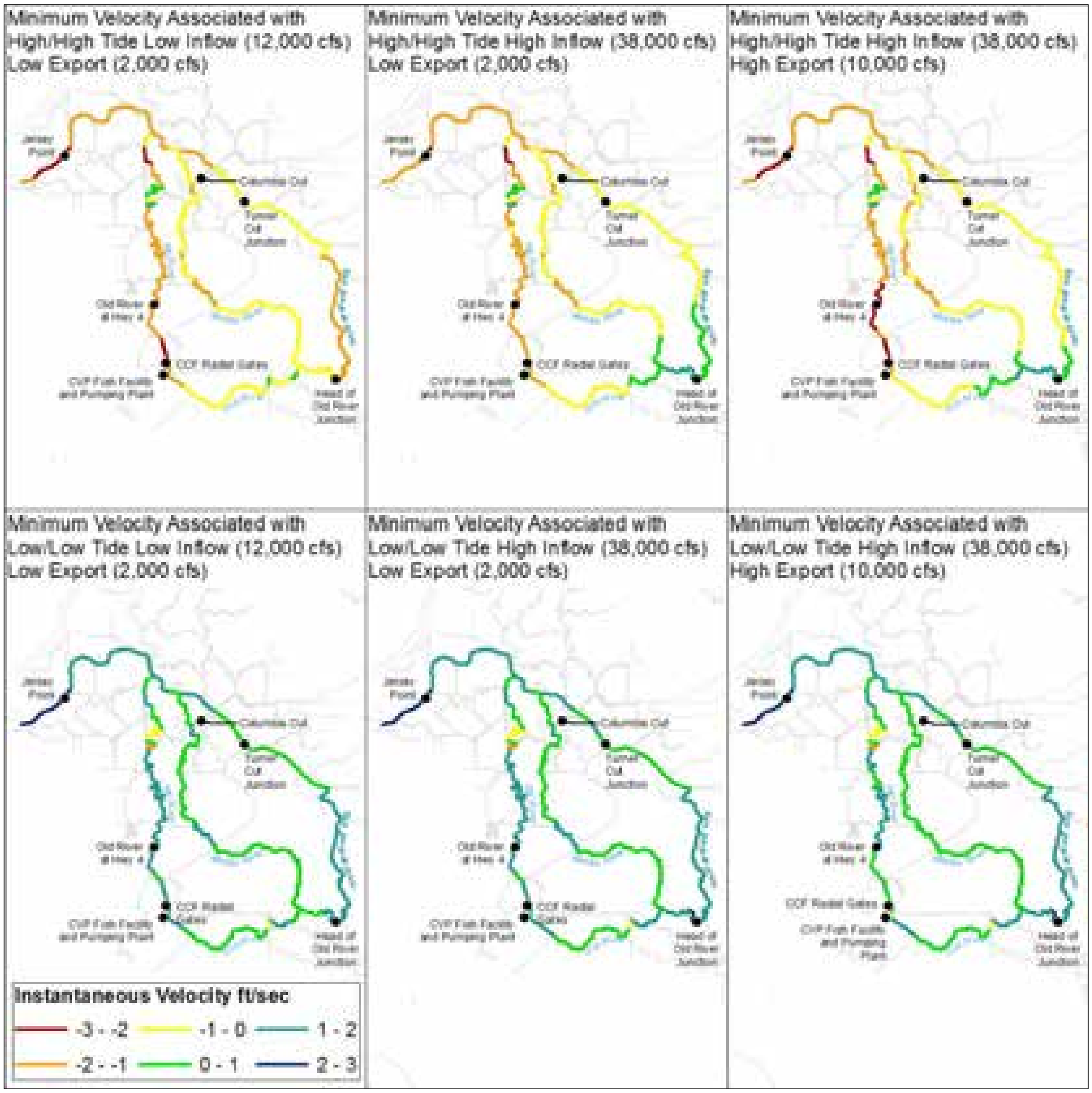


Figure B.5-16. DSM2 Modeled Instantaneous Minimum and Maximum Velocity Associated With the Ebb and Flood Tide Phases, Respectively, in Each Channel for Each of Three Model Scenarios, in Each of Three Routes in the South Delta

Notes: The three scenarios are low inflow/low export, high inflow/low export, and high inflow/high export. The three routes are the San Joaquin River mainstem, Old River, and Middle River. The upper three panels are the flood tide, and the lower three panels are the ebb tide.

Figure B.5-17 is a "heat" map of the difference between scenarios illustrated in Figure B.5-16. The upper three panels are the difference in minimum velocity between: 1) the high inflow/low export scenario and the low inflow/low export scenario (the first and second panels in the upper half of Figure B.5-16); 2) the high inflow/high export and the high inflow/low export scenario (the second and third panels in the upper half of Figure B.5-16); and 3) the high inflow/high export and low inflow/low export scenario (the first and third panels in the upper half of Figure B.5-16). The lower three panels are the difference in maximum velocity between the three scenarios as described in the previous sentence.

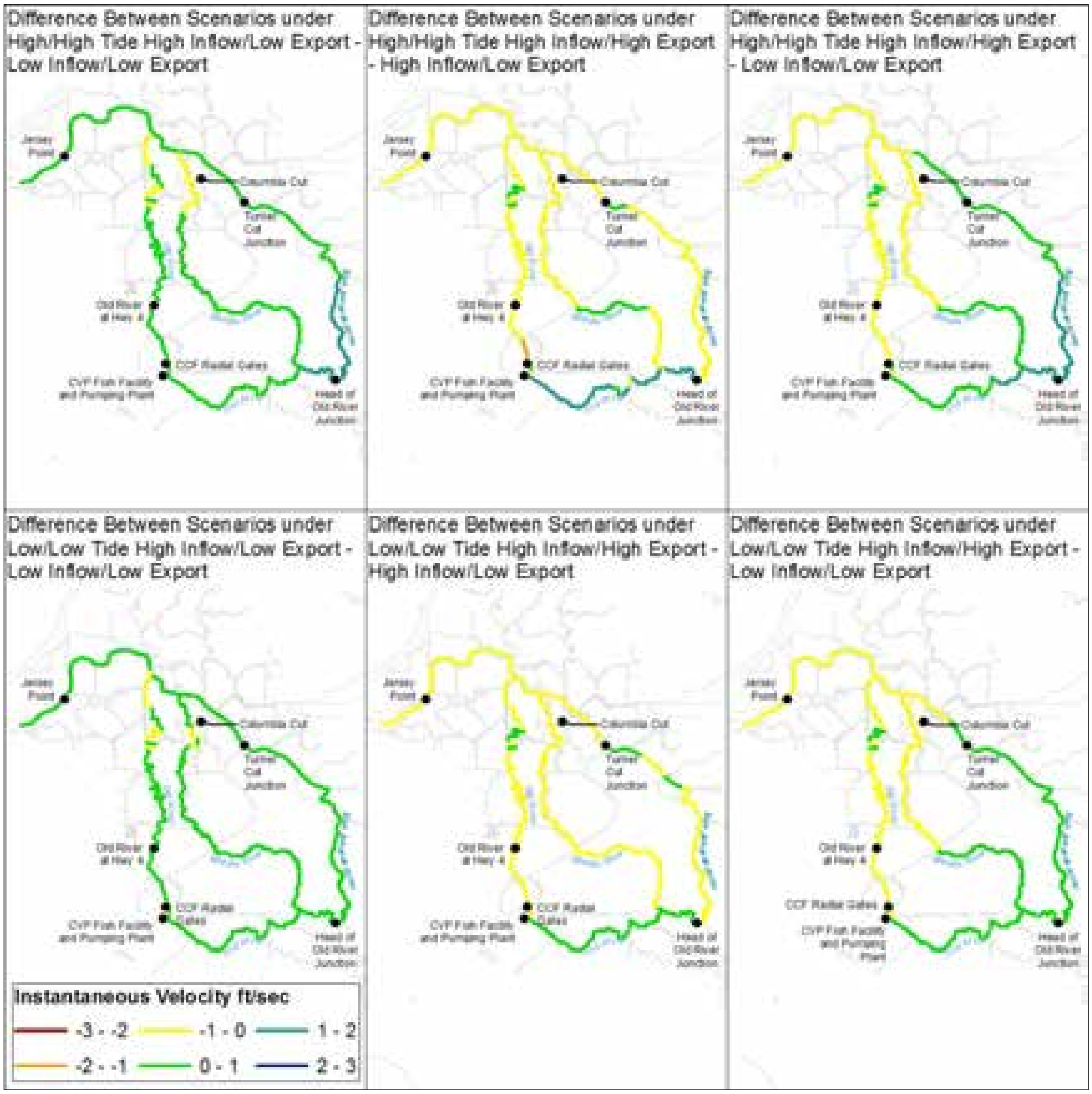


Figure B.5-17. Difference Between DSM2 Modeled Scenarios of Instantaneous Minimum and Maximum Velocity Associated With the Ebb and Flood Tide Phases, Respectively, in Each Channel for Each of Three Model Scenarios, in Each of Three Routes in the South Delta

Notes: The three scenarios are low inflow/low export, high inflow/low export, and high inflow/high export. The three routes are the San Joaquin River mainstem, Old River, and Middle River. The upper three panels are the difference of the minimum velocities and the lower three panels are the difference of the maximum velocities.

Table B.5-3 is a tabulation of the range of minimum and maximum instantaneous velocities in each route and all scenarios, and the differences in velocity between scenarios as a function of increased Delta inflow and export.

Results were further examined for each of three routes to describe changes in instantaneous minimum and maximum velocities associated with the low/low and high/high tide phase. The basis of knowledge for the relationships between different routes' maximum and minimum velocities and drivers such as exports, barriers, or Clifton Court radial gate operations is low because it is based on non-peer reviewed agency reports. Understanding the relationship between the migration route's velocity and these drivers is based on non-peer reviewed agency reports and information presented in this report. Results of simulation model predictions (DMS2) of the effects of SWP and CVP exports, and Sacramento River and San Joaquin River inflows, on hydrodynamic conditions in the San Joaquin River, Old River, and Middle River are summarized below.

B.5.4.1 San Joaquin River Mainstem

In the context of the three South Delta routes, the mainstem San Joaquin River, on average, had the least change in modeled velocity due to exports without the HORB, under the scenarios modeled. The change in velocity due to Delta inflow was more similar among the three routes (Figures B.5-14 through B.5-17).

- Similar to flow, the San Joaquin River had the least negative change in instantaneous velocity due to exports relative to OMR (Figure B.5-14 through Figure B.5-16; Table B.5-3). As an example of the difference between the San Joaquin River and OMR, the difference in minimum velocity due to an increase in exports from 2,000 to 10,000 cfs (high inflow, no HORB) in the San Joaquin River was greatest just downstream of the head of Old River (-0.21 ft/sec). For comparison, in Old River, the difference in minimum velocity due to the export increase was greatest at CCF (-1.19 ft/sec) (Figure B.5-17; Table B.5-3). In Middle River, at Victoria Canal, the difference in minimum velocity was -0.53 ft/sec (Table B.5-3). The differences in maximum velocity for the above analysis were similar in trend, but smaller in magnitude.
- From upstream to downstream, in the San Joaquin River route, the change in instantaneous minimum velocity due to increasing exports was greatest just downstream of the head of Old River (-0.21 ft/sec), then dissipated to less than -0.1 ft/sec upstream of French Camp Slough (Figure B.5-15 and Figure B.5-17).
- The San Joaquin River had a positive change in instantaneous velocity due to increasing Delta inflow that was similar to Old River, but greater than Middle River (
- Figure B.5-14 through Figure B.5-17; Table B.5-3). Increasing Delta inflow from 12,000 to 38,000 cfs (low export, no HORB) affected the instantaneous minimum and maximum velocities the most from the head of Old River to Rough and Ready Island, and then dissipated towards Jersey Point (Figure B.5-14 through Figure B.5-17). At the head of Old River the positive change in minimum velocity was +1.45 ft/sec, and then dissipated to less than +0.2 ft/sec downstream of Rough and Ready Island (Figure B.5-15 and Figure B.5-17).

Table B.5-3. Summary of Hydrodynamic Simulation Model Results for Changes in Water Velocities at Specific Locations Within the South Delta Without the Head of Old River Barrier for the Three Scenarios: 1) Low Inflow/Low Export; 2) High Inflow/Low Export; and 3) High Inflow/High Export

Metric	San Joaquin River Route Head of Old River to Jersey Point	Middle River Route Head to Mouth of Middle River	Old River Route Head to Mouth of Old River
Barrier Status	HORB out	HORB out	HORB out
Locations of high and low minimum velocity (associated with high/high tide) in the route for scenarios 1, 2, and 3	Upstream of head of Old River -0.20, +1.25, +1.31 ft/sec Downstream of mouth of False River -2.10, -2.08, -2.14 ft/sec	Head of Middle River -0.19, +0.44, +0.17 ft/sec Victoria Canal -1.32, -1.24, -1.77 ft/sec	Downstream of head of Old River -0.14, +1.31, +1.63 ft/sec CCF -2.04, -1.81, -3.01 ft/sec
Locations of low and high maximum velocity (associated with low/low tide) in the route for scenarios 1, 2, and 3	Downstream of Rough and Ready Island +0.33, +0.38, +0.37 ft/sec Downstream of Jersey Point +2.19, +2.23, +2.13 ft/sec	Columbia Cut +0.21, +0.21, +0.19 ft/sec Victoria Canal +1.11, +1.19, +0.96 ft/sec	Downstream of Delta Mendota Canal +0.38, +0.44, -0.41 ft/sec Downstream of head of Old River +1.33, +2.08, +2.16 ft/sec
Locations of high and low difference in minimum velocity between Scenarios 2 and 1 (effect of increasing inflow at low export)	Upstream of head of Old River +1.45 ft/sec Downstream of mouth of Old River 0.00 ft/sec	Downstream of head of Middle River +0.64 ft/sec Downstream of Connection Slough -0.03 ft/sec	Downstream of head of Old River +1.44 ft/sec Mouth of Old River -0.03 ft/sec
Locations of high and low difference in maximum velocity between Scenarios 2 and 1 (effect of increasing inflow at low export)	Upstream of head of Old River +0.89 ft/sec Downstream of mouth of Old River 0.00 ft/sec	Downstream of head of Middle River +0.31 ft/sec Downstream of Connection Slough -0.01 ft/sec	Upstream of head of Middle River +0.84 ft/sec Mouth of Old River -0.03 ft/sec
Locations of low and high difference in minimum velocity between Scenarios 3 and 2 (effect of increasing export at high inflow)	Downstream of head of Old River -0.21 ft/sec Upstream of head of Old River +0.05 ft/sec	Downstream of Victoria Canal -0.53 ft/sec Upstream of Victoria Canal +0.09 ft/sec	Downstream of Clifton Court -1.19 ft/sec Downstream of Paradise Cut +0.54 ft/sec
Locations of low and high difference in maximum velocity between Scenarios 3 and 2 (effect of increasing export at high inflow)	Downstream of Jersey Point -0.09 ft/sec Upstream of head of Old River +0.01 ft/sec	Downstream of Victoria Canal -0.24 ft/sec Upstream of Tracy Boulevard +0.09 ft/sec	Downstream of Delta Mendota Canal -0.85 ft/sec Downstream of head of Old River +0.13 ft/sec

- At the head of Old River junction, the effect of increasing exports from 2,000 cfs to 10,000 cfs (high inflow, no HORB) was an increase in instantaneous velocity in Old River just downstream of the head towards the Interior Delta. The maximum increase was 0.35 ft/sec. Increasing exports also increased instantaneous velocity in the San Joaquin River upstream of the junction a maximum of 0.08 cfs, and decreased velocity downstream of the junction by a maximum of -0.2 ft/sec. The effect of increasing inflow from 12,000 cfs to 38,000 cfs (low export, no HORB) was an increase in velocity upstream and downstream of the head of Old River and just downstream in Old River of about 1.5 ft/sec (Figure B.5-18).
- At the Turner Cut junction, the effect of increasing exports from 2,000 cfs to 10,000 cfs (high inflow, no HORB) was an increase in velocity in Turner Cut towards the Interior Delta. The maximum increase was +0.16 ft/sec. Increasing exports also decreased instantaneous velocity in the San Joaquin River upstream and downstream of the junction by a maximum of about -0.01 ft/sec. The effect of increasing inflow from 12,000 cfs to 38,000 cfs (low export, no HORB) was an increase in velocity in the San Joaquin River above and below the Turner Cut junction of about +0.15 ft/sec, and in Turner Cut of about +0.01 ft/sec (Figure B.5-19).
- At the Middle River junction, the effect of increasing exports from 2,000 cfs to 10,000 cfs (high inflow, no HORB) was a decrease in velocity in Middle River towards the Interior Delta (note: the default direction in that channel is away from the Interior Delta). The maximum increase was -0.16 ft/sec. The effects of increasing exports and increasing inflow from 12,000 cfs to 38,000 cfs in the other channels was about 0.05 to 0.01 ft/sec (Figure B.5-20).

B.5.4.2 Old River

Relative to the three routes, in the context of tides, Old River had the greatest negative change in instantaneous minimum and maximum modeled velocity due to an increase in exports:

- The largest relative changes occurred downstream of the CVP and SWP export facilities and then dissipated toward the mouth (Figure B.5-14 and Figure B.5-15; Table B.5-3).
- From upstream to downstream, in the Old River route, the change in instantaneous minimum velocity due to increasing exports was positive upstream of the delta Mendota Canal, and then became negative downstream. The greatest negative change in instantaneous minimum velocity was just downstream of Clifton Court, then dissipated to less than -0.2 ft/sec downstream of Bacon Island (Figure B.5-15 and Figure B.5-17).

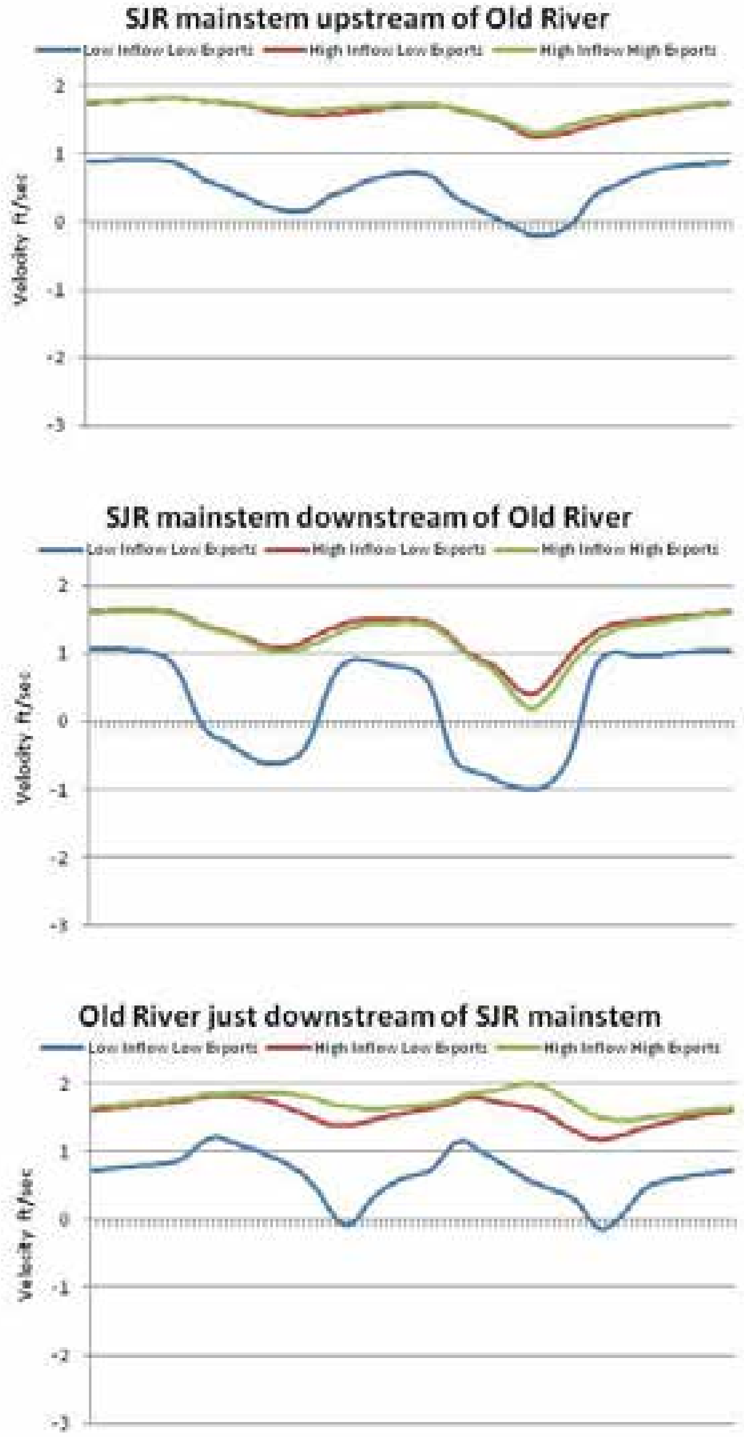


Figure B.5-18. DMS2 Modeled Instantaneous 15-minute Velocity Versus Time Over a Complete Tidal Cycle (~25 Hours) in Three Channels at the Junction of the San Joaquin River Mainstem and the Head of Old River

Notes: There are three DSM2 channel reaches at the junction (three panels). Within each panel there are three scenarios: low inflow/low export, high inflow/low export, and high inflow /high export.

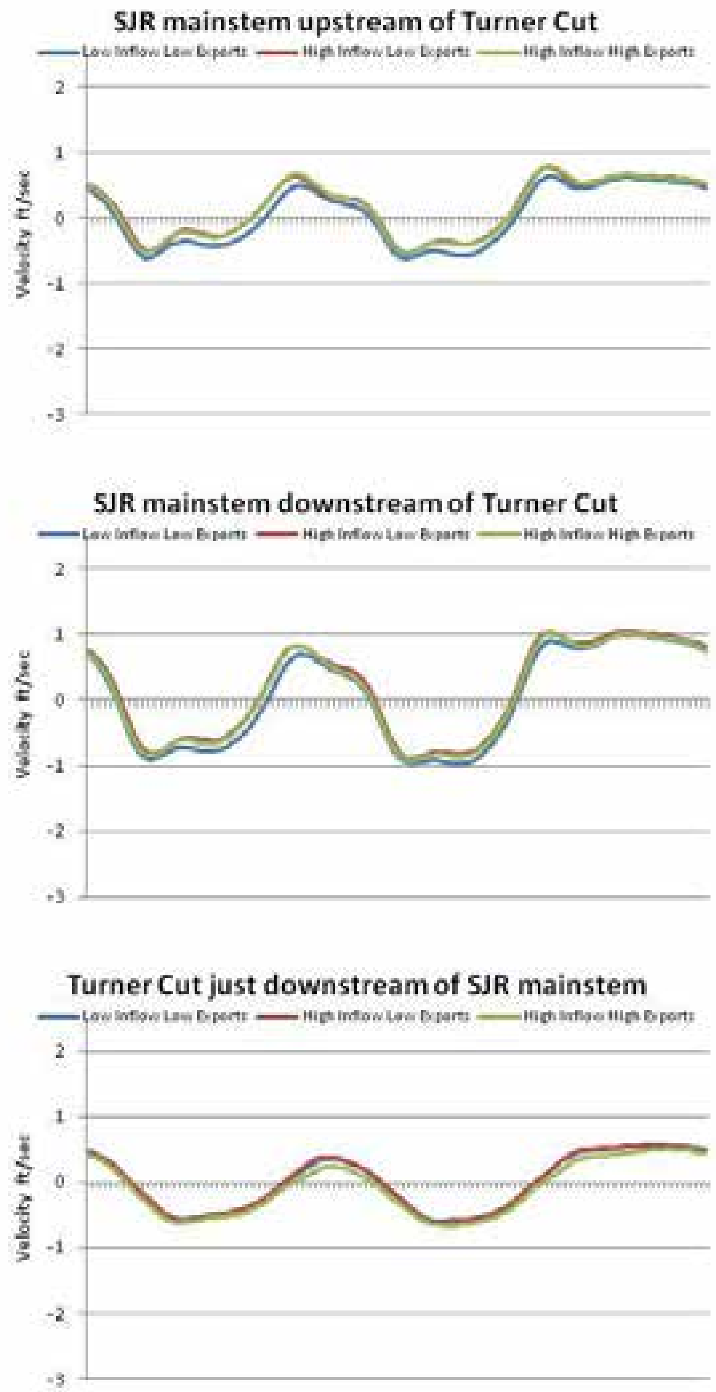
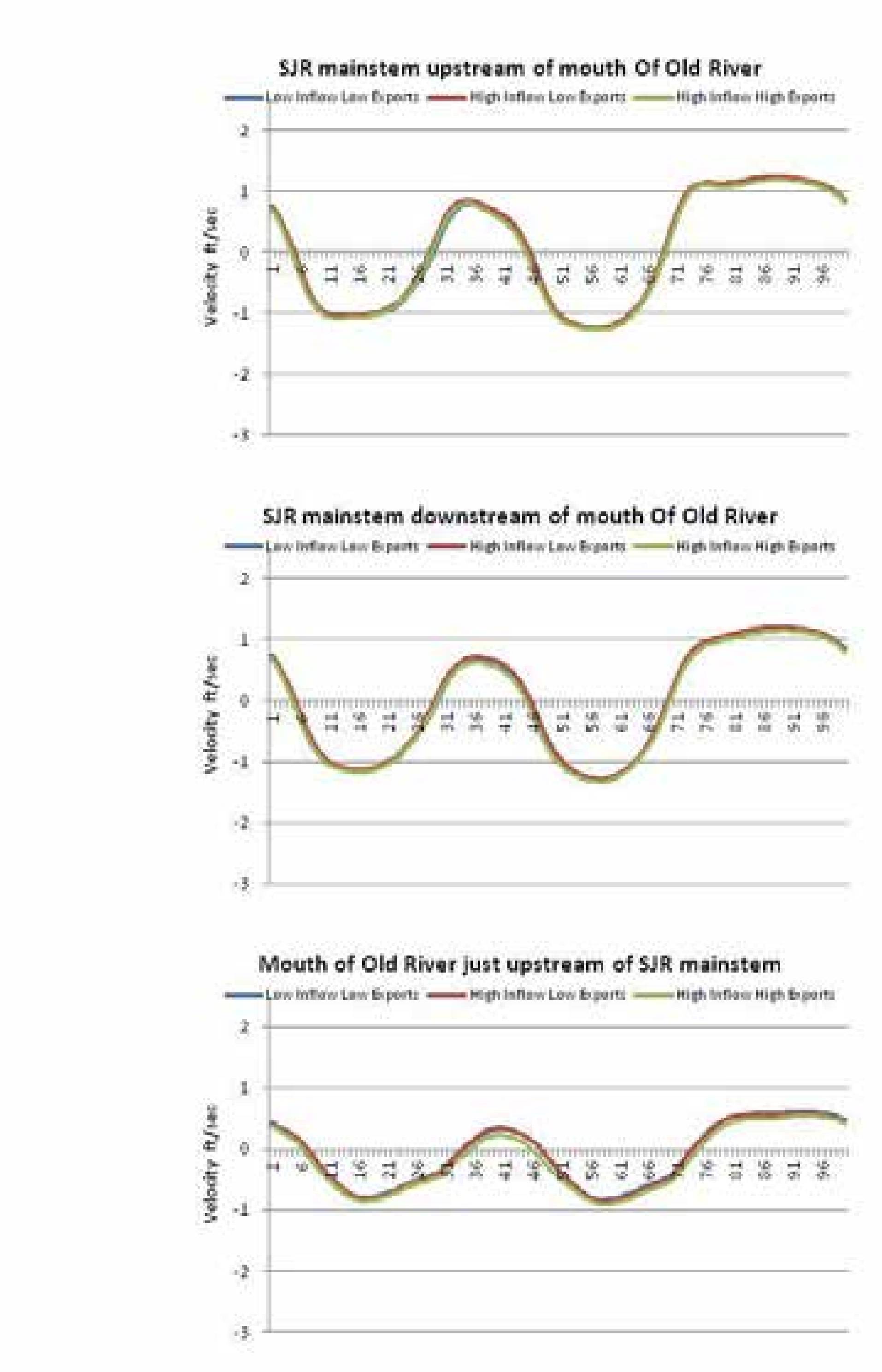


Figure B.5-19. DMS2 Modeled Instantaneous 15-minute Velocity Versus Time Over a Complete Tidal Cycle (~25 Hours) in Three Channels at the Junction of the San Joaquin River Mainstem and Turner Cut

Notes: There are three DSM2 channel reaches at the junction (three panels). Within each panel there are three scenarios: low inflow/low export, high inflow/low export, and high inflow/high export.


SJR mainstem upstream of mouth Of Old River

SJR mainstem downstream of mouth Of Old River

Mouth of Old River just upstream of SJR mainstem

Figure B.5-20. DMS2 Modeled Instantaneous 15-minute Velocity Versus Time Over a Complete Tidal Cycle (~25 Hours) in Three Channels at the Junction of the San Joaquin River Mainstem and the Mouth of Old River

Notes: There are three DSM2 channel reaches at the junction (three panels). Within each panel there are three scenarios: low inflow/low export, high inflow/low export, and high inflow/high export.

- Old River had a positive change in instantaneous velocity, in the context of tides, due to Delta inflows that was similar to the San Joaquin River, but greater than Middle River (
- Figure B.5-14 through Figure B.5-17; Table B.5-3). As an example of the positive effect of inflow in upper Old River, near the head, the difference in instantaneous minimum velocity due to a change in Delta inflow from 12,000 to 38,000 cfs (low export, no HORB) was +1.44 ft/sec. For comparison, in Middle River at the head, the difference in minimum velocity was +0.64 ft/sec (Figure B.5-17; Table B.5-3).
- From upstream to downstream, in the Old River route, the positive change in instantaneous minimum velocity due to increasing Delta inflow was greatest downstream of the head of Old River (+1.44 ft/sec), then dissipated to less than +0.2 ft/sec downstream of Grant Line Canal (Figure B.5-15 and Figure B.5-17).

B.5.4.3 Middle River

Relative to the three routes, Middle River had the least change in minimum and maximum velocities due to inflows, and an intermediate change in minimum and maximum velocities due to exports (Figure B.5-14 through Figure B.5-17; Table B.5-3).

- Increasing exports from 2,000 to 10,000 cfs (high inflow, no HORB) resulted in a decrease in instantaneous minimum velocity at the head of Middle River (-0.27 ft/sec), which dissipated to upstream of Victoria Canal (+0.09 ft/sec), then decreased again at Victoria Canal (-0.52 ft/sec), and dissipated to less than -0.1 ft/sec at Connection Slough (Figure B.5-15 and Figure B.5-17).
- Increasing Delta inflow from 12,000 cfs to 38,000 cfs (low export, no HORB) increased instantaneous minimum velocity at the head of Middle River (+0.64 ft/sec), then dissipated to less than 0.1 ft/sec at Tracy Boulevard (Figure B.5-15 and Figure B.5-17).

B.5.4.4 Conclusions

Modeled exports had the greatest negative effect on instantaneous minimum and maximum velocity in Old River; immediately downstream of the export facilities and gradually dissipating towards the mouth:

- Exports had a positive effect upstream of the exports and a negative effect downstream.
- Modeled exports had the least effect on instantaneous maximum and minimum velocity in the San Joaquin River mainstem, and an intermediate effect on Middle River.
- Modeled Delta inflow had the greatest effect on instantaneous minimum and maximum velocities in Old River between the head of Old River and Grant Line Canal, and in the San Joaquin River mainstem between the head of Old River and Rough and Ready Island.
- The effect of modeled Delta inflow at the head of Old River had a greater positive effect on instantaneous minimum and maximum velocity than the negative effect of exports at the export facilities.
- Modeled Delta inflow had the least effect on Middle River. In Middle River, the greatest effect of Delta inflow was between the head of Middle River and Tracy Boulevard.

B.5.4.5 Gaps in Information

The same gaps described in Section B.5.3.6 are applicable here:

- The flow and velocity of water in Clifton Court channel are not measured directly—they are estimated.
- Delta Consumptive Use, diversions on to and returns from the Delta islands, is not estimated adequately. Delta Consumptive Use becomes extremely important at low net Delta outflows. There are ongoing efforts to improve the estimations.
- Channel bathymetry data in the South Delta are inadequate. Channel configuration has a major effect on the influence of inflow and exports on the magnitude, direction, and proportion of flow entering downstream channels through the Interior, Central, and South Delta.

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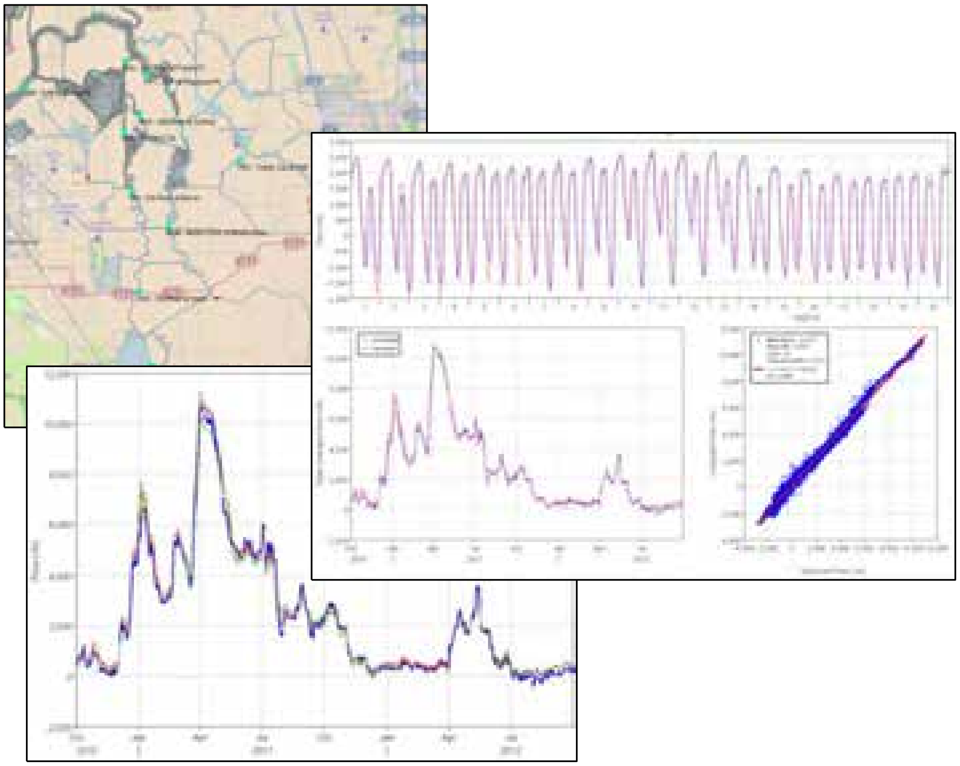
Appendix C
DSM2 and RMA2
South Delta Flow Comparison
Draft Technical Memorandum

January 2017

CAMT – DSM2 and RMA2 South Delta Flow Comparison Draft Technical Memorandum

May 2015



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Overview

The Collaborative Adaptive Management Team (CAMT) Salmon Scoping Team has requested that comparative modeling simulations be performed to help determine if there is a model that can be used in a short time scale and at a small geographic scale to compliment the fine scale acoustic tagged fish data they have collected.

Hydrodynamic modeling and individual based modeling of salmon are useful tools in understanding salmon entrainment and the effectiveness of any measures to decrease this entrainment. Several modeling platforms are potentially suitable for modeling hydrodynamics and particle-tracking/individual based modeling in the Delta. Two models that are currently frequently applied are DSM2 and RMA2. The purpose of this document is to assess the accuracy of the two models by comparing the calibration of up to date versions of the models in the south Delta region.

Model simulations were performed for the period of October 1, 2010 through September 30, 2012. Water year (WY) 2011 was a wet year, and WY 2012 was a below normal/dry year.

Models

DSM2

The Delta Simulation Model II (DSM2), developed by State of California, Department of Water Resources (DWR), is a one-dimensional mathematical model for dynamic simulation of one-dimensional hydrodynamics, water quality and particle tracking in a network of riverine or estuarine channels (https://dsm2ug.water.ca.gov/home).

Geometric Extents

The DSM2 model grid, shown in Figure 1, extends from Martinez to the at the west end of Suisun Bay to the Sacramento River at Sacramento, and to the San Joaquin River near Vernalis.

RMA2

RMA2 is a two-dimensional depth-averaged finite element hydrodynamic model developed by Resource Management Associates (RMA) (http://www.water.ca.gov/frankstract/docs/%288%29RMA-Calibration%20Report.pdf). The “salinity-coupled” version of the RMA2 program has been applied in this study. This version includes the relevant water quality transport routines from the RMA11 program in order to compute the salinity distribution throughout the model domain during the hydrodynamic simulation. The salinities or Electrical Conductivity (EC) values are then utilized in the computation of the baroclinic term of the flow equation. Salinity transport and flow are not computed simultaneously. Rather, the salinities from the previous computational time step are used to compute the fluid densities for the current hydrodynamic time step. Once a converged solution for the flow computation is achieved, the resulting flow field is utilized for the computation of the salinity transport. On average, the “salinity-coupled” model increases computed Delta stages about 0.3 feet over the standard RMA-2 model, with the effect greater in the summer and fall, and less during the wet season when Suisun Bay salinities are lower.

Geometric Extents

The RMA Delta model, shown in Figure 2, extends from Martinez at the west end of Suisun Bay to the Sacramento River above the confluence with the American River, and to the San Joaquin River near Vernalis. A two-dimensional depth-averaged approximation is used to represent the Suisun Bay region, the Sacramento-San Joaquin confluence area, Sherman Lake, the Sacramento River up to Rio Vista, Cache Slough, Liberty Island, Shag Slough, portions of Lindsey Slough, the Sacramento River Deep Water Ship Channel (DWSC) and Miner Slough, Big Break, the San Joaquin River up to its confluence with Middle River, False River, Franks Tract and surrounding channels, Mildred Island, Old River south of Franks Tract, and the Delta Cross Channel area. The other Delta and Suisun Marsh channels and tributary streams are represented using a one-dimensional cross-sectionally averaged approximation.

Boundary Conditions

The DSM2 grid and boundary condition locations are shown here in Figure 1.

The RMA Bay-Delta model grid and boundary condition locations are shown in Figure 2. The typical RMA2 model applied boundary conditions are slightly different than what is applied in DSM2. There are several reasons for the differences, including:

- Boundary location – in RMA2 the Sacramento River extends further upstream than DSM2 and includes the American River, while DSM2 does not. Therefore, Sacramento and American River flows are typically applied separately in RMA2.
- Internally calculated flows versus boundary condition inputs – DSM2 calculates Paradise Cut flows internally while RMA2 applies them as boundary conditions estimated from observed San Joaquin River flows upstream and downstream of the Paradise Cut weir.
- Selection of different data sets – many agencies collect and publish data, resulting in multiple non-identical data sets at some locations. For RMA2, we use what we feel are the best data sets available from US Geological Survey (USGS), California Data Exchange Center (CDEC), Water Data Library (WDL) and DWR to set model boundary conditions. Where data are not available, RMA2 uses flows estimated based on flow balances or seasonal trends (these methods have been used to estimate Yolo Bypass/Cache Slough region flows).

To more carefully compare the results of the DSM2 and RMA2 model simulations and differentiate between the effects of boundary conditions and the effects of the models themselves (computational engine, model geometry, model parameters, etc.), the RMA2 model was run with boundary conditions identical to DSM2 (to the extent possible) and with typical RMA2 boundary conditions. DSM2 and typical RMA2 model boundary conditions are plotted in Figure 3 through Figure 13 below.

Sacramento River

On the Sacramento River (Figure 3), the RMA model extends upstream above the American River. Therefore, American River and Sacramento River flows are both applied, whereas DSM2 has only a Sacramento River inflow boundary. There are slight differences between the DSM2 Sacramento River flows and the RMA2 Sacramento + American River flows that are likely due to the use of different data sources.

San Joaquin River

DSM2 and RMA2 San Joaquin River flows (Figure 4) differ slightly. RMA2 uses USGS Vernalis flows while DSM2 uses DWR Vernalis flows (CH2MHill, 2009).

Yolo Bypass/Cache Slough Region

DSM2 and RMA2 flow boundary conditions in the Yolo Bypass/Cache Slough region (Figure 5) differ significantly. RMA2 uses a combination of WDL, USGS, DWR and CDEC data to estimate and set flows for the Bypass, Toe Drain and other inflows and withdrawals in the region. The summed RMA2 flows in the region are higher than the single DSM2 inflow to Yolo Bypass during the high flow period. Figure 6 shows the same boundary conditions with the flow scale enhanced to emphasize the low flow periods. This plot indicates that DSM2 generally applies higher flows during the summer and fall and the RMA2 model actually applies negative flows (representing agricultural withdrawals) during this period with the theory that DICU is not high enough to account for the actual withdrawals. The “Upper Cache Slough Flows” plotted in diversion and return flows in the Cache Slough complex were derived by mass balance using ADCP flow measurements in Upper Cache Slough and Lindsey Slough.

Calaveras, Cosumnes and Mokelumne Rivers

DSM2 and RMA2 Calaveras, Cosumnes and Mokelumne River flows (Figure 7) differ slightly. DSM2 uses DWR data for each of these inflows. RMA2 uses a combination of DWR, CDEC and USGS flows with some time shifts to account for travel time.

Paradise Cut

DSM2 computes Paradise Cut flow during the model simulation based on flow in the San Joaquin River. RMA2 uses applied flow boundary conditions, withdrawing flow from the San Joaquin River at Paradise Cut, with a corresponding inflow to Paradise Cut. The flow is estimated by subtracting Mossdale flows from Vernalis flows when Vernalis flows exceed 15,000 cfs. Paradise Cut flows for both models are plotted in Figure 8.

Sacramento Regional Wastewater Treatment Plant (SRWWTP) Discharge

RMA2 applies discharge from SRWWTP (Figure 9), whereas this is not included in DSM2.

SWP and CVP Exports

SWP and CVP exports are generally identical between the two models (Figure 10). The SWP exports applied in RMA2 are in fact computed by DSM2.

During periods when gate opening heights and water surface elevation data inside and outside Clifton Court Forebay are available, RMA uses SWP exports that are computed using this data with gate equations, resulting in a more accurate boundary condition. These data are not, however, available during the WY2011-2012 simulation period used in this study.

Contra Costa Exports

Contra Costa exports at Rock Slough, Old River and Victoria Canal (Figure 11) are identical between the two models.

North Bay Aqueduct Exports

North Bay Aqueduct exports in Barker Slough (Figure 12) are generally identical between the two models.

Martinez Stage

DSM2 and RMA2 stage boundary conditions (Figure 13) are identical throughout most of the simulation period. There are some brief periods of difference resulting from employment of different methods of filling data gaps or correcting bad data.

The two models use identical DICU and gate and barrier operation schedules.

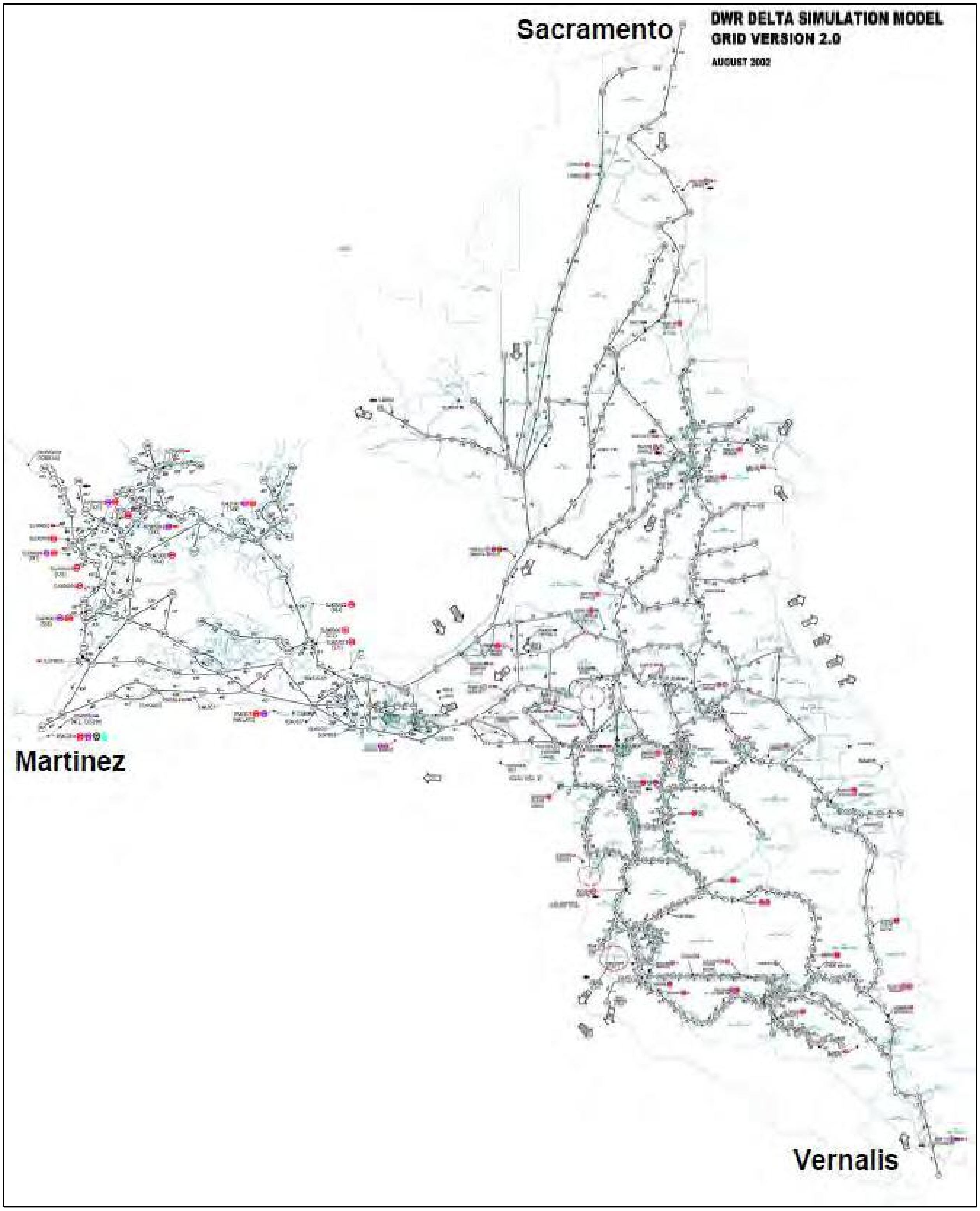


Figure 1 DSM2 model grid (CH2MHill, 2009).

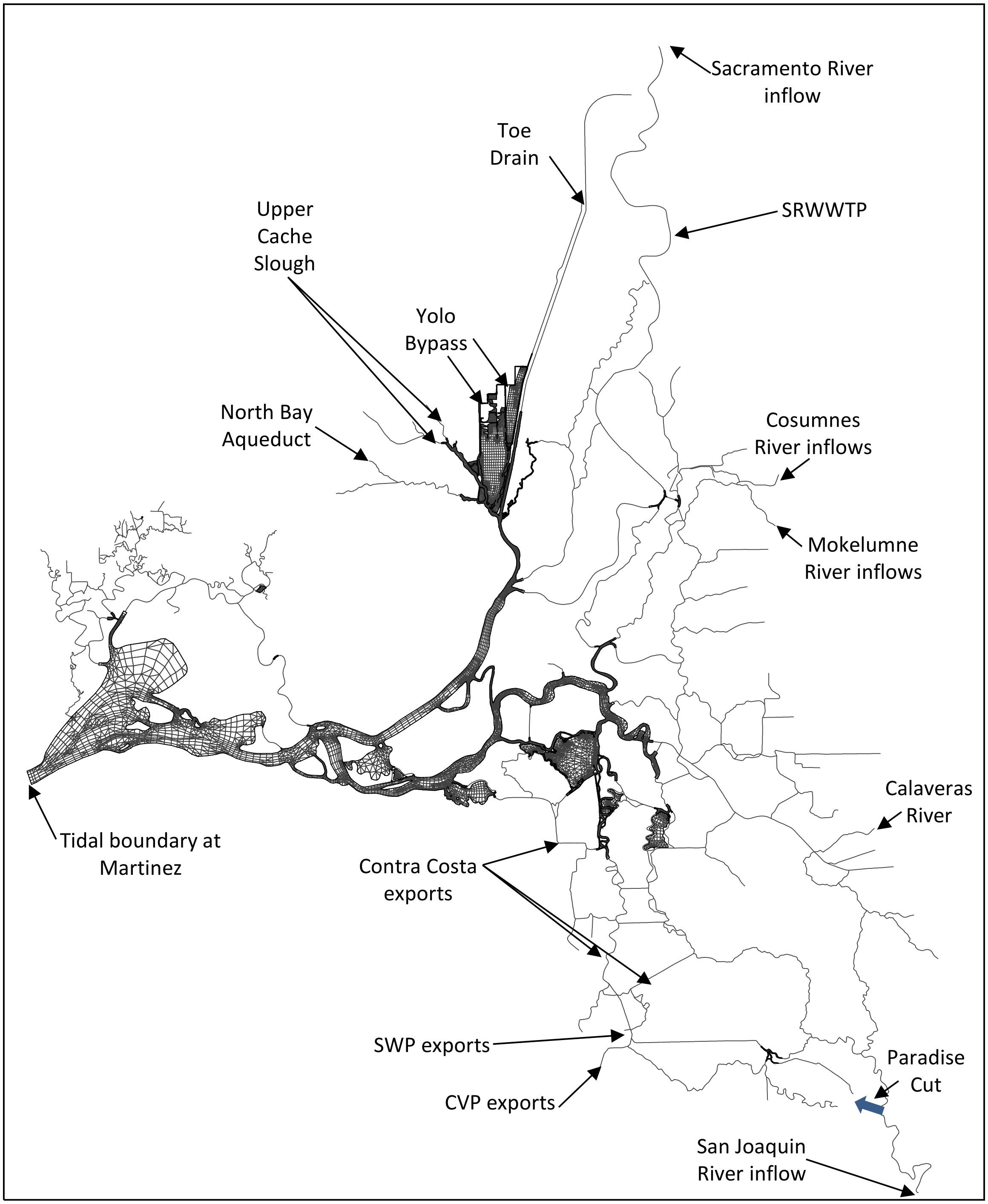


Figure 2 RMA2 model grid with boundary condition locations.

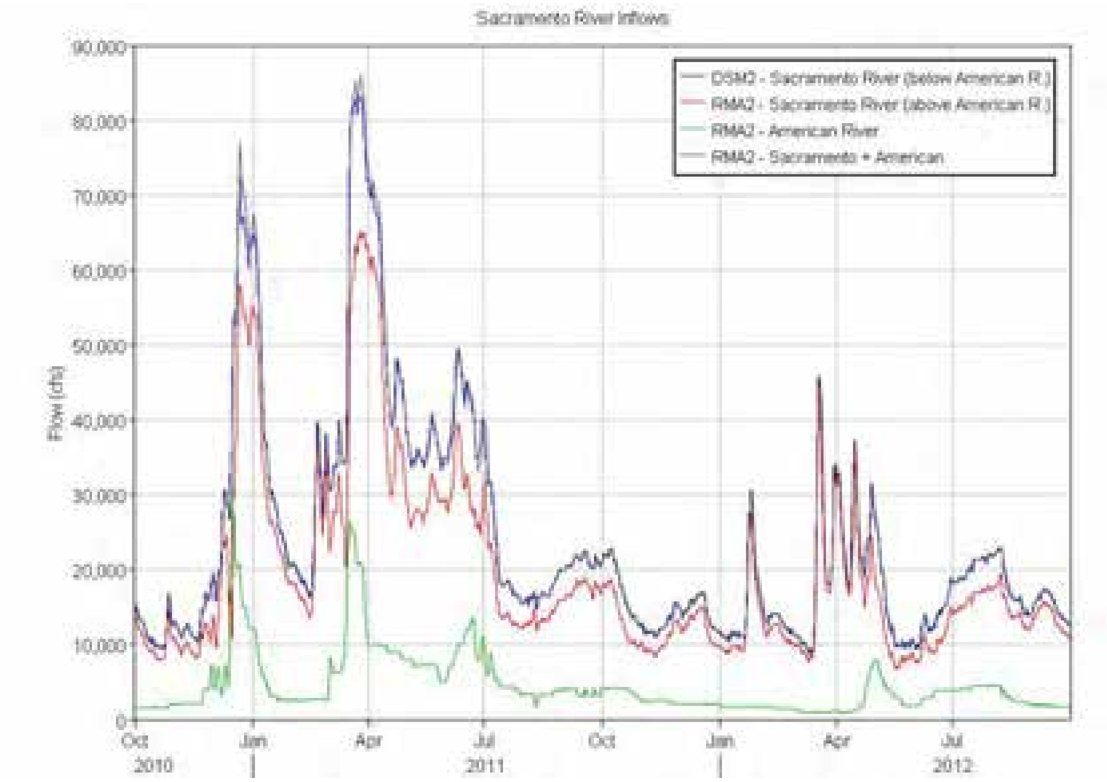


Figure 3 DSM2 and RMA2 Sacramento River inflows.

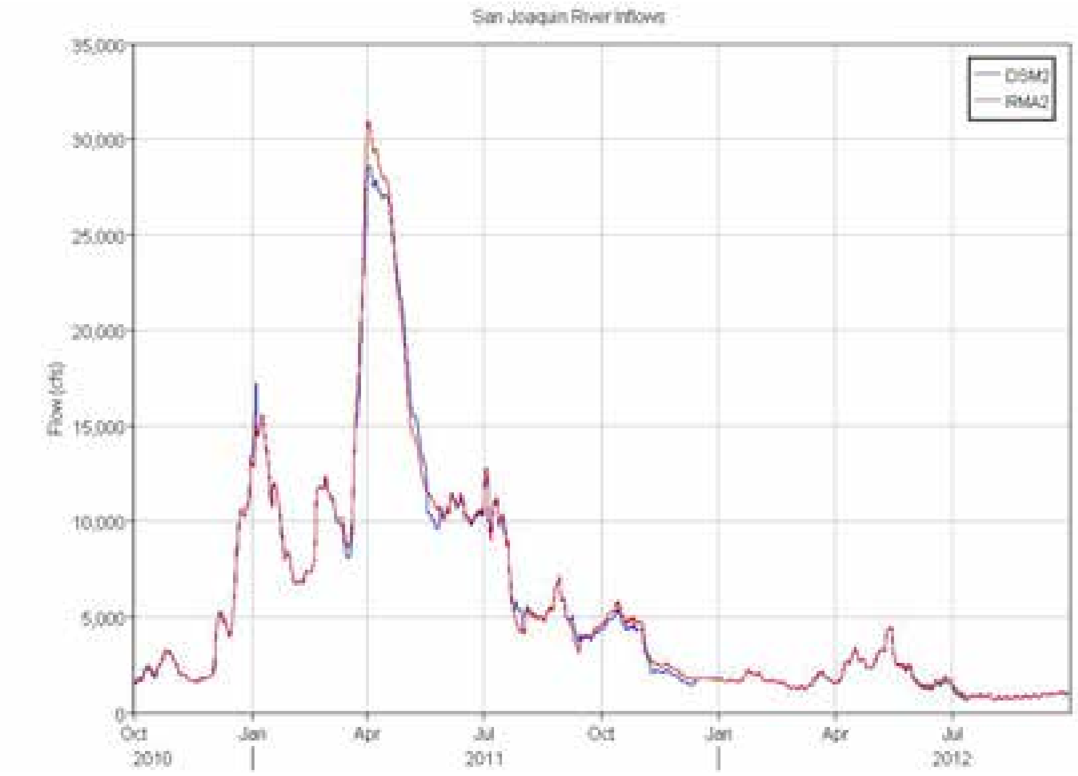


Figure 4 DSM2 and RMA2 San Joaquin River inflows.

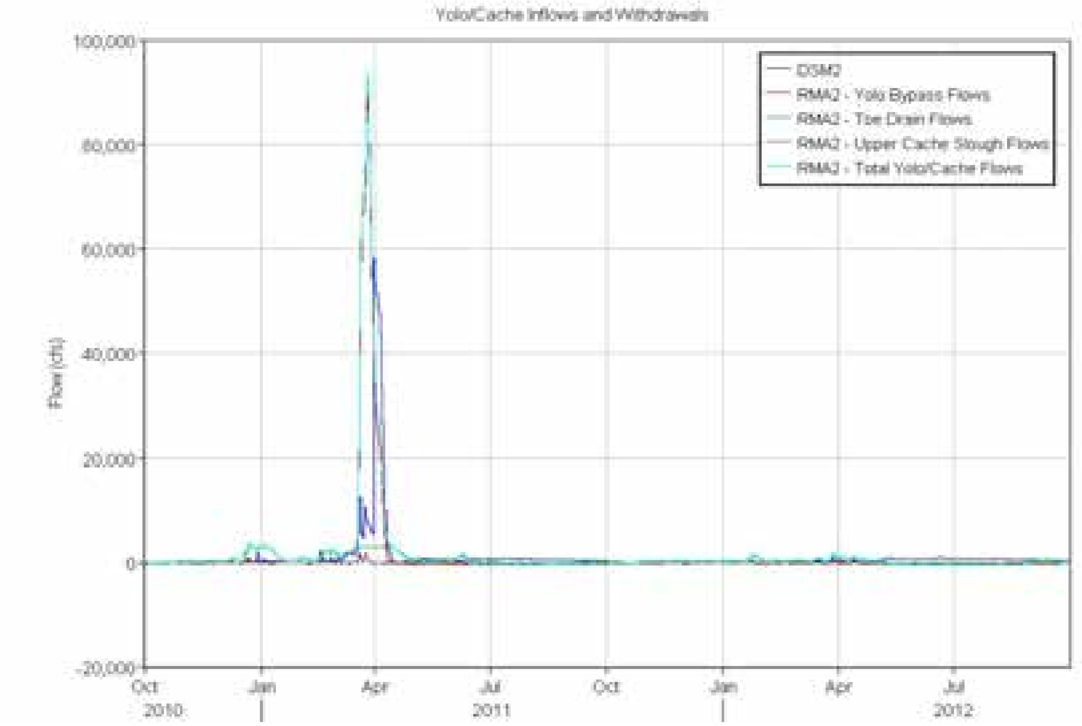


Figure 5 DSM2 and RMA2 Yolo Bypass/Cache Slough region inflows and withdrawals.

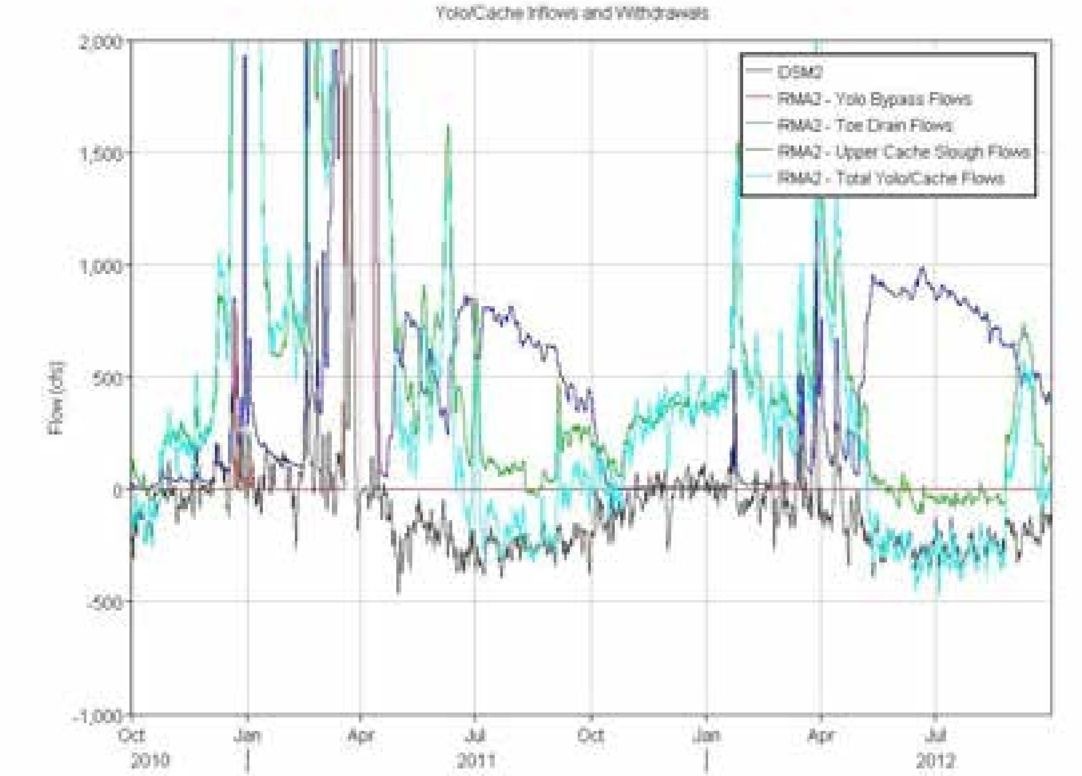


Figure 6 DSM2 and RMA2 Yolo Bypass/Cache Slough region inflows and withdrawals (enhanced flow scale).

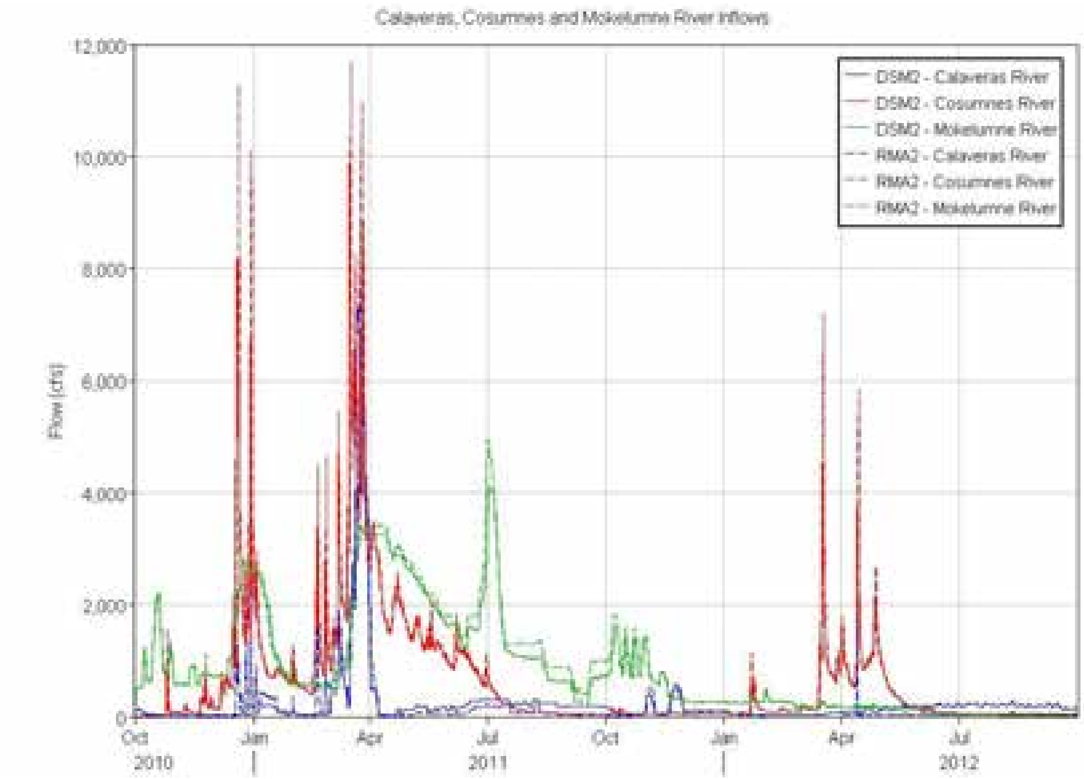


Figure 7 DSM2 and RMA2 Calaveras, Cosumnes and Mokelumne River inflows.

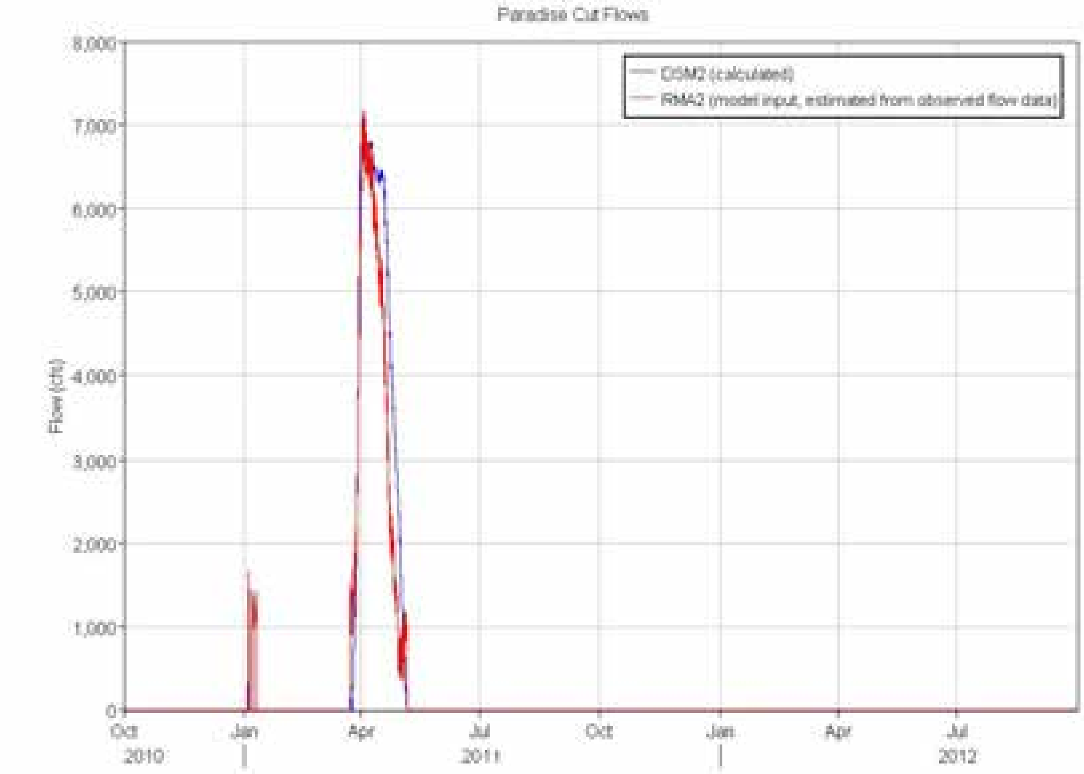


Figure 8 DSM2 and RMA2 Paradise Cut flows.

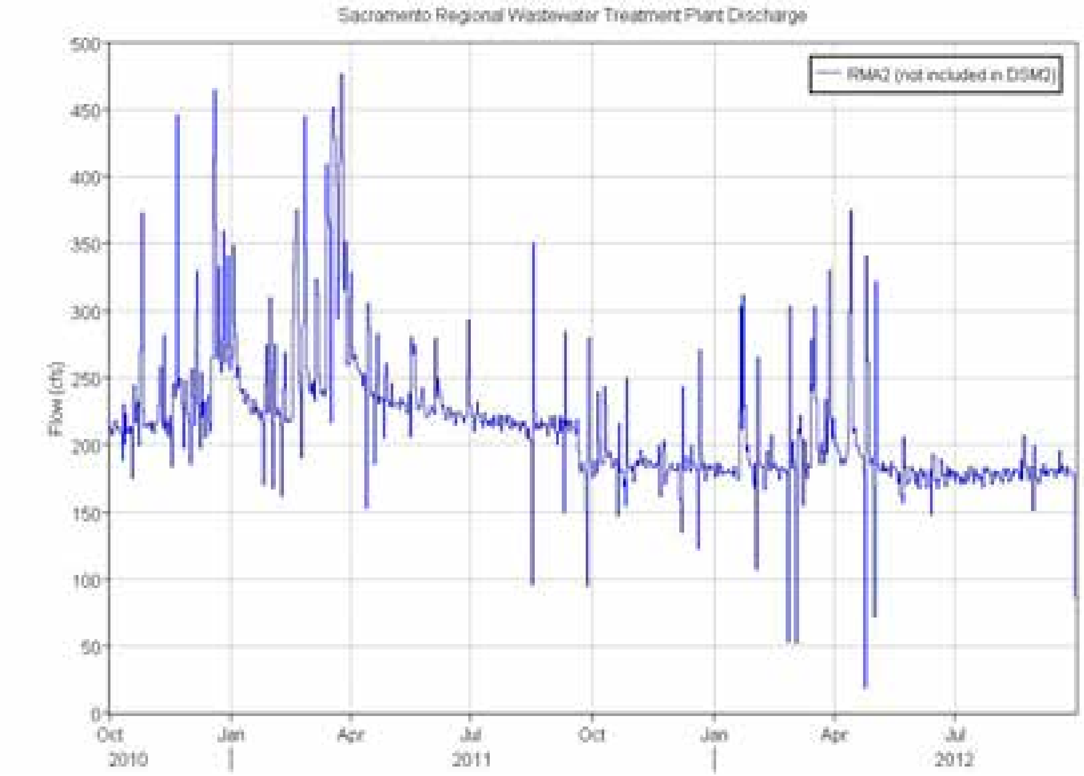


Figure 9 RMA2 Sacramento Regional Wastewater Treatment Plant Discharge flows (not included in DSM2).

Figure 10 DSM2 and RMA2 export flows for SWP (daily average of 15-minute values) and CVP.

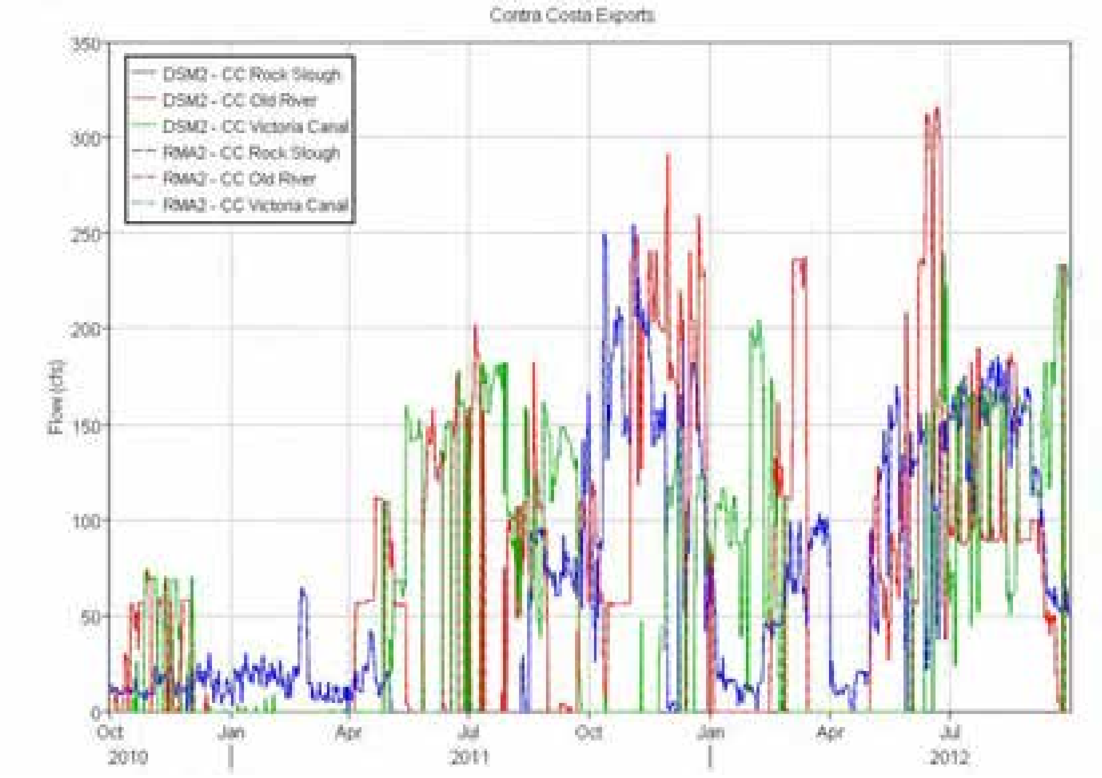


Figure 11 DSM2 and RMA2 Contra Costa export flows at Rock Slough, Old River and Victoria Canal.

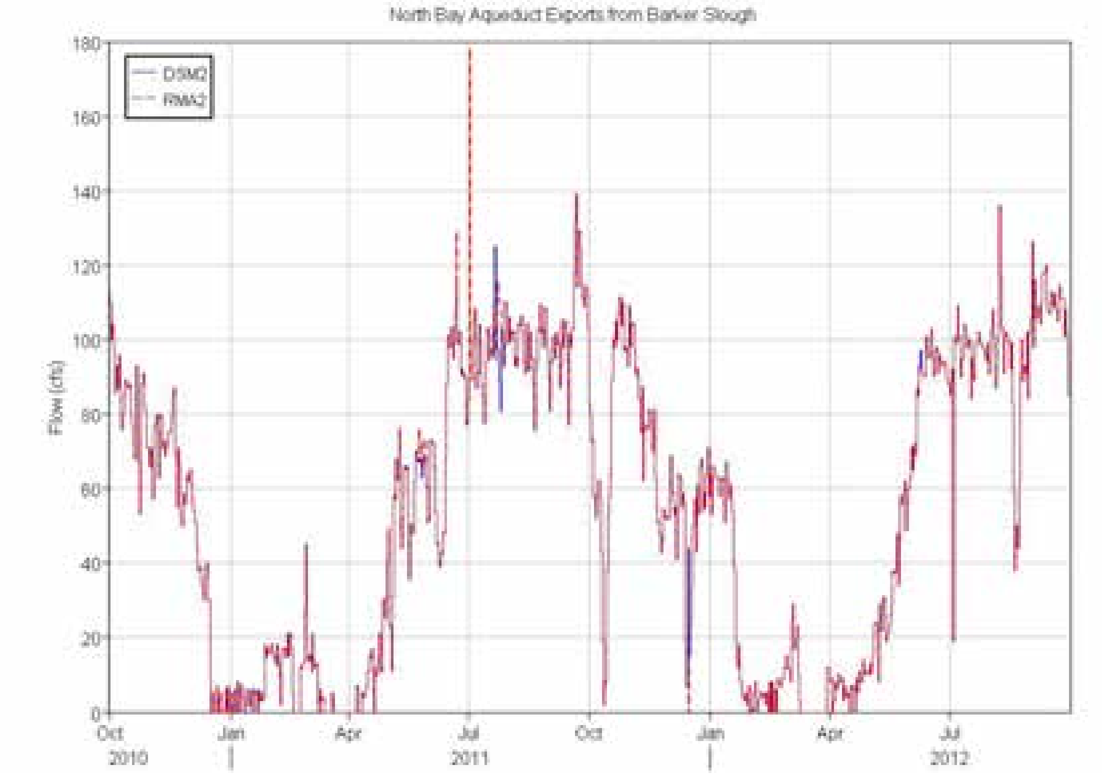


Figure 12 DSM2 and RMA2 North Bay Aqueduct exports from Barker Slough.

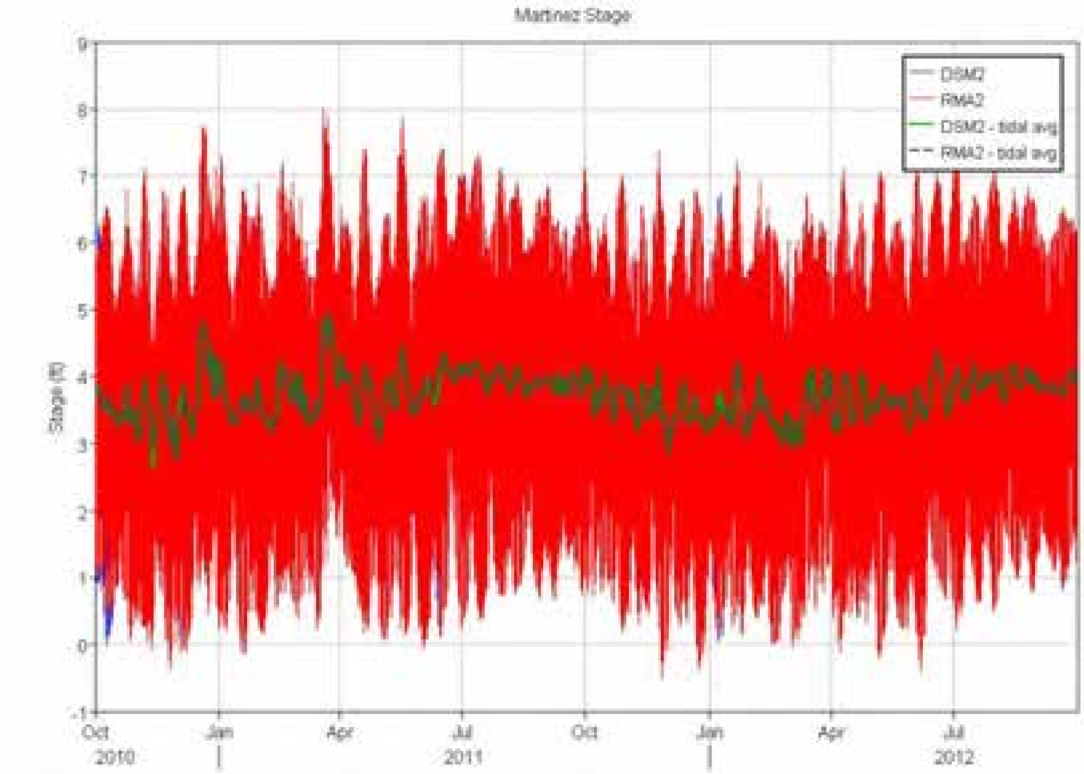


Figure 13 DSM2 and RMA2 15-minute and tidally averaged stage at Martinez.

Model Error Metrics and Model Skill

The quality of fit between computed model results and observed data in a tidally driven system is typically presented in the form of time series plots of dynamic and tidally averaged values. A visual comparison of the "dynamic" plot of 15-minute interval observed and computed flow/velocity/stage illustrates how well the model reproduces the tidal dynamics of the system. A comparison of the tidally averaged or tidal filtered time series shows how well model reproduces the net channel flows/velocities or overall stage. In addition to the visual representations, statistics can be derived to quantify the differences between computed and observed records for the tidally driven system.

Error Metrics

Four types of error metrics have been selected for presentation in this report.

Mean: Comparison of simple mean value of the computed and observed time series. This provides a measure of how well the model matches net observed channel flows or average stage. The mean diff is calculated as mean computed minus mean observed. This is also viewed as a percent difference from observed.

Lag: The average lag, or phase shift in time between the computed and observed tidal signals determined from a cross-correlation analysis.

Linear Regression: After the phase shift is removed, the observed and computed time series are compared on a point by point basis through a linear regression analysis. The better the model is at reproducing detailed variation of the observed tidal signal and base values, the smaller the scatter will be. One measure of the scatter is the coefficient of determination, R^2 (R2 in plots and tables). Additionally, the slope of the regression line should be close to 1 and the intercept should be close to 0.

Amp Ratio (Amplitude Ratio): This is computed from a second linear regression analysis where the tidally averaged signal is removed from the observed and computed records. The remaining times series is more representative of the daily tides, and the Tidal Amplitude Ratio is taken as the slope of the regression line.

For each observed data location, three plots of computed and observed flow/velocity/stage are provided: dynamic and tidally averaged time series plots and a scatter plot of computed versus observed data with linear regression statistics.

"Tidally averaged" stage, shown in the lower left of each figure, is plotted for the entire simulation period. The "tidally averaged" time series is computed with two passes of a 24.75 hour moving average window. With only a single pass of the averaging window, a significant tidal signal was still present especially for a flow record where the net flow may be a small fraction of the peak tidal flow. A Godin tidal filter produces somewhat more smoothing than the two pass filter, which may not always be desirable. Digital filters can provide better control of the frequency content of the filtered record but can have undesirable effects at the ends of the time series, and at data gaps, which are common in the observed records.

The lower right plot shows a scatter plot of observed and computed data and the "best-fit" linear regression line. The scatter plot is produced by first computing a cross-correlation between the observed data and model result to find the average model phase lag over the simulation period. The phase lag is removed from the computed time series before creating the scatter plot and performing the linear regression analysis. The regression plot includes error between the observed and model tidal signal, but also includes the variation in differences in the "Tidally Averaged Stage" shown in the lower left plot. To get a better measure of how the modeled and observed tidal signals match, a second regression analysis is performed by first subtracting out the tidally filtered values from the "dynamic" record. The slope of the linear regression line for the derived records should thus provide a better measure of the computed vs. observed tidal amplitude. The plots show the scatter plots and regression statistics for the computed and observed time series where tidal averages are not removed. The slope of the regression line for the time series with the tidal averages removed is presented in the plots and the tables as the "Tidal Amplitude Ratio".

Along with the regression and correlation statistics, the mean values are listed for the observed and computed flows/velocities/stages. The "observed" mean value is computed using the available data points of the calibration or verification period. The "computed" mean value computation excludes the times where the observed data are missing.

Error metrics are summarized in tabular format at the beginning of each series of plots.

Model Skill

Model skill is a measure of hydrodynamic model performance which captures the degree to which deviations in the observed data about the observed data average correlate with deviations in the modeled data about the observed data average (Willmott 1981). Values range from 0.0 (completely uncorrelated) to 1.0 (model exactly matches observed). This metric has the advantage of being used in many recent studies to evaluate model performance, which provides some context in evaluating how well a model performs. A review of these recent studies by MacWilliams et al. (2015) led the authors to propose skill metric threshold values for different parameters to separate model performance into "accurate," "acceptable," and "poor agreement" classes. Threshold values are shown in Table 1. These classes were adopted for this report after visually assessing their validity on model results presented herein. (I.e., we verified that what appeared to be an accurate model result fell into the "accurate" class and what looked like a poor model result fell into the "poor agreement" class.) It is important to note, however, that the model skill should always be considered alongside the error metrics, as it may not tell the whole story alone. As an example, a flow result may fall into the accurate category despite large net flow errors.

Model skill is calculated for each model parameter and at each location. From these values, an overall average skill for each model and parameter is computed.

Table 1 Skill metric threshold values for three categories of model accuracy (MacWilliams et al., 2015).

Model Accuracy Category	Flow	Water Surface Elevation	Velocity
Accurate	> 0.975	> 0.975	> 0.9
Acceptable	0.95–0.975	0.95–0.975	0.8–0.9
Poor agreement	< 0.95	< 0.95	< 0.8

Flow Results Comparison

In Figure 15 through Figure 68, computed flows from each model simulation are compared with observed data from USGS and Water Data Library (WDL) (plot titles indicate data source). Error metrics from these plots are summarized by location in Table 2. Plot locations are shown in Figure 14. For easy comparison among the models at each of these locations, tidally averaged flows from all three models are plotted with tidally averaged observed flows in Figure 72 through Figure 89.

Table 3 summarizes flow results for each model by error metric (percent difference from observed, lag, amplitude ratio and R^2) and model skill. Table cells are color coded for a quick assessment of goodness of fit with observed data, ranging from green for better fit to red for worse fit. The DSM2 and RMA models both compare favorably with observed data throughout much of the south Delta. The RMA model compares more favorably with observed data than DSM2 with regard to percent difference from observed and lag, while amplitude ratio and R^2 values for DSM2 are slightly better than for the RMA simulations. For flow, a skill accuracy greater than 0.975 is considered accurate, 0.95-0.975 is considered acceptable and a skill accuracy below 0.95 is considered poor agreement. The average flow model skill for DSM2 is 0.957. The RMA2 flow model skill is 0.976.

For the RMA model, the mean percent difference from observed is generally within about 10% or less at most locations analyzed (notable exceptions are discussed below) with an average absolute difference of 17%. DSM2 has a few more problem locations, but is within about 10% of observed at about half of the stations as well. The DSM2 average of absolute difference from observed is 50%.

DSM2 lags observed data at all stations, with an average lag of 28 minutes. The RMA model has a mix of positive and negative lags with an average of the absolute lag values of 12 minutes.

Amplitude ratios and slopes range from about 0.8 to 1.1 at most locations for both models, with averages of 0.94. R^2 values exceed 0.9 at most locations for both models and average about 0.94 for both models.

During low flow periods, DSM2 and RMA2 produce similar flow results at many locations in the south Delta. The differences between DSM2 and RMA2 San Joaquin River and Paradise Cut flows impact results in the south Delta, particularly during high flow periods, however the effects of other boundary condition differences appear to be small.

There tends to be more disparity among the models and between the model result and observed data during the high flow period in April 2011. One contributing factor could be that geometry in either model may not be as accurate at higher water levels, particularly where trapezoidal channel cross-sections are employed such as in the 1D sections of the RMA2 model grid, which represents most of the south Delta. Additionally, gauges may not be as accurate at high flows for some locations.

The largest differences between DSM2 and RMA2 occur at Old River at Franks Tract, Old River at Quimby, Turner Cut and Holland Cut.

At Old River at Franks Tract, model skill shows DSM2=poor agreement and RMA2=acceptable. The tidally averaged RMA2 result is about 200 to 700 cfs below observed throughout most of the simulation period. During March through October 2011 RMA2 is as much as 4000 cfs low compared with CDEC data and as much as 2000 cfs low compared with USGS data. DSM2 is generally 2000 – 3000 cfs lower than RMA2. The RMA2 tidal flows are slightly muted while the DSM2 tidal flows match well in the ebb tide direction but are quite low on the flood tide. On average, DSM2 flows are about 250% lower than observed flows, while RMA2 is about 85% lower at this location.

At Old River at Quimby, both models show accurate model skill. The RMA2 results are generally in good agreement with observed data with the exception of January through April 2011. The DSM2 tidally averaged result is generally 1000-4000 cfs lower than observed. On average, DSM2 flows are 305% lower than observed, while RMA2 is about 20% lower than observed at this location.

In Turner Cut, both models fall into the poor agreement category for model skill. The RMA2 tidally averaged flows are generally in good agreement with observed data, with the exception of April – May

2011. The tidal flows are dampened, particularly on the flood tide. On a tidally averaged basis, DSM2 misses the larger negative flows by as much as about 750 cfs. The tidal flows are out of phase with observed, but match the flood tide flow magnitudes more closely than RMA2. Ebb tide flows are too large. On average, DSM2 flows are 40% higher than observed, while RMA2 is about 10% lower than observed at this location.

At Holland Cut, tidally averaged DSM2 flows are generally less in the upstream direction than RMA2. Peak flows in April 2011 are slightly lower for DSM2 than for RMA2. DSM2 shows less tidal variation than RMA2. Observed data at this location are suspect. The characteristics of the flow data change rather suddenly in 2011. On average, DSM2 flows are 90% higher than observed, while RMA2 is 55% higher than observed at this location.

Both models have difficulties at Prisoner Point. DSM2 average flows are 150% high and RMA2 average flows are about 80% high. DSM2 lags observed by 44 minutes and RMA2 lags by 27 minutes. The model skill falls in in the poor agreement range for DSM2 and in the accurate range for RMA2. After July 2012, the flow data at this location are suspect, as there is a gap in the time series and then a large shift. If these data are invalid, they do unfavorably skew the error metrics.

Table 2 Flow error metrics summary by location.

	DSM2	RMA2 w DSM2 BC	RMA2	DSM2	RMA2 w DSM2 BC	RMA2	DSM2	RMA2 w DSM2 BC	RMA2
	SJR at Brandt Bridge			Old River at Quimby			SJR at Rough-n-Ready		
mean diff (cfs)	139	14	66	-1788	-136	-128	-37	-33	14
lag (minutes)	-24	2	2	-11	-15	-15	-29	-4	-4
ampRatio	1.013	1.047	1.045	0.900	1.023	1.023	0.831	1.095	1.095
slope	1.020	0.989	1.017	0.896	1.012	1.013	0.816	0.995	1.005
intercept	90.3	40.3	25.5	-1848.5	-129.0	-120.2	373.6	-22.7	3.0
R2	0.987	0.985	0.990	0.965	0.967	0.969	0.928	0.913	0.921
	SJR at Prisoners Point			Middle River at Middle River			SJR at Garwood		
mean diff (cfs)	3308	1826	1864	182	68	79	110	-10	42
lag (minutes)	-44	-27	-27	-39	-11	-11	-34	-12	-11
ampRatio	0.808	0.970	0.970	0.815	0.878	0.880	0.950	1.097	1.096
slope	0.806	0.967	0.967	0.821	0.887	0.888	0.976	0.988	1.012
intercept	2880.3	1752.8	1791.6	-331.9	-258.1	-241.5	168.1	19.3	12.8
R2	0.975	0.972	0.973	0.960	0.967	0.968	0.973	0.968	0.978
	SJR at Jersey Pt			Turner Cut at Holt			Old River at Head		
mean diff (cfs)	-236	-211	-13	456	-97	-100	-65	49	115
lag (minutes)	-27	-14	-14	-96	-7	-7	-16	14	14
ampRatio	0.879	0.961	0.961	1.103	0.568	0.569	0.939	0.862	0.858
slope	0.878	0.959	0.960	1.068	0.581	0.581	0.954	0.999	1.050
intercept	511.5	37.5	232.0	530.9	-556.2	-558.4	68.2	51.8	-30.6
R2	0.987	0.988	0.989	0.907	0.816	0.816	0.956	0.960	0.977
	Old River at Franks Tr			Old River near DMC			SJR nr Lathrop		
mean diff (cfs)	-3071	-1046	-1070	150	-25	-24	321	201	253
lag (minutes)	-23	7	7	-30	7	7	-20	4	4
ampRatio	1.199	0.776	0.776	0.875	0.892	0.894	0.914	0.970	0.967
slope	1.196	0.777	0.778	0.964	0.929	0.930	1.063	1.028	1.059
intercept	-2827.2	-1323.9	-1346.7	173.0	19.8	19.9	183.0	139.3	122.2
R2	0.935	0.915	0.916	0.894	0.901	0.900	0.954	0.955	0.959
	Holland Cut			Old River at Tracy			Old R at Clifton Court Intake		
mean diff (cfs)	1312	794	803	50	-62	-60	-177	-5	5
lag (minutes)	-28	-21	-20	-23	23	23	-11	9	9
ampRatio	0.670	1.007	1.007	1.247	0.858	0.861	0.879	0.879	0.879
slope	0.671	1.005	1.005	1.393	1.097	1.098	0.944	0.970	0.971
intercept	837.2	800.9	810.3	-135.6	-107.8	-106.3	-196.9	-15.7	-4.7
R2	0.974	0.973	0.974	0.916	0.879	0.876	0.858	0.859	0.859
	Old River at Bacon			Old River at Hwy 4			West Canal at Clifton Ct Intake		
mean diff (cfs)	-100	159	167	-103	-71	-63	-335	38	47
lag (minutes)	-17	-18	-17	-25	-9	-9	-4	12	12
ampRatio	0.934	1.058	1.059	0.984	1.035	1.036	0.973	0.918	0.919
slope	0.944	1.058	1.060	1.004	1.044	1.047	0.996	0.949	0.952
intercept	-219.0	281.9	293.2	-92.1	67.8	83.8	-350.8	-156.4	-138.8
R2	0.973	0.977	0.979	0.922	0.928	0.930	0.873	0.882	0.883

Table 3 Summary of flow error metrics and model skill with shading ranging from green for better fit to red for worse fit.

	% diff from observed			lag (minutes)			ampRatio			R2			Model Skill		
Station	DSM2	RMA2 w DSM2 BC	RMA2	DSM2	RMA2 w DSM2 BC	RMA2	DSM2	RMA2 w DSM2 BC	RMA2	DSM2	RMA2 w DSM2 BC	RMA2	DSM2	RMA2 w DSM2 BC	RMA2
SJR at Brandt Bridge	5.9%	0.6%	2.8%	-24	2	2	1.013	1.047	1.045	0.987	0.985	0.990	0.994	0.996	0.997
SJR at Prisoners Point	149.9%	82.7%	84.4%	-44	-27	-27	0.808	0.970	0.970	0.975	0.972	0.973	0.945	0.978	0.979
SJR at Jersey Pt	-3.9%	3.4%	0.2%	-27	-14	-14	0.879	0.961	0.961	0.987	0.988	0.989	0.980	0.993	0.994
Old River at Franks Tr	-246.7%	-84.0%	-85.9%	-23	7	7	1.199	0.776	0.776	0.935	0.915	0.916	0.939	0.962	0.962
Holland Cut	90.9%	55.0%	55.6%	-28	-21	-20	0.670	1.007	1.007	0.974	0.973	0.974	0.938	0.983	0.984
Old River at Bacon	-4.8%	7.6%	8.0%	-17	-18	-17	0.934	1.058	1.059	0.973	0.977	0.979	0.987	0.987	0.988
Old River at Quimby	-305.5%	-23.3%	-21.8%	-11	-15	-15	0.900	1.023	1.023	0.965	0.967	0.969	0.979	0.987	0.987
Middle River at Middle River	-6.3%	2.4%	2.8%	-39	-11	-11	0.815	0.878	0.880	0.960	0.967	0.968	0.952	0.987	0.987
Turner Cut at Holt	41.6%	-8.8%	-9.1%	-90	-7	-7	1.103	0.568	0.569	0.907	0.816	0.816	0.811	0.900	0.901
Old River near DMC	23.7%	4.0%	3.8%	-30	7	7	0.875	0.892	0.894	0.894	0.901	0.900	0.953	0.973	0.973
Old River at Tracy	10.6%	13.2%	12.7%	-23	23	23	1.247	0.858	0.861	0.916	0.879	0.876	0.940	0.957	0.956
Old River at Hwy 4	-3.3%	-2.3%	-2.0%	-25	-9	-9	0.984	1.035	1.036	0.922	0.928	0.930	0.970	0.978	0.979
SJR at Rough-n-Ready	-1.6%	1.5%	-0.6%	-29	-4	-4	0.831	1.095	1.095	0.928	0.913	0.921	0.956	0.976	0.978
SJR at Garwood	4.6%	0.4%	-1.8%	-34	-12	-11	0.950	1.097	1.096	0.973	0.968	0.978	0.985	0.991	0.993
Old River at Head	-2.3%	-1.7%	-4.0%	-16	14	14	0.939	0.862	0.858	0.956	0.960	0.977	0.988	0.990	0.993
SJR nr Lathrop	14.6%	-9.1%	-11.5%	-20	4	4	0.914	0.970	0.967	0.954	0.955	0.959	0.982	0.986	0.986
Old R at Clifton Court Intake	-50.1%	-1.4%	1.5%	-11	9	9	0.879	0.879	0.879	0.858	0.859	0.859	0.958	0.960	0.960
West Canal at Clifton Ct Intake	-8.7%	1.0%	1.2%	-4	12	12	0.973	0.918	0.919	0.873	0.882	0.883	0.964	0.967	0.967
Average of absolute values	54.2%	16.8%	17.2%	28	12	12	0.940	0.939	0.939	0.941	0.934	0.937	0.957	0.975	0.976

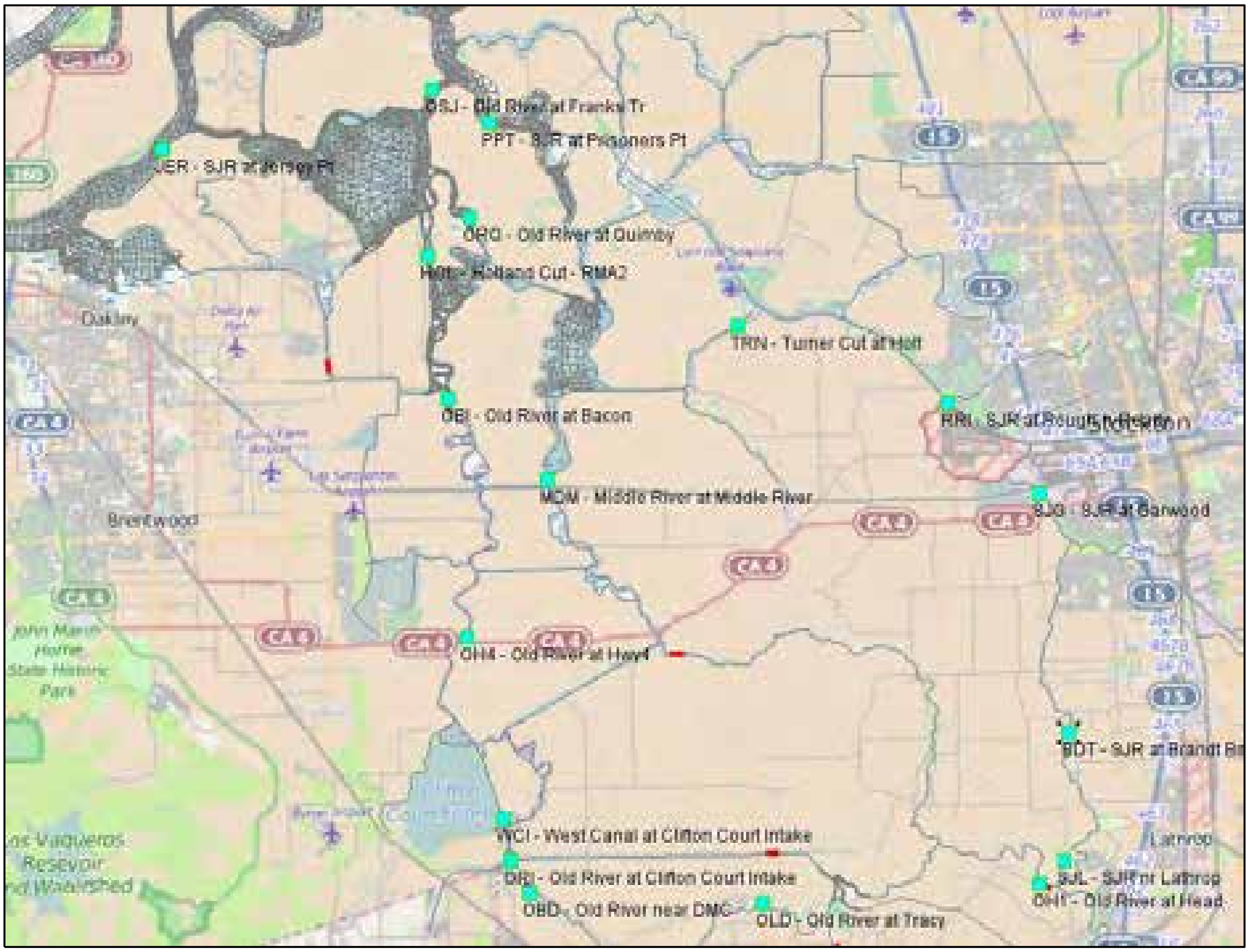


Figure 14 Flow comparison plot locations.

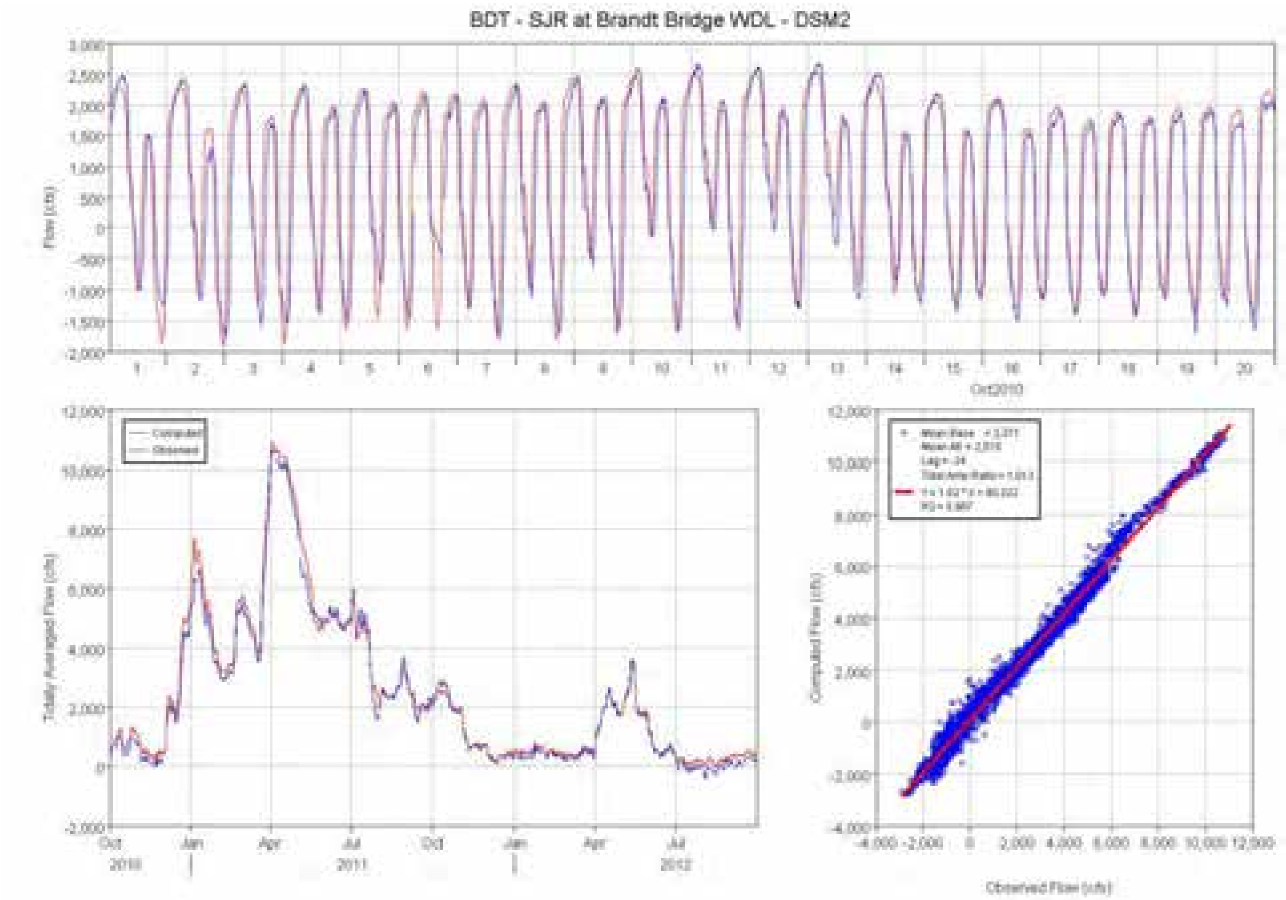


Figure 15 Computed (DSM2) and observed flow comparison plots for San Joaquin River at Brandt Bridge.

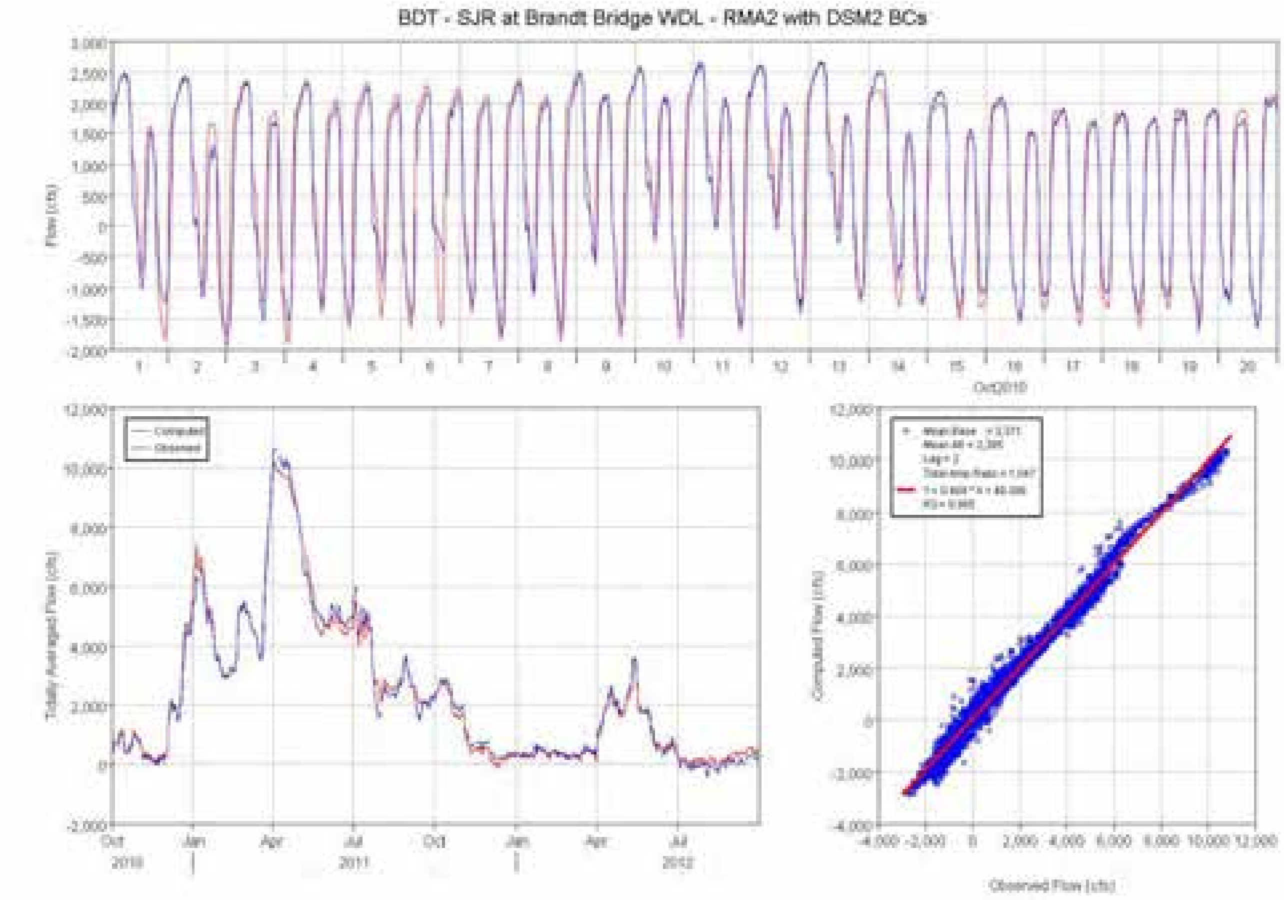


Figure 16 Computed (RMA2 with DSM2 BCs) and observed flow comparison plots for San Joaquin River at Brandt Bridge.

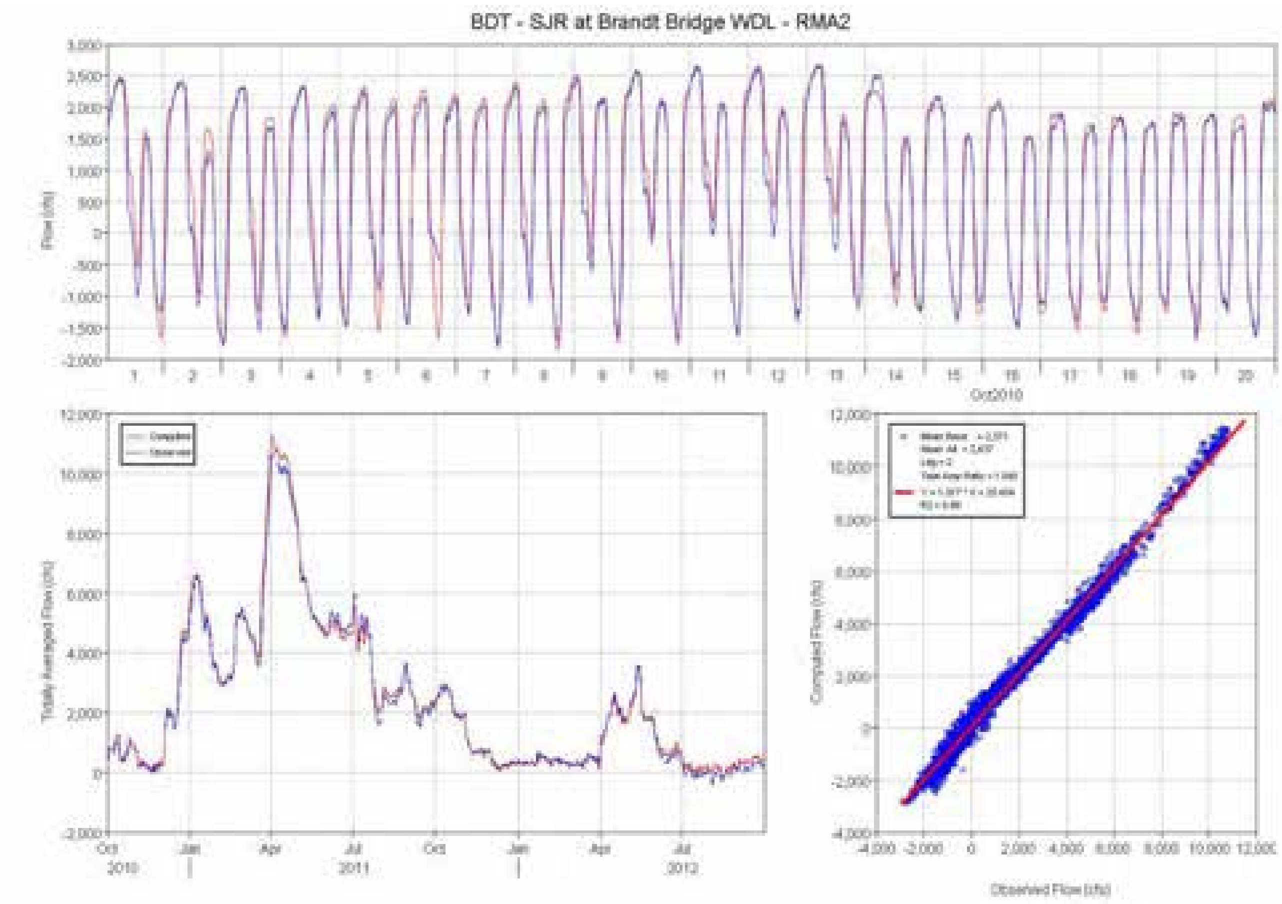


Figure 17 Computed (RMA2) and observed flow comparison plots for San Joaquin River at Brandt Bridge.

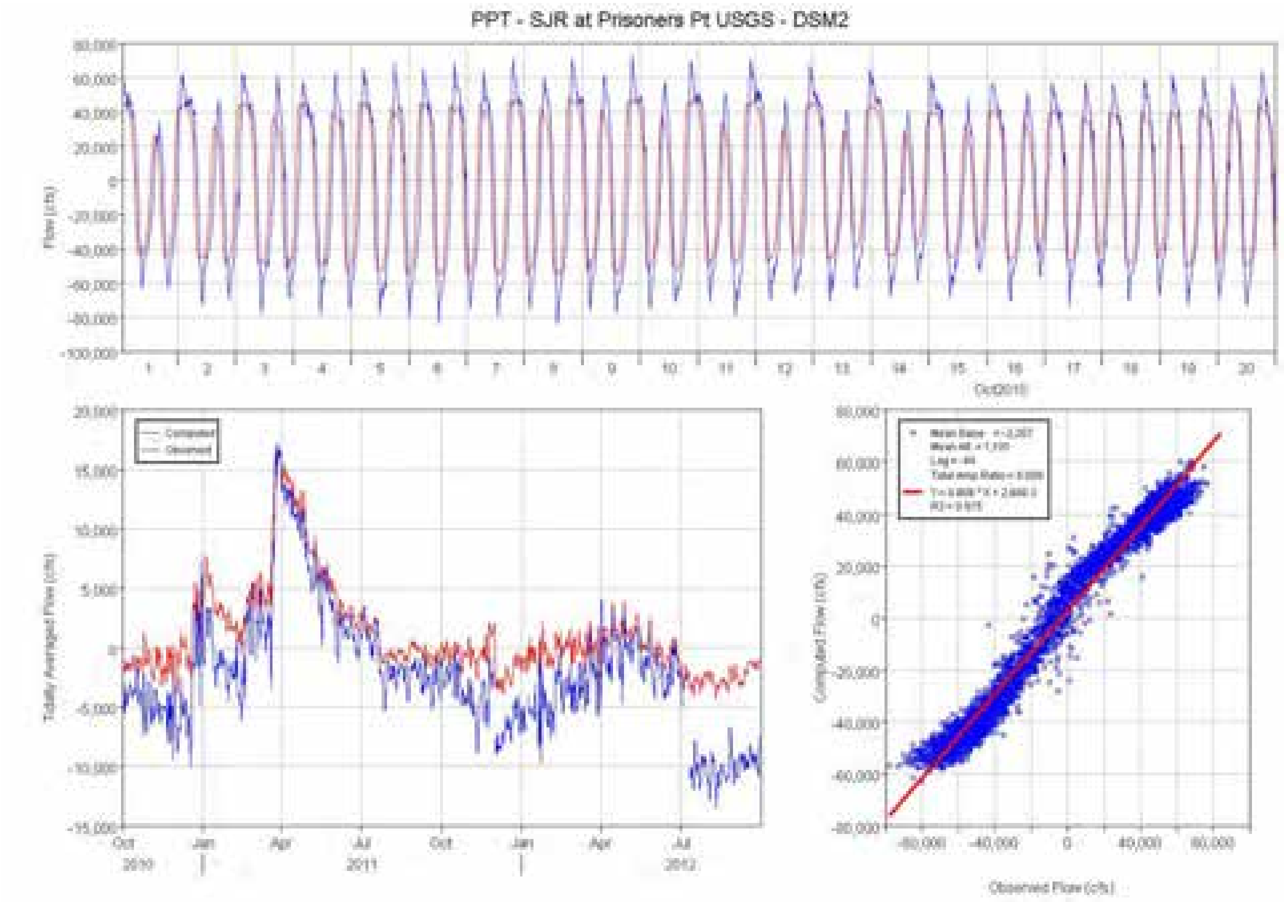


Figure 18 Computed (DSM2) and observed flow comparison plots for Prisoners Point.

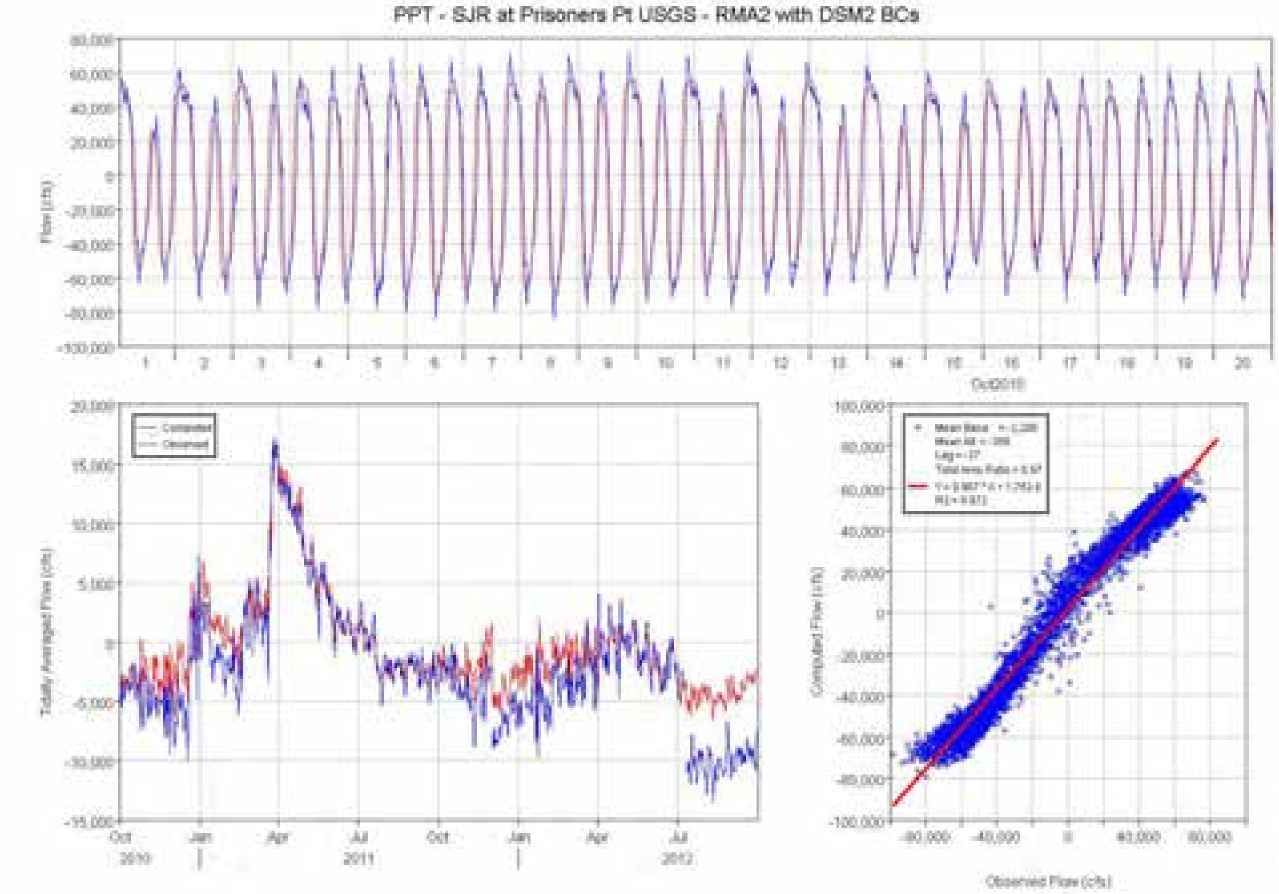


Figure 19 Computed (RMA2 with DSM2 BCs) and observed flow comparison plots for Prisoners Point.

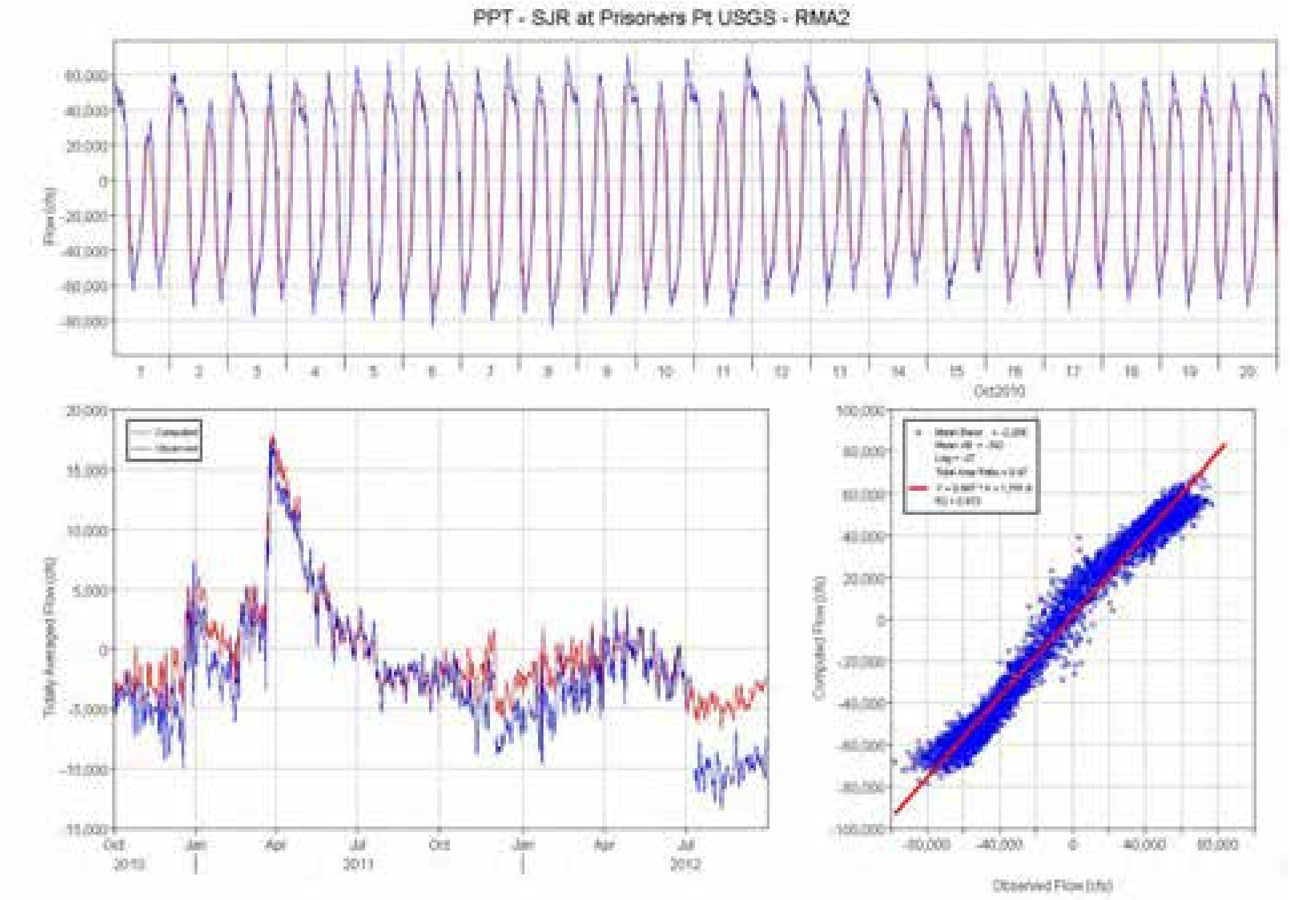


Figure 20 Computed (RMA2) and observed flow comparison plots for Prisoners Point.

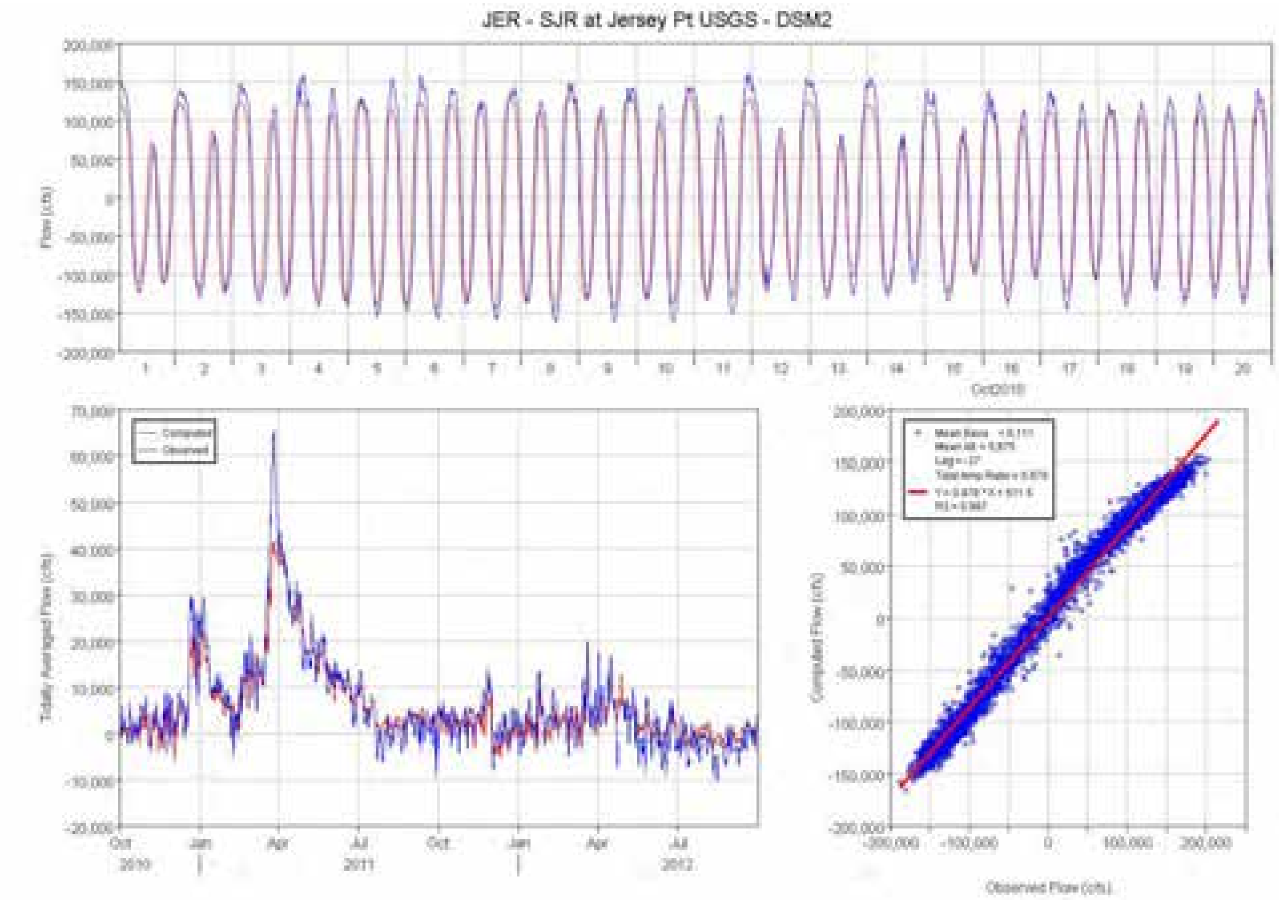


Figure 21 Computed (DSM2) and observed flow comparison plots for Jersey Point.

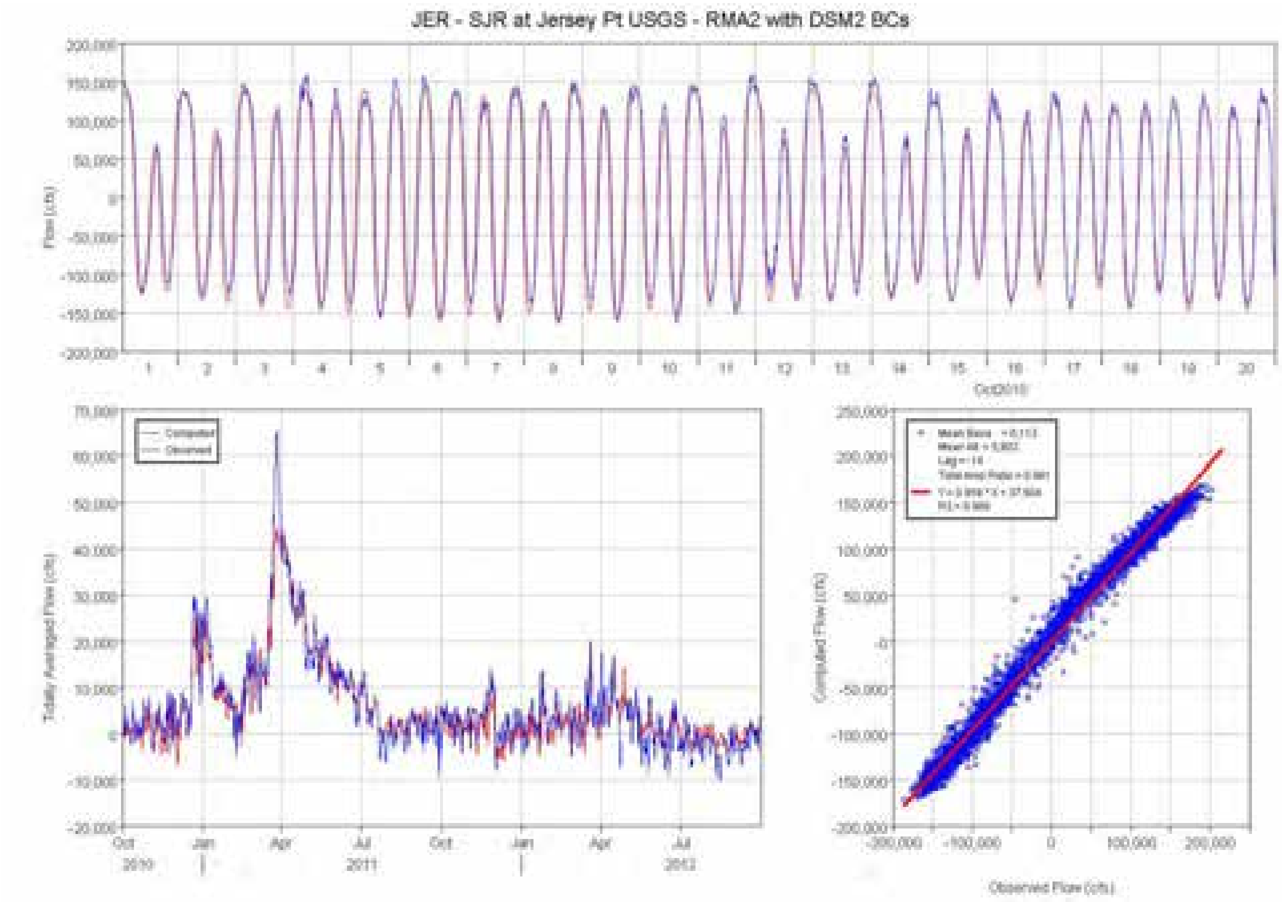


Figure 22 Computed (RMA2 with DSM2 BCs) and observed flow comparison plots for Jersey Point.

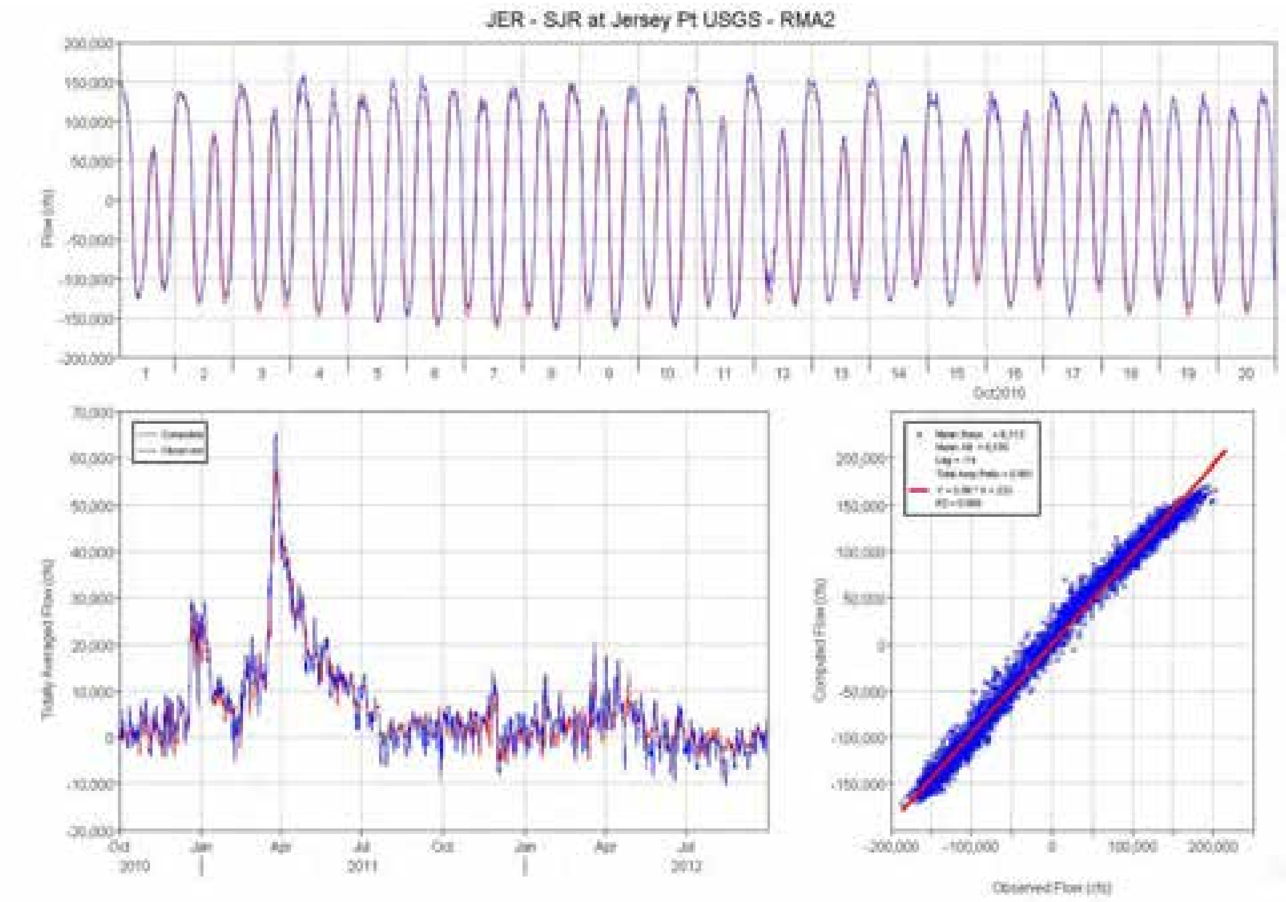


Figure 23 Computed (RMA2) and observed flow comparison plots for Jersey Point (USGS observed data).

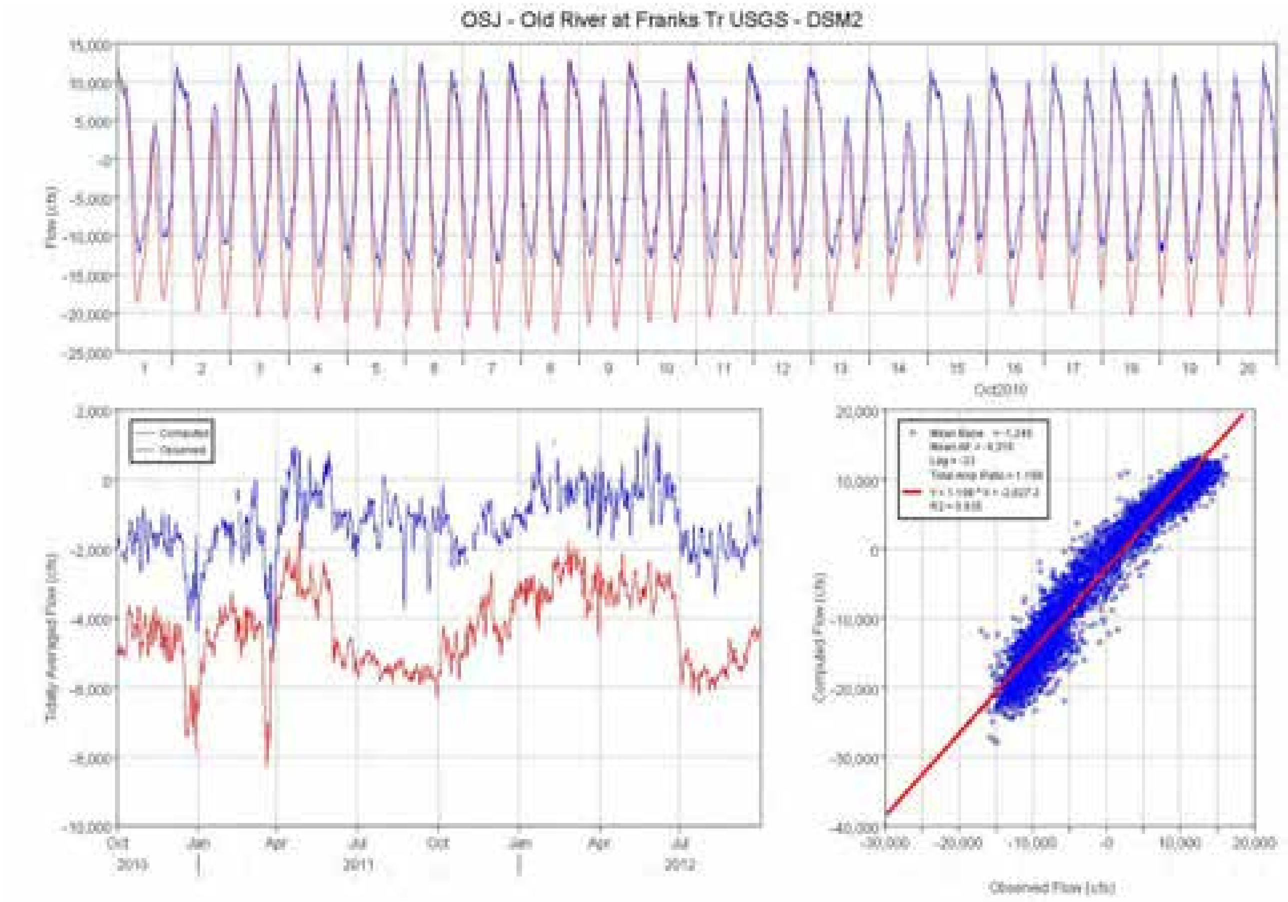


Figure 24 Computed (DSM2) and observed flow comparison plots for Old River at Franks Tract.

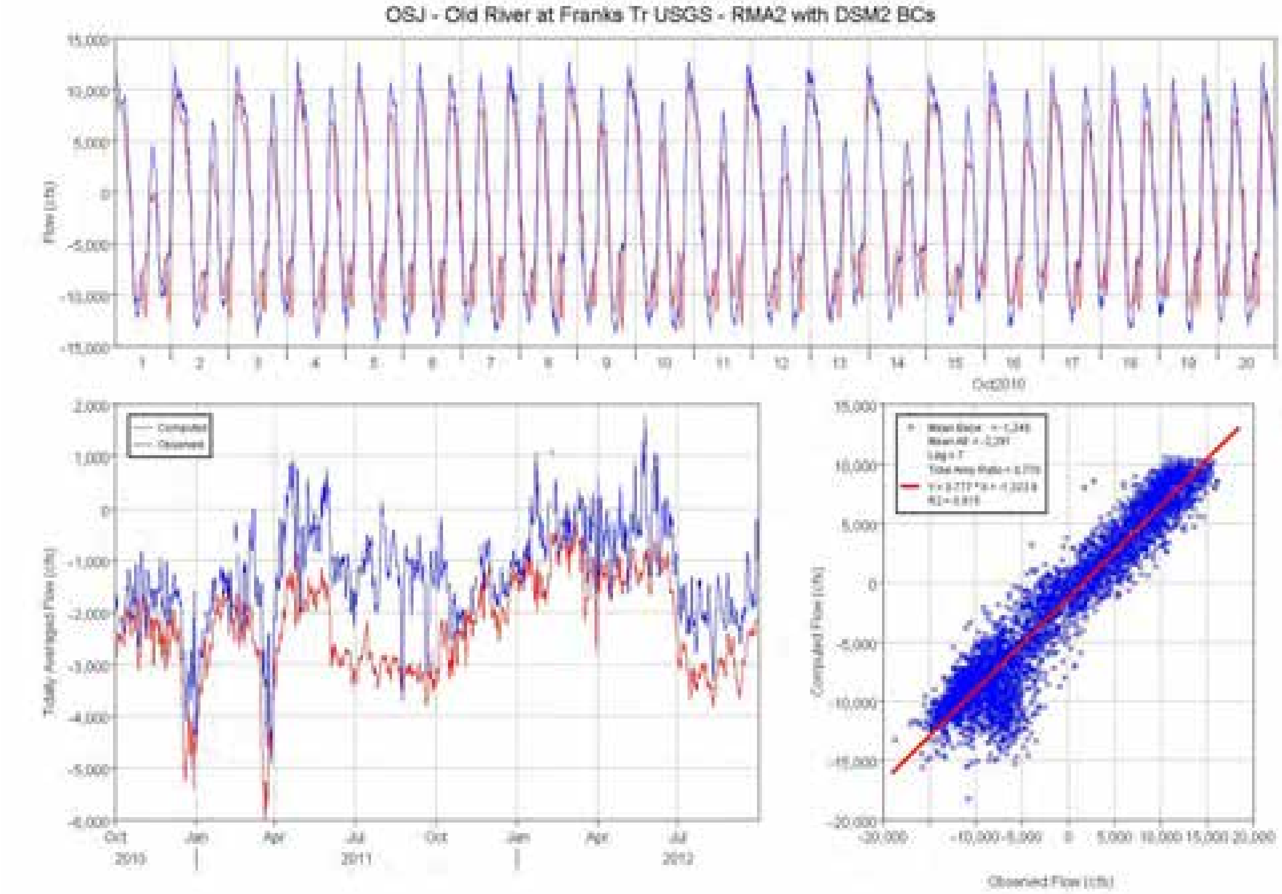


Figure 25 Computed (RMA2 with DSM2 BCs) and observed flow comparison plots for Old River at Franks Tract.

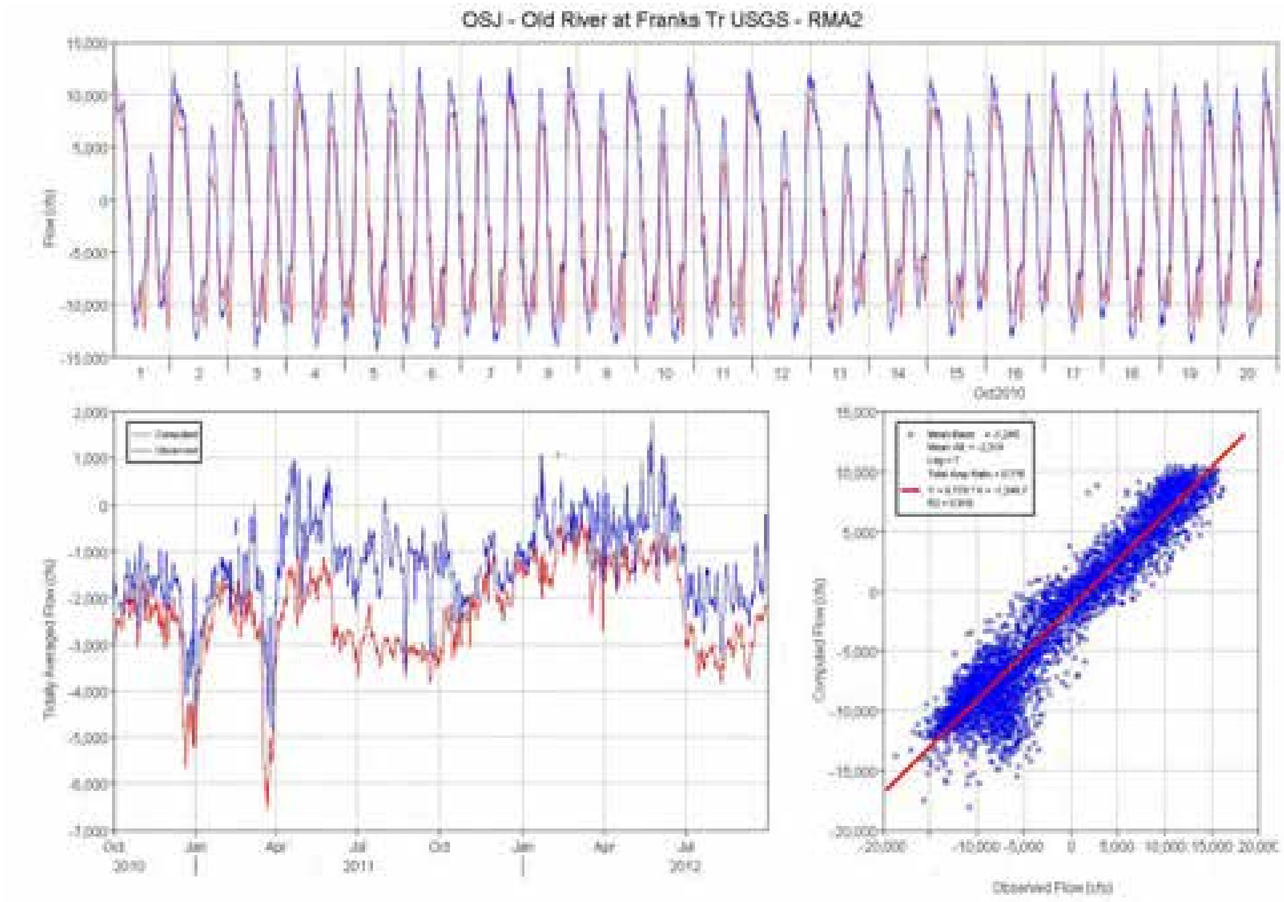


Figure 26 Computed (RMA2) and observed flow comparison plots for Old River at Franks Tract.

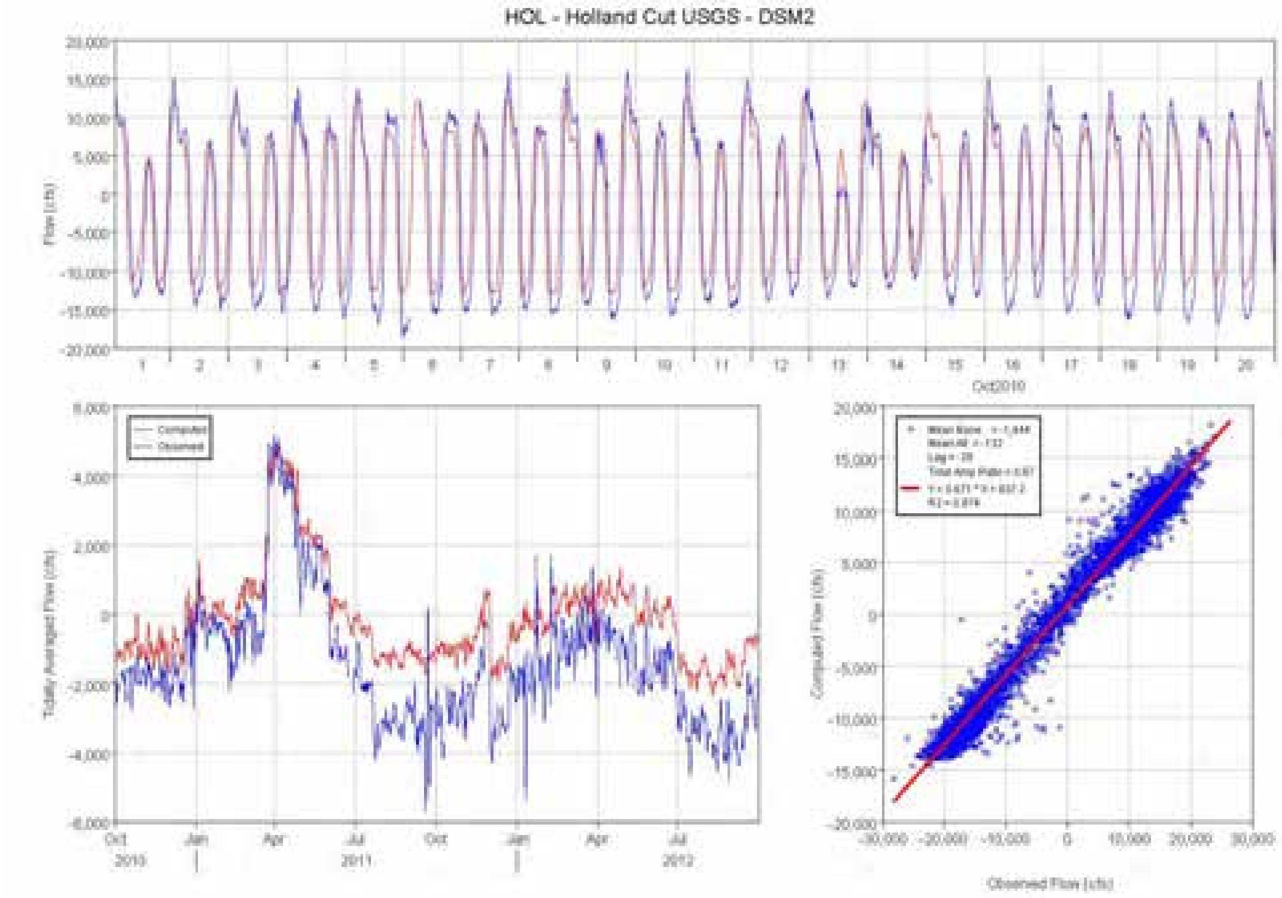


Figure 27 Computed (DSM2) and observed flow comparison plots for Holland Cut.

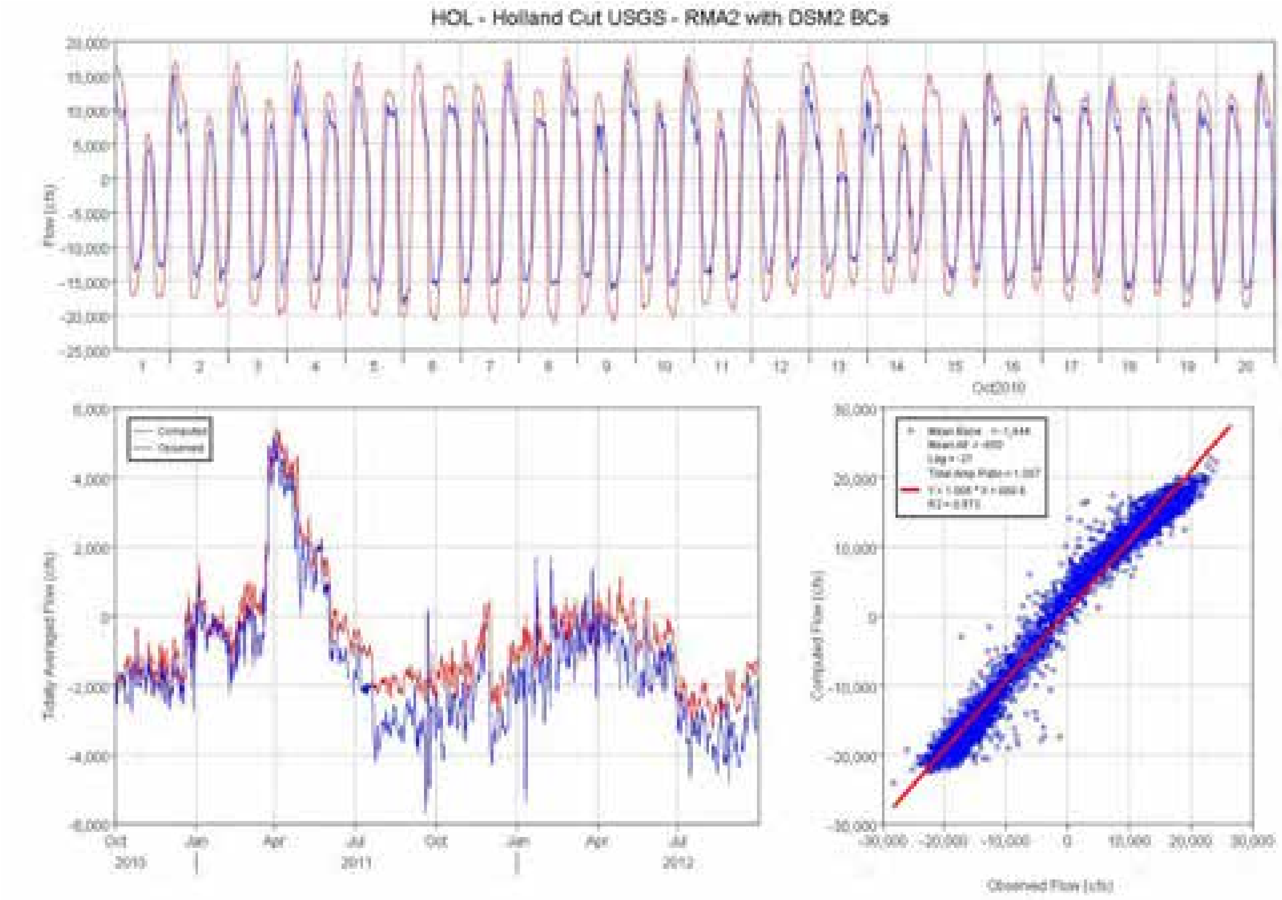


Figure 28 Computed (RMA2 with DSM2 BCs) and observed flow comparison plots for Holland Cut.

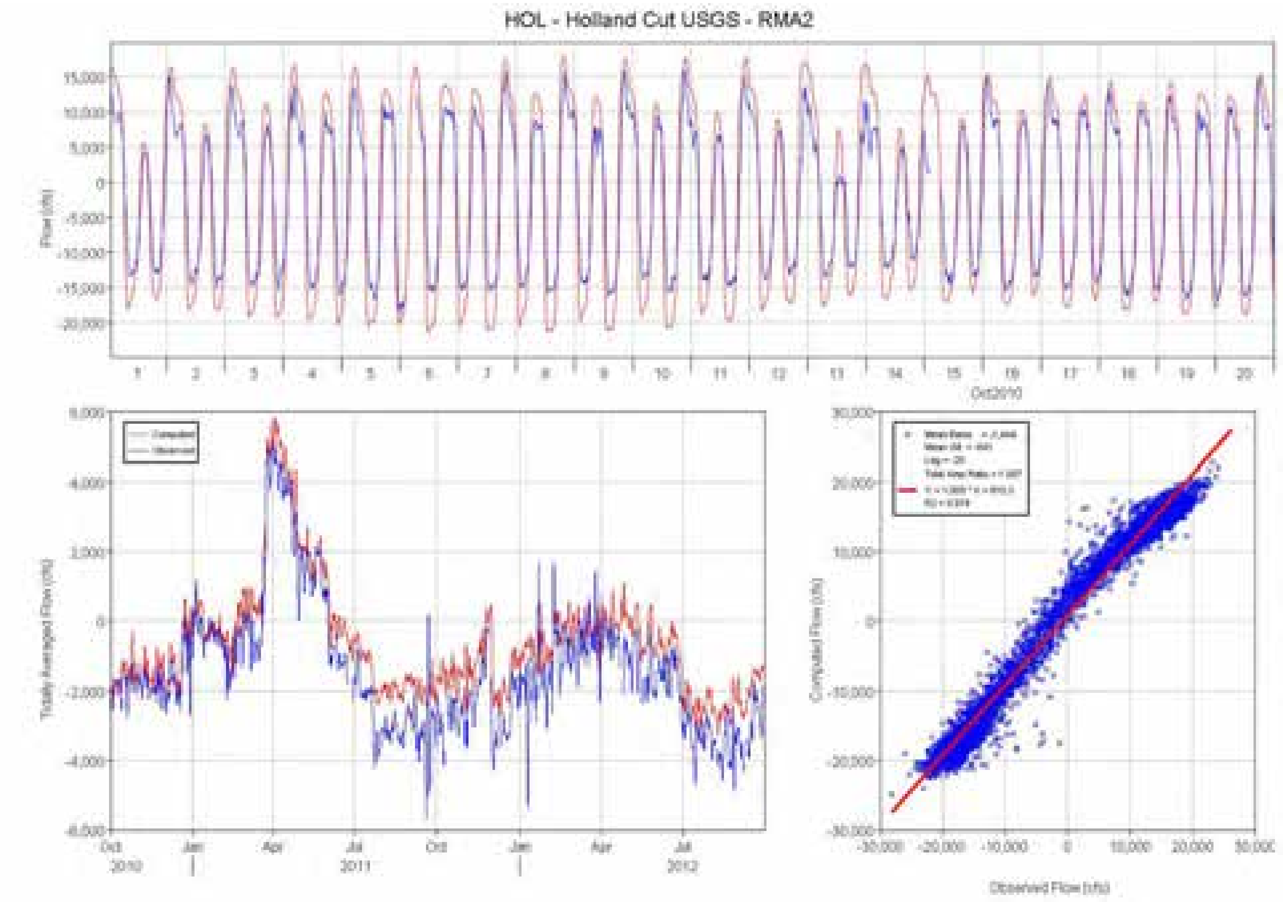


Figure 29 Computed (RMA2) and observed flow comparison plots for Holland Cut.

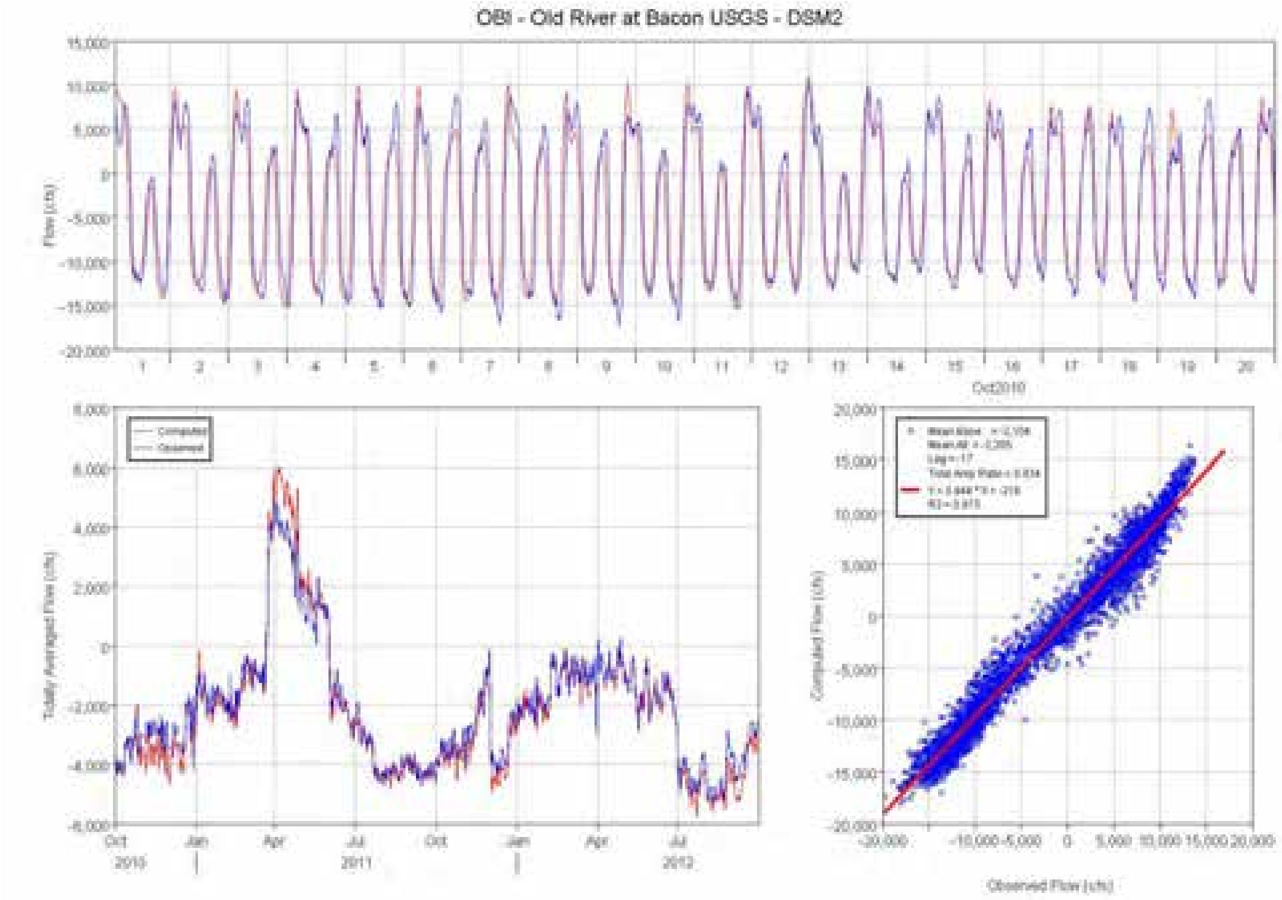


Figure 30 Computed (DSM2) and observed flow comparison plots for Old River at Bacon.

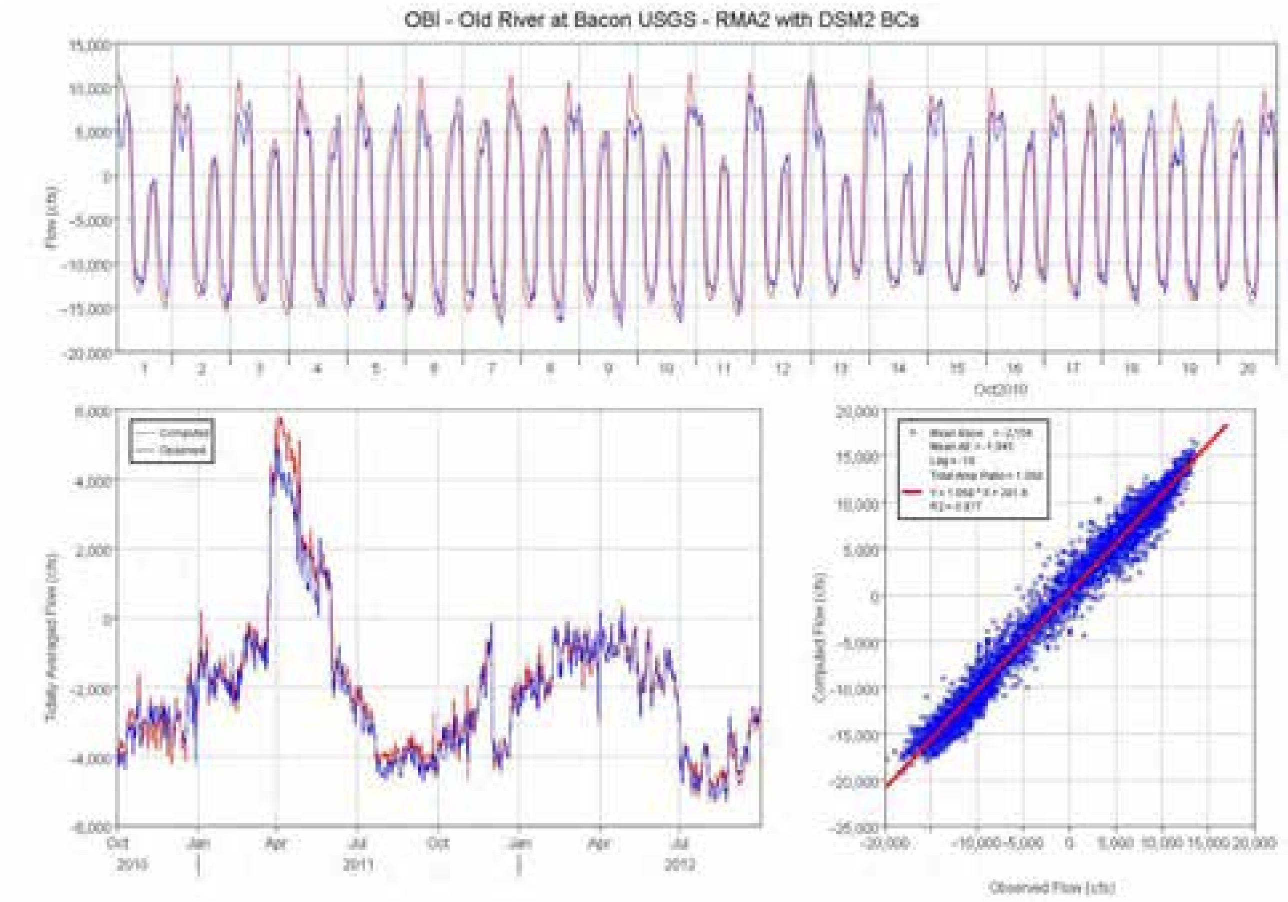


Figure 31 Computed (RMA2 with DSM2 BCs) and observed flow comparison plots for Old River at Bacon.

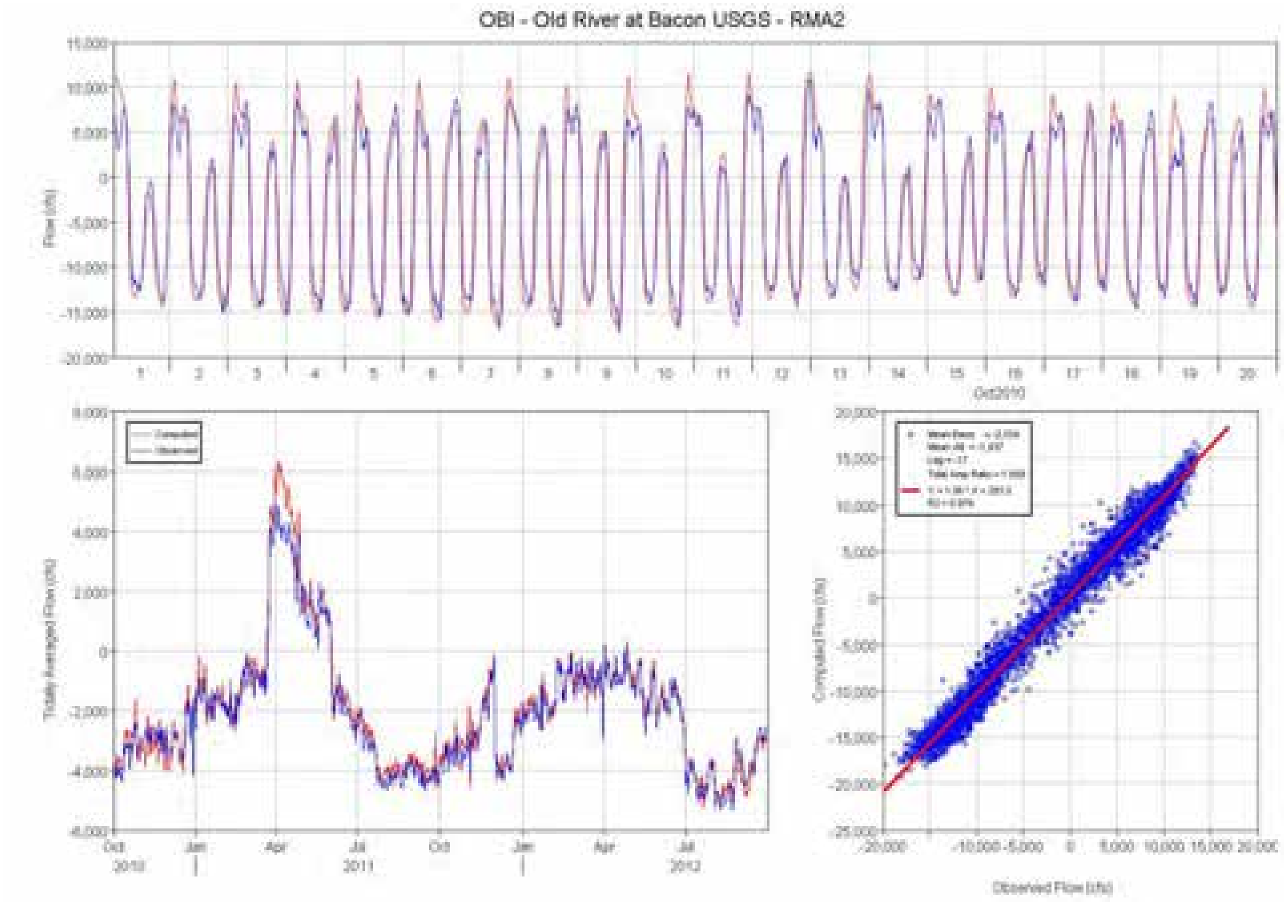


Figure 32 Computed (RMA2) and observed flow comparison plots for Old River at Bacon.

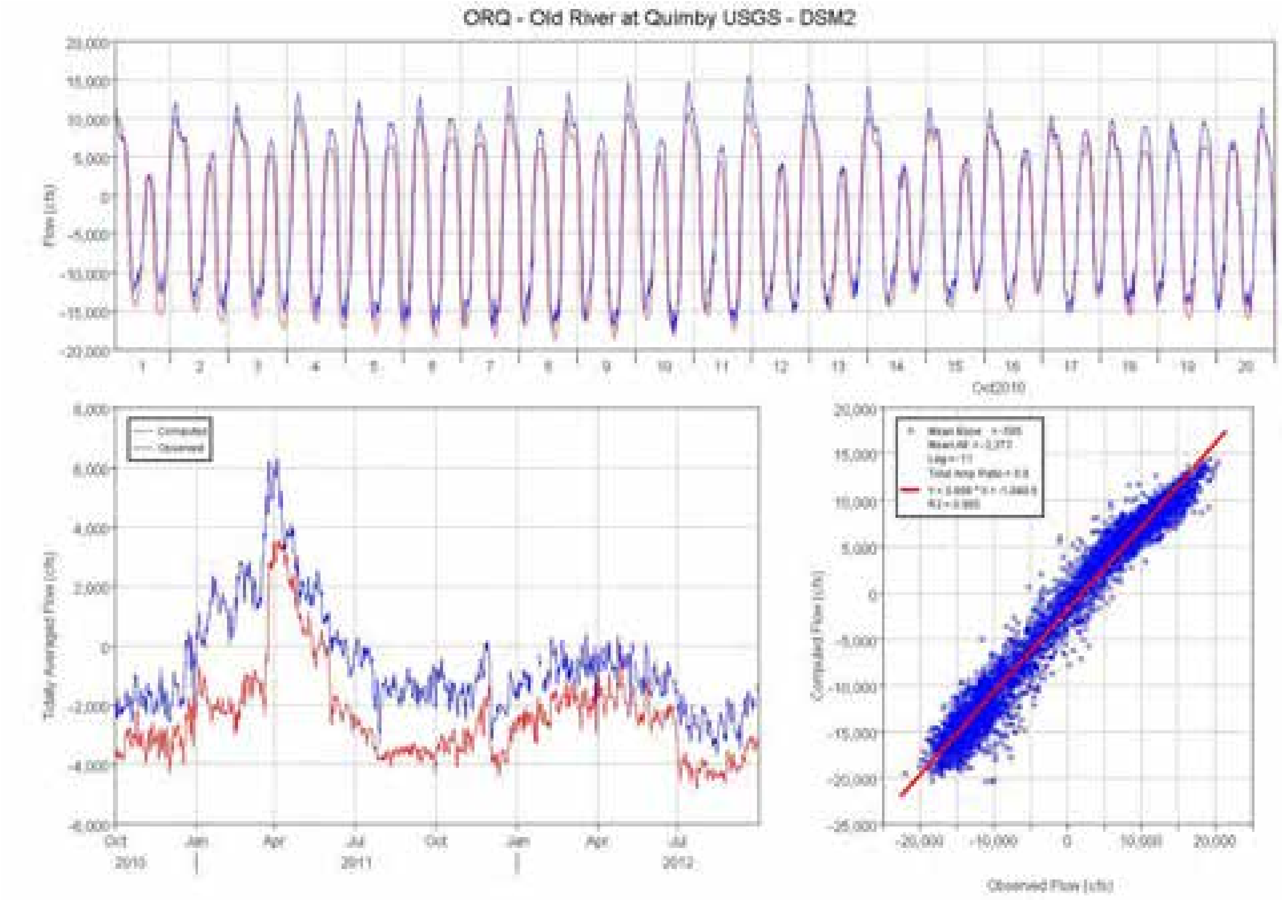


Figure 33 Computed (DSM2) and observed flow comparison plots for Old River at Quimby.

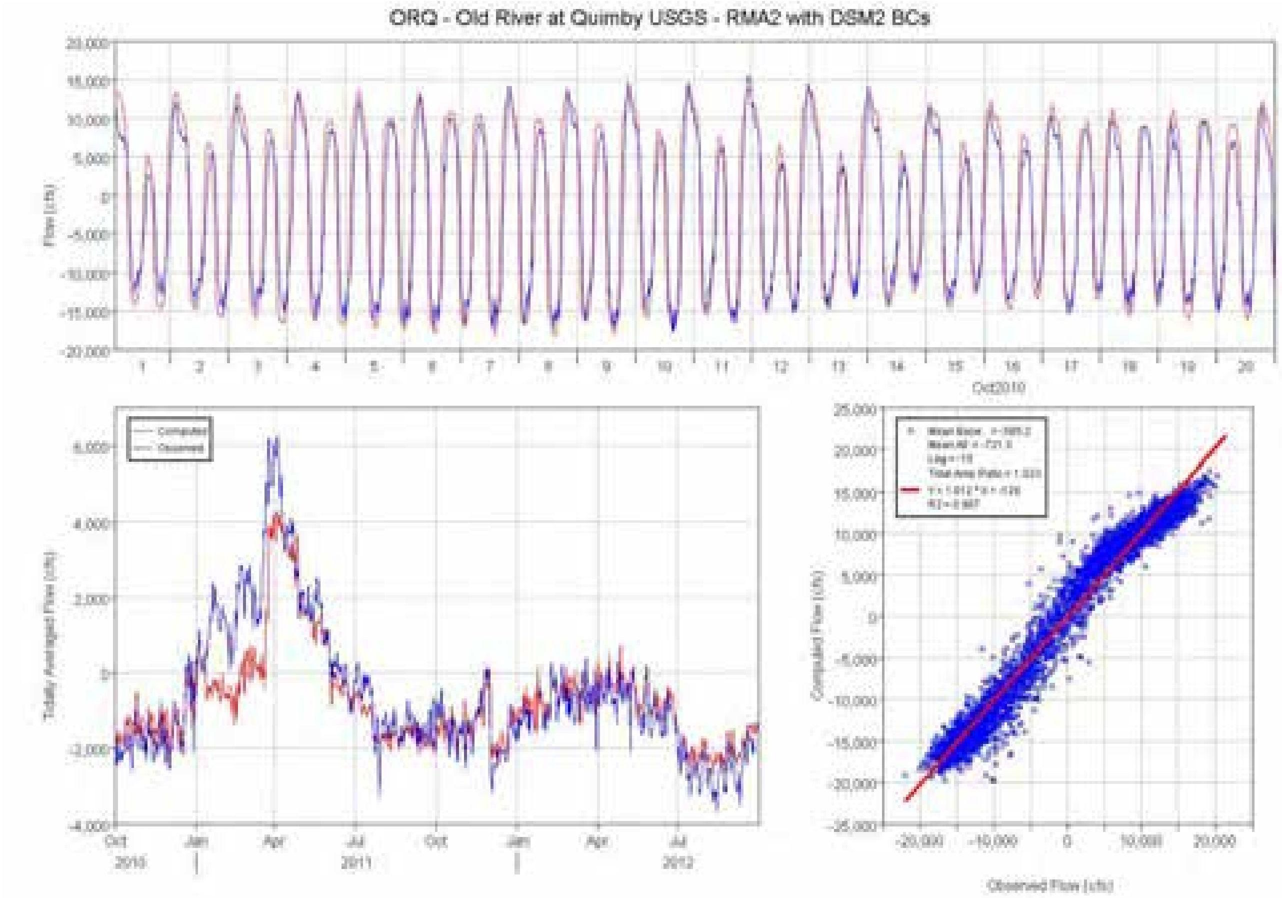


Figure 34 Computed (RMA2 with DSM2 BCs) and observed flow comparison plots for Old River at Quimby.

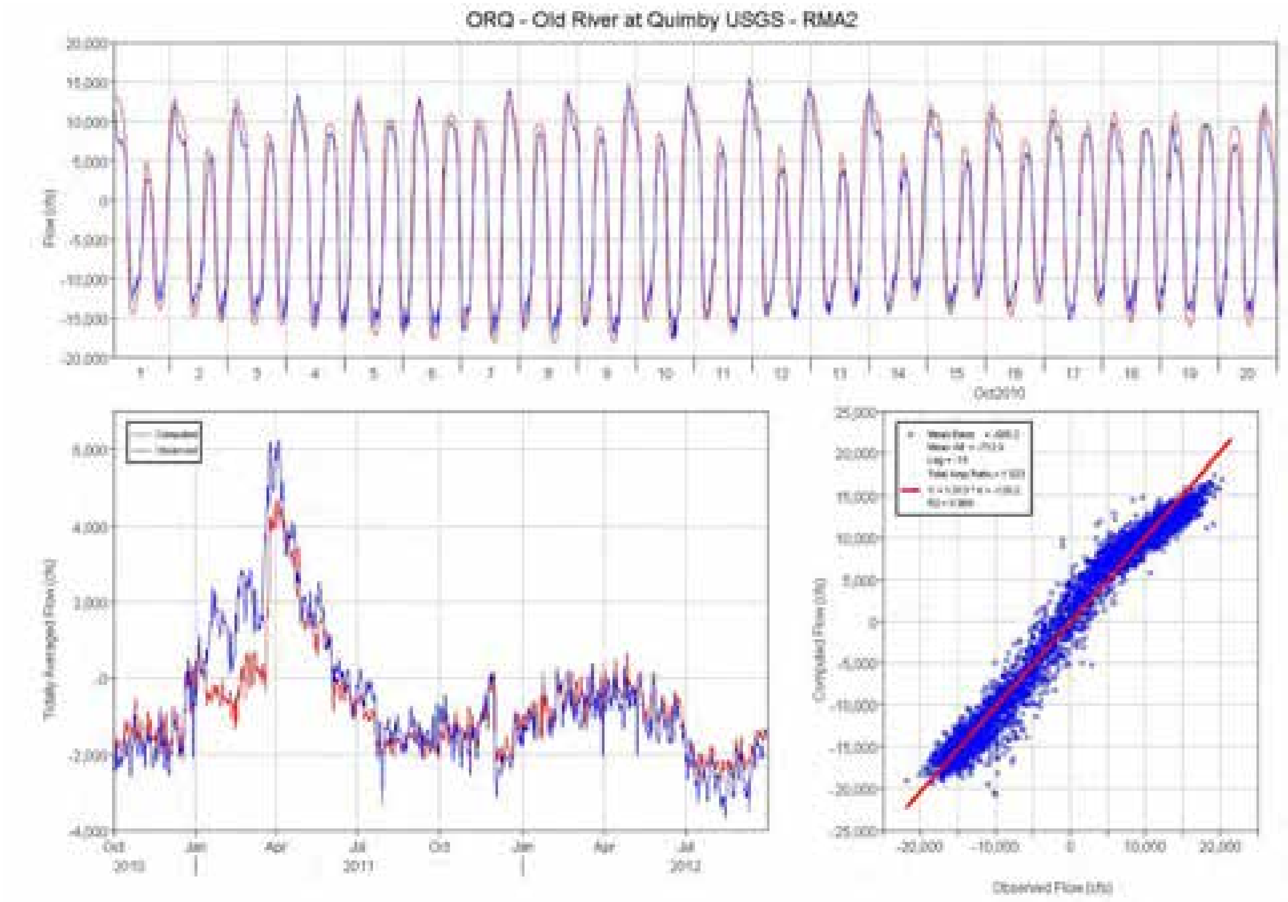


Figure 35 Computed (RMA2) and observed flow comparison plots for Old River at Quimby.

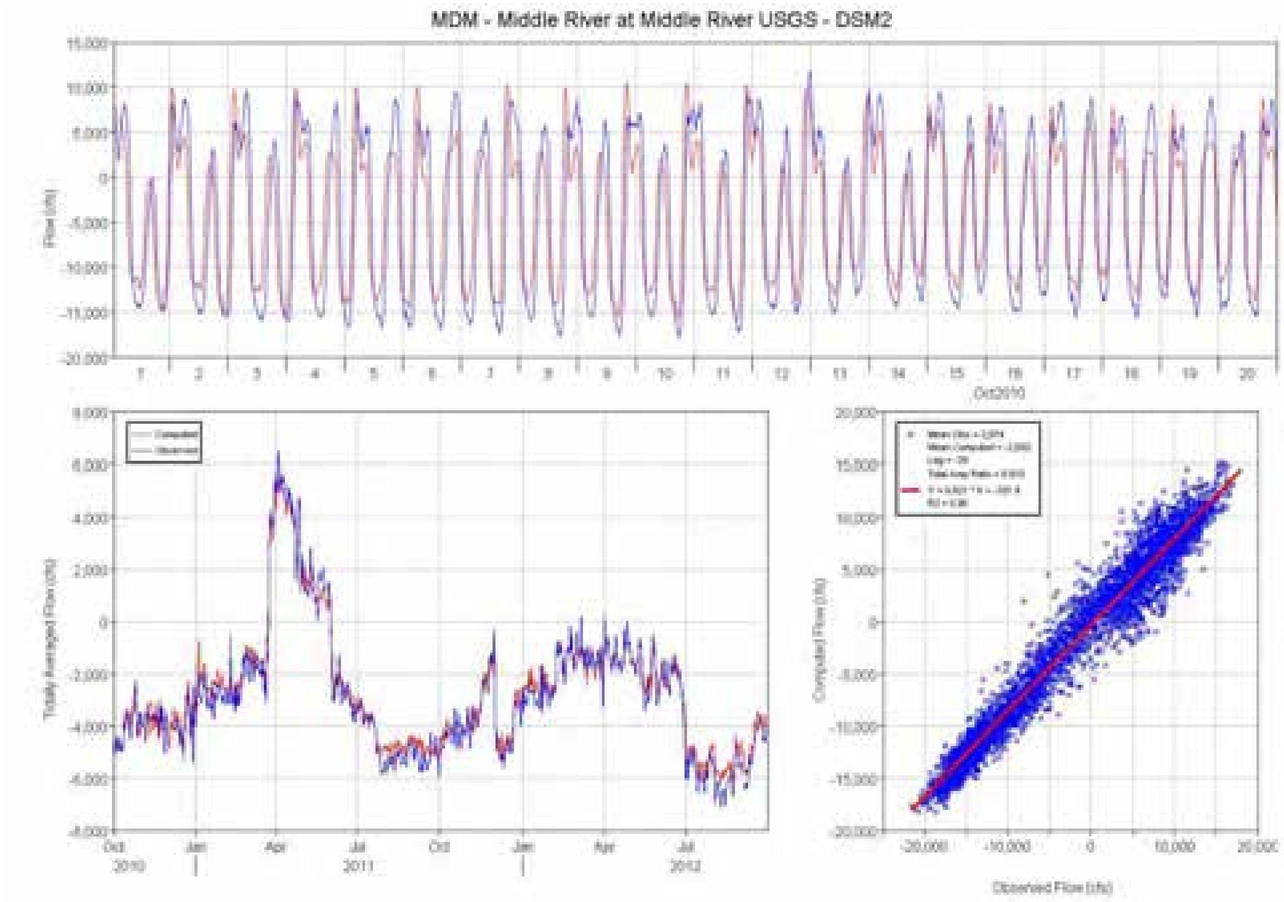


Figure 36 Computed (DSM2) and observed flow comparison plots for Middle River at Middle River.

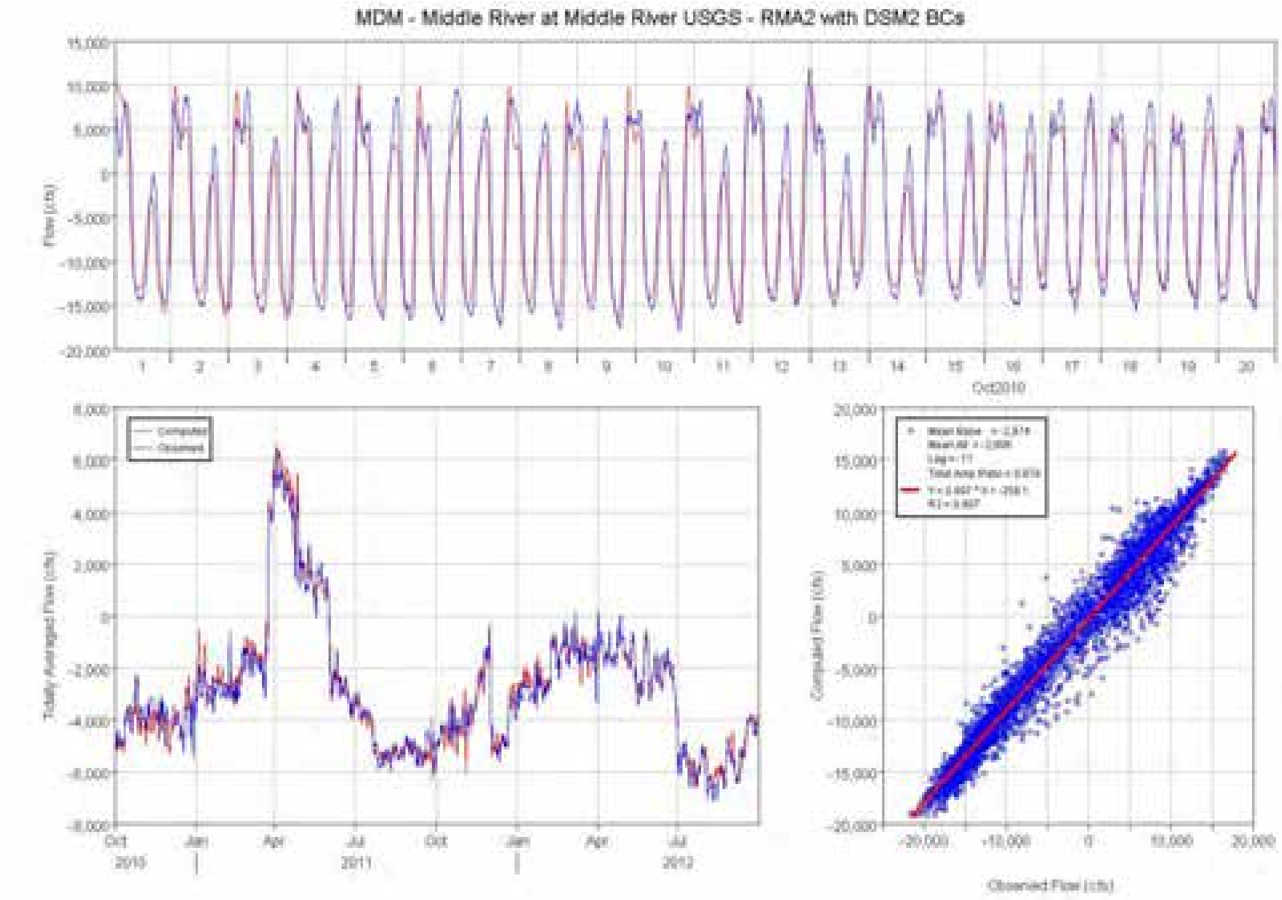


Figure 37 Computed (RMA2 with DSM2 BCs) and observed flow comparison plots for Middle River at Middle River.

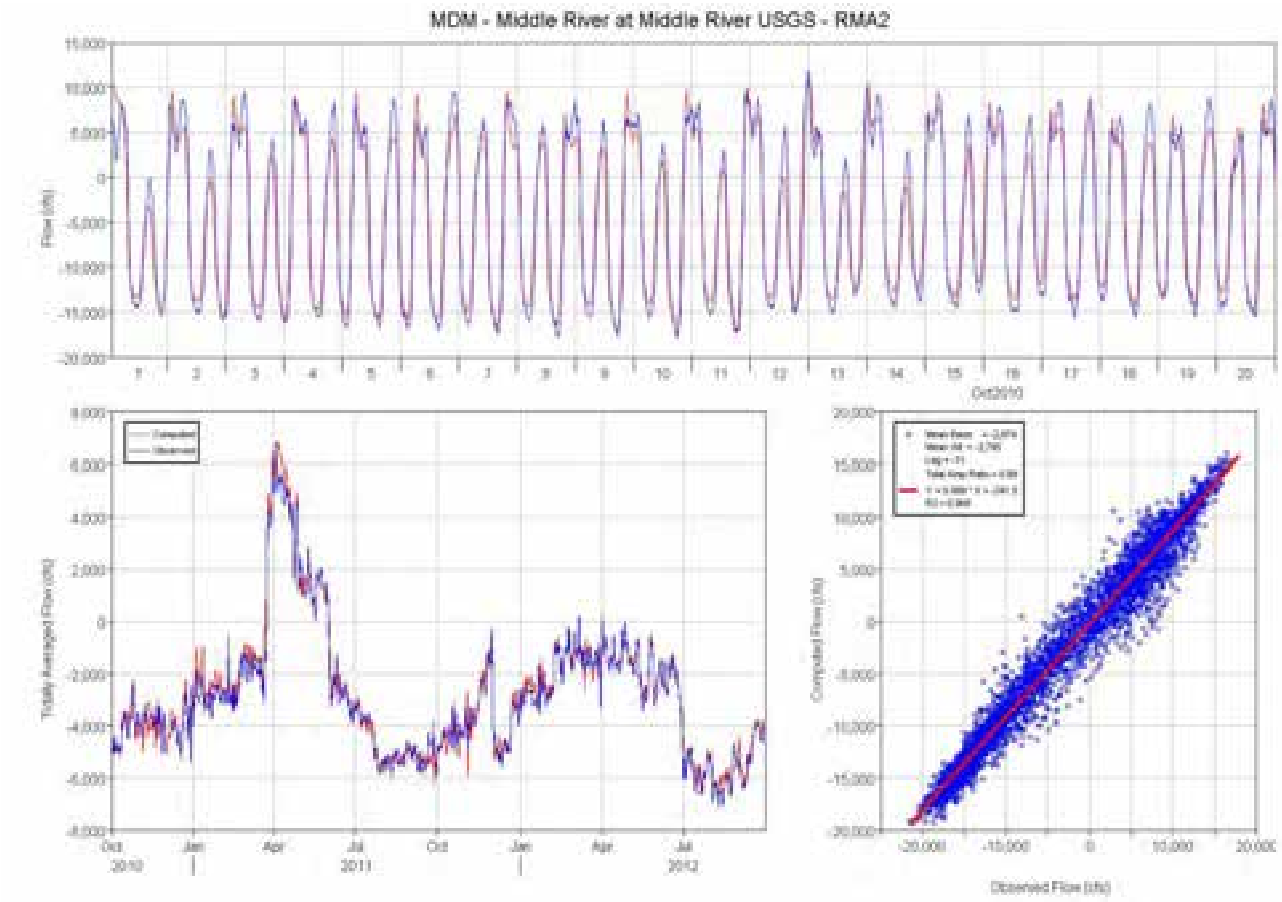


Figure 38 Computed (RMA2) and observed flow comparison plots for Middle River at Middle River.

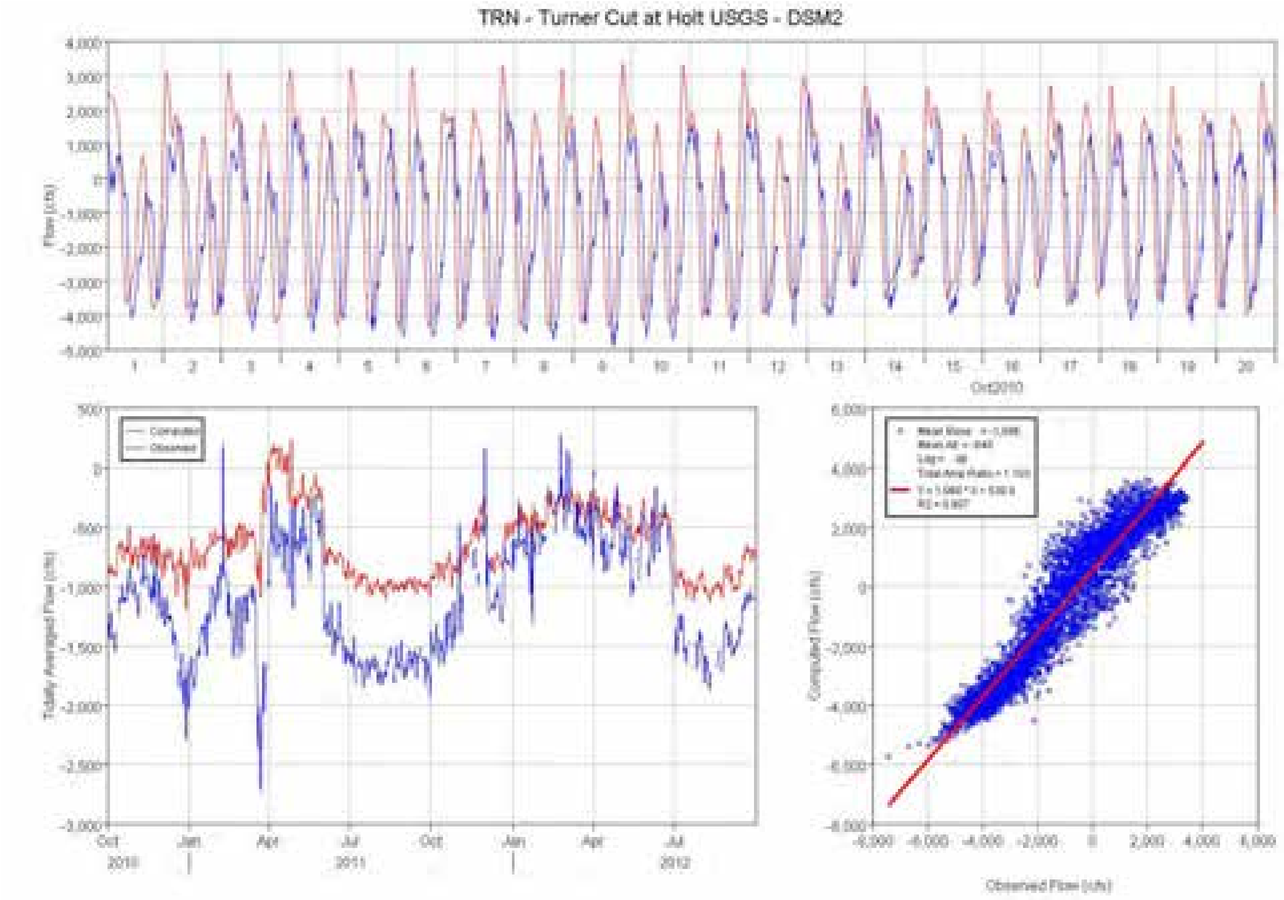


Figure 39 Computed (DSM2) and observed flow comparison plots for Turner Cut at Holt.

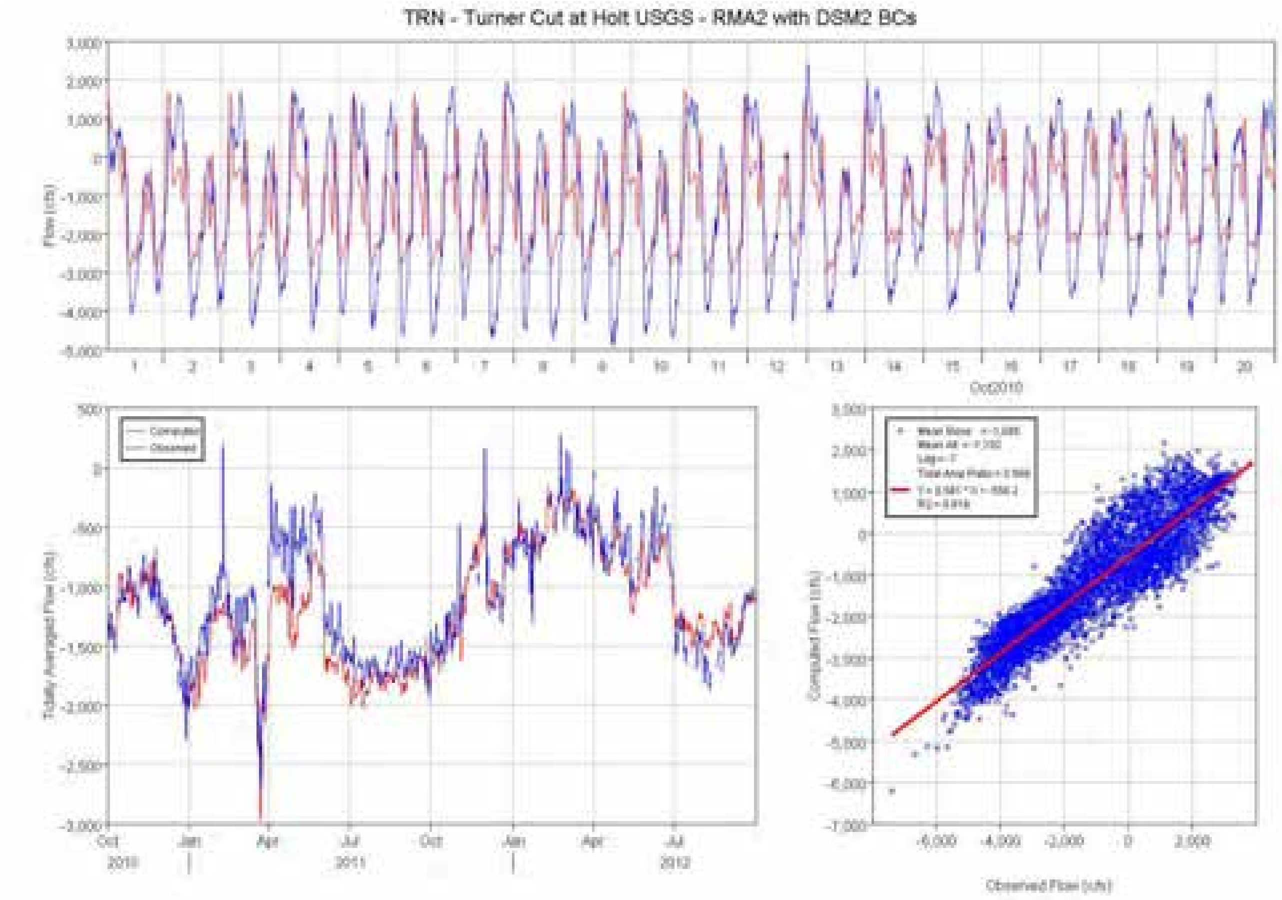


Figure 40 Computed (RMA2 with DSM2 BCs) and observed flow comparison plots for Turner Cut at Holt.

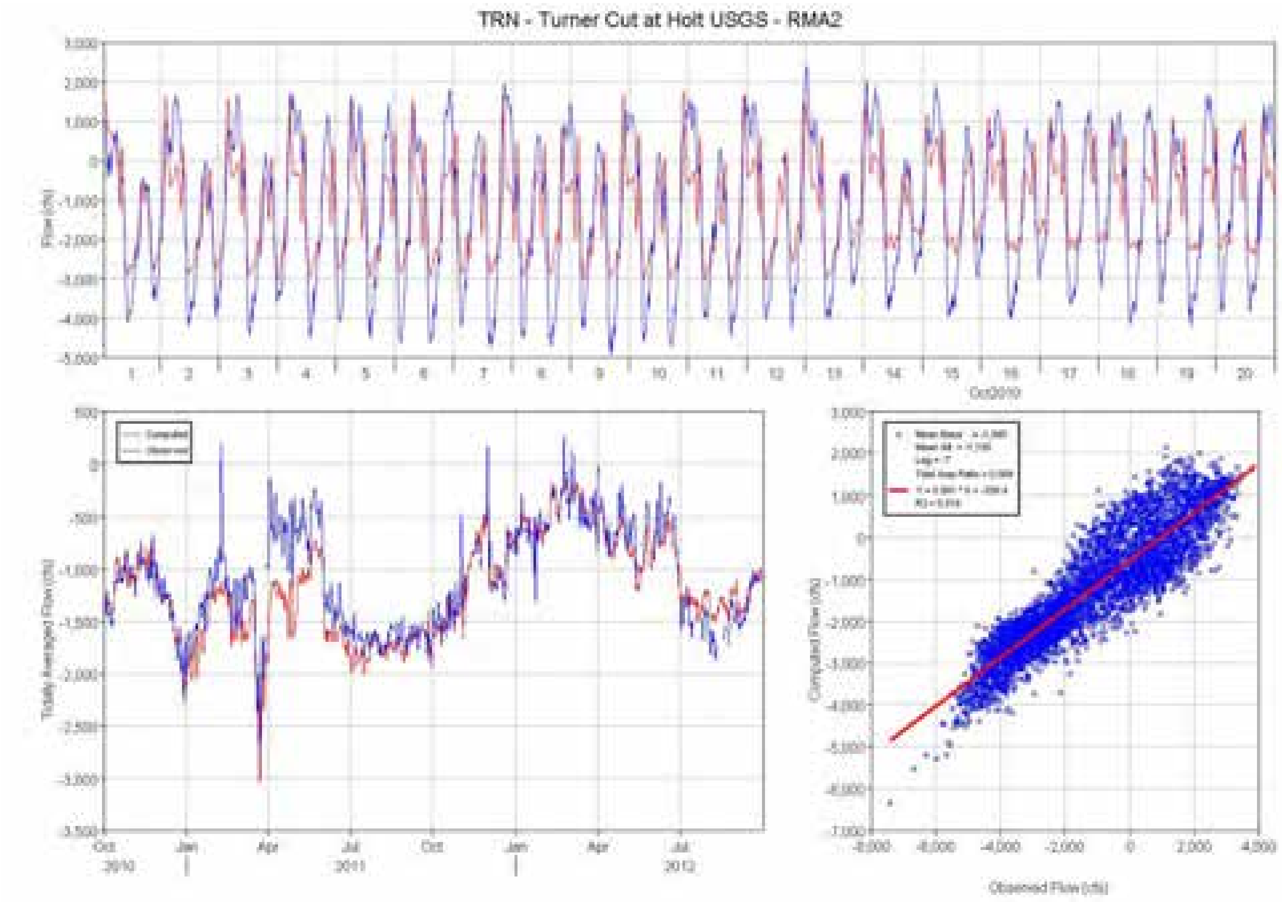


Figure 41 Computed (RMA2) and observed flow comparison plots for Turner Cut at Holt.

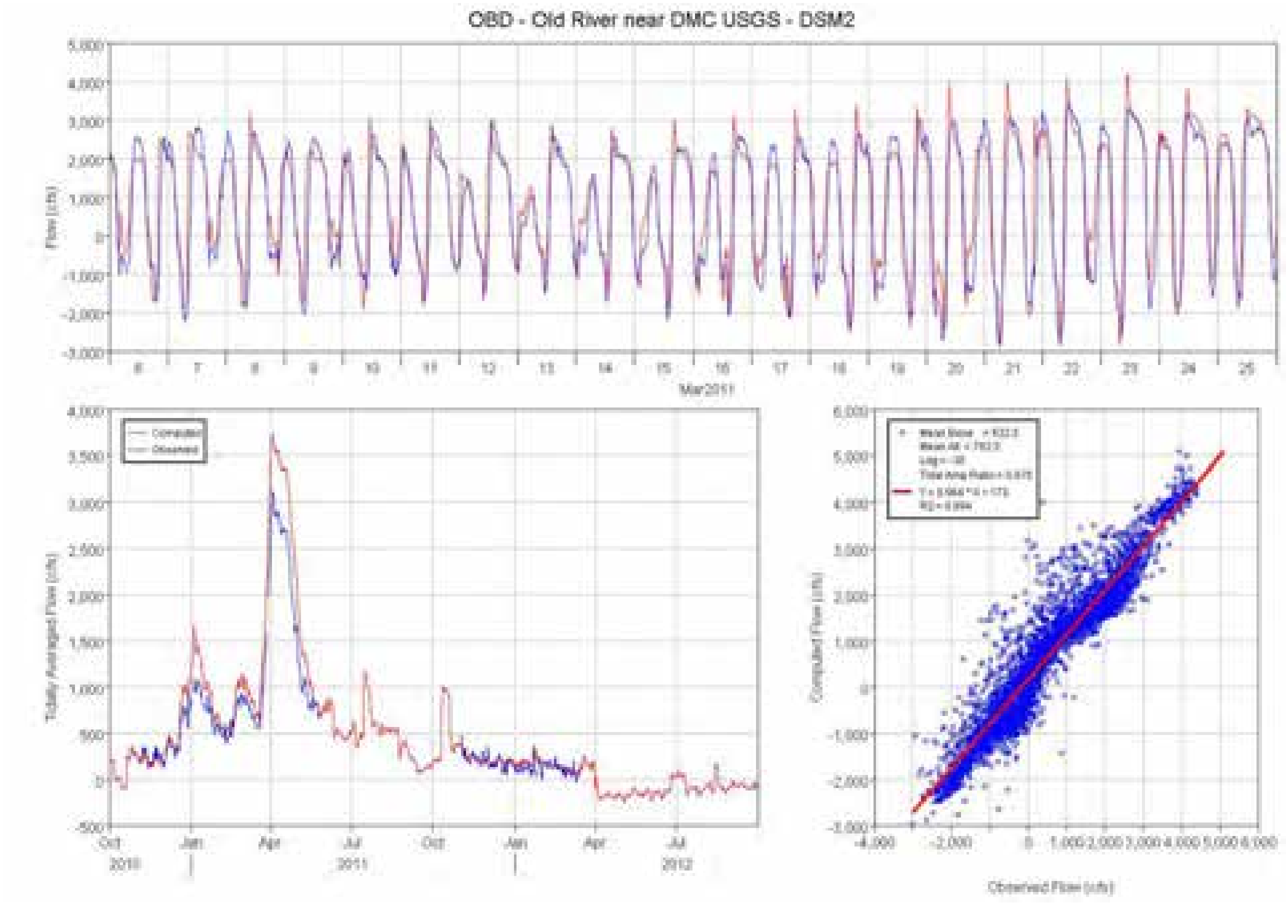


Figure 42 Computed (DSM2) and observed flow comparison plots for Old River near DMC.

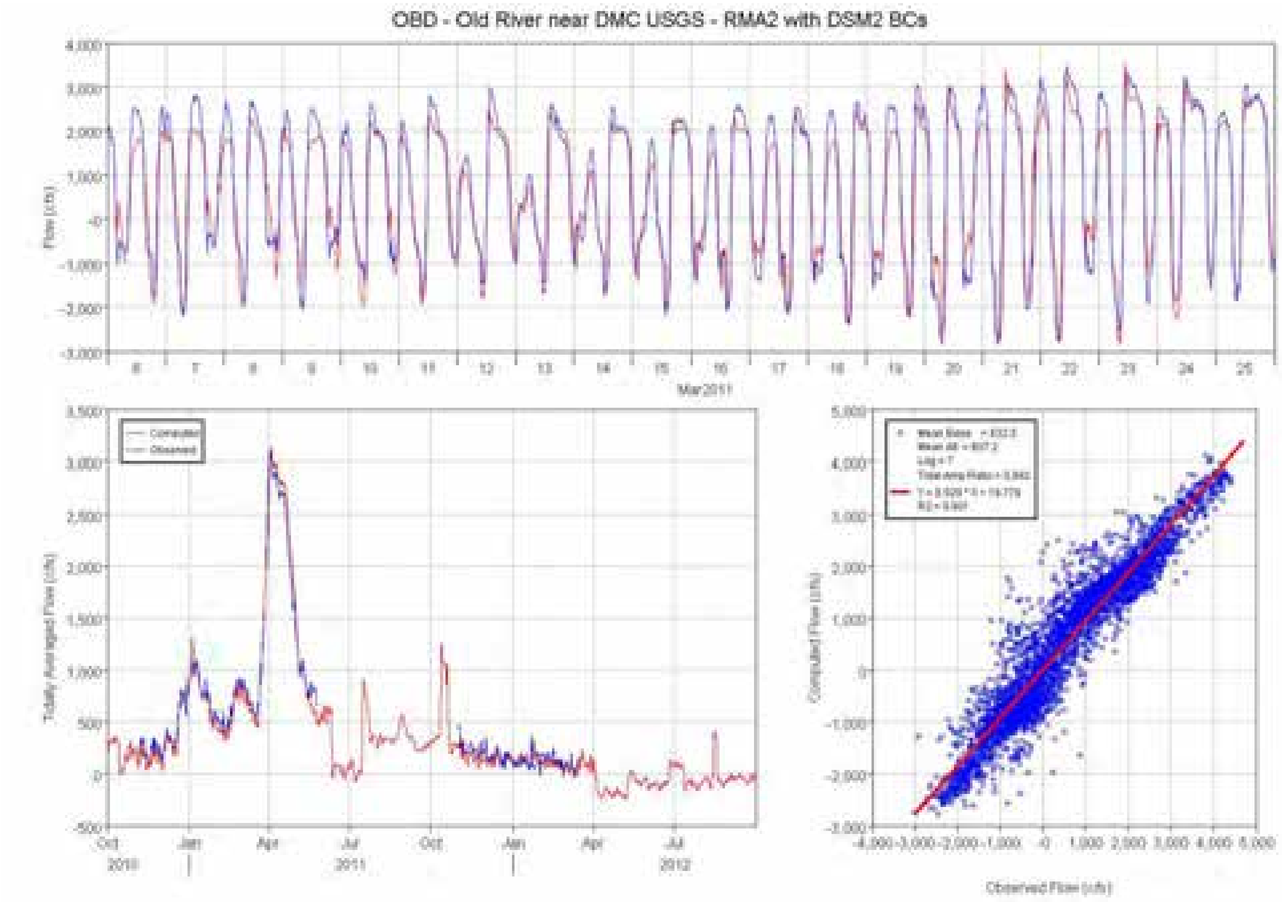


Figure 43 Computed (RMA2 with DSM2 BCs) and observed flow comparison plots for Old River near DMC.

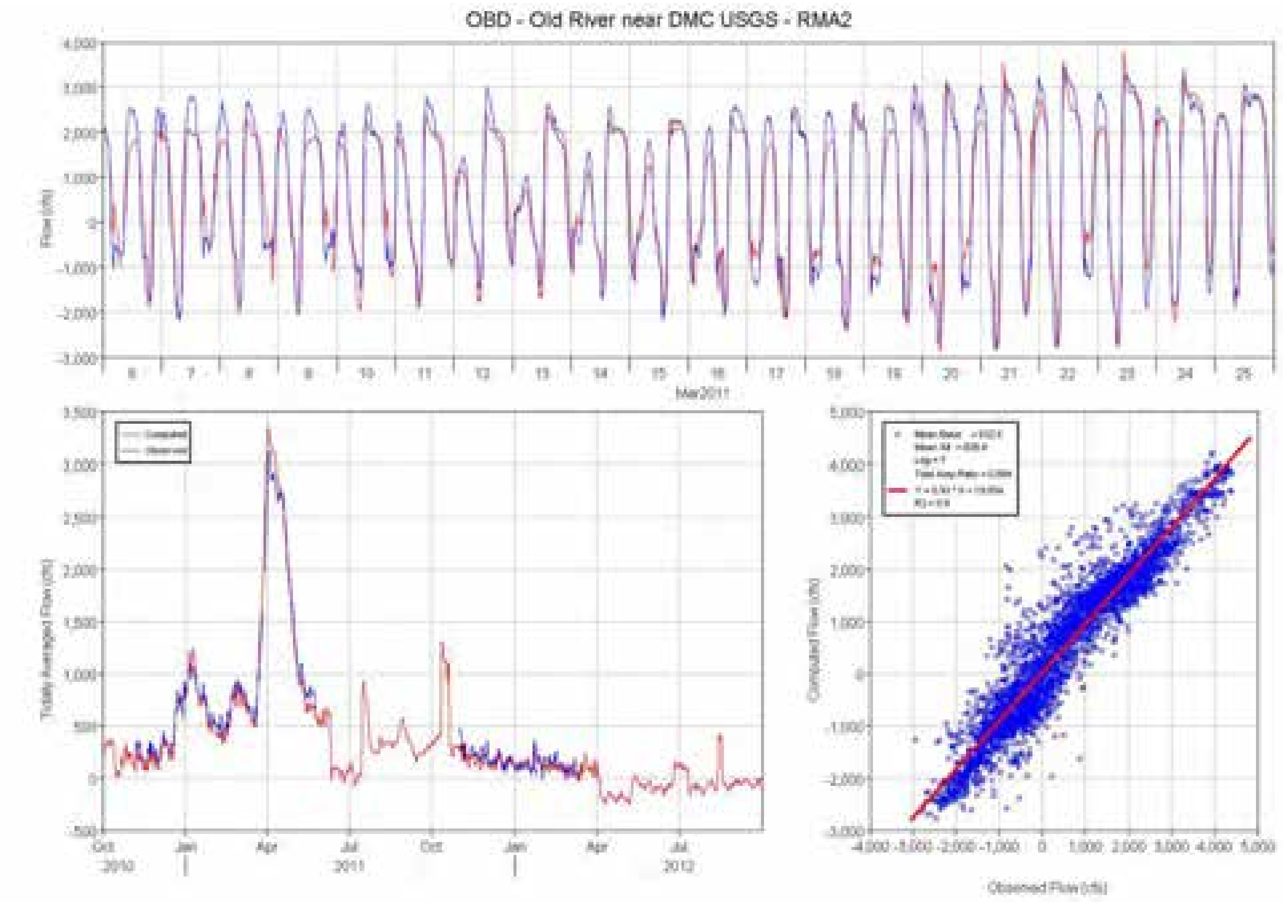


Figure 44 Computed (RMA2) and observed flow comparison plots for Old River near DMC.

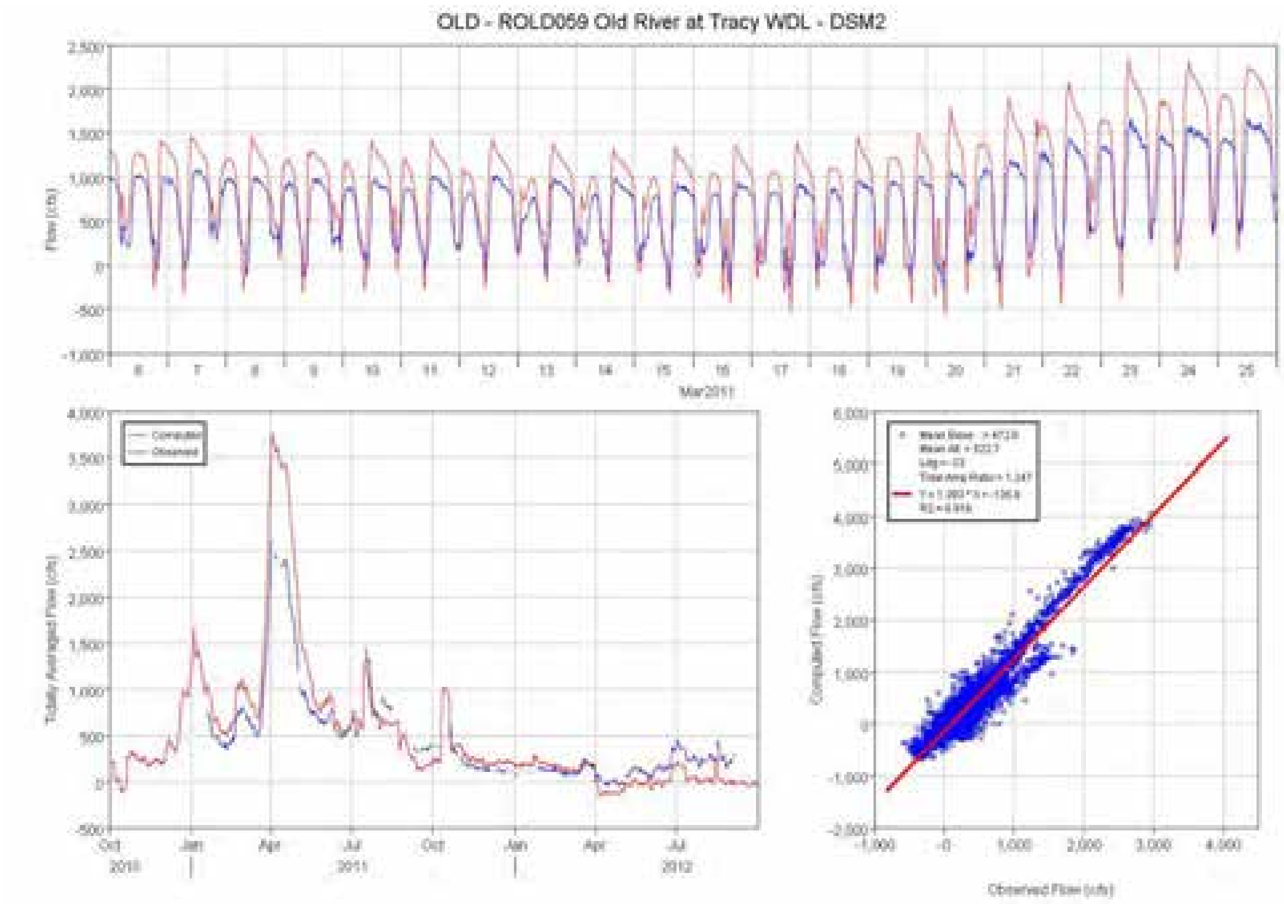


Figure 45 Computed (DSM2) and observed flow comparison plots for Old River at Tracy.

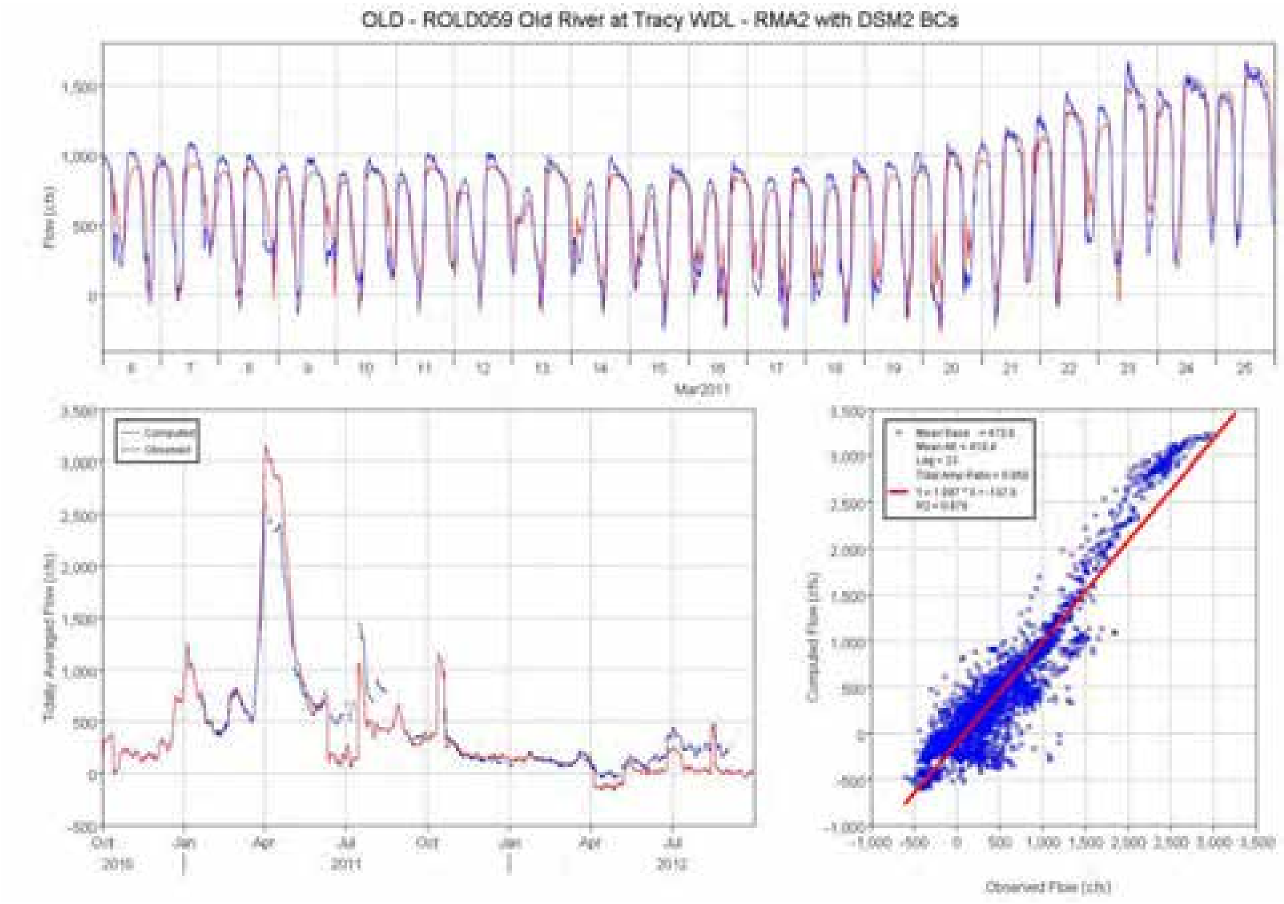


Figure 46 Computed (RMA2 with DSM2 BCs) and observed flow comparison plots for Old River at Tracy.

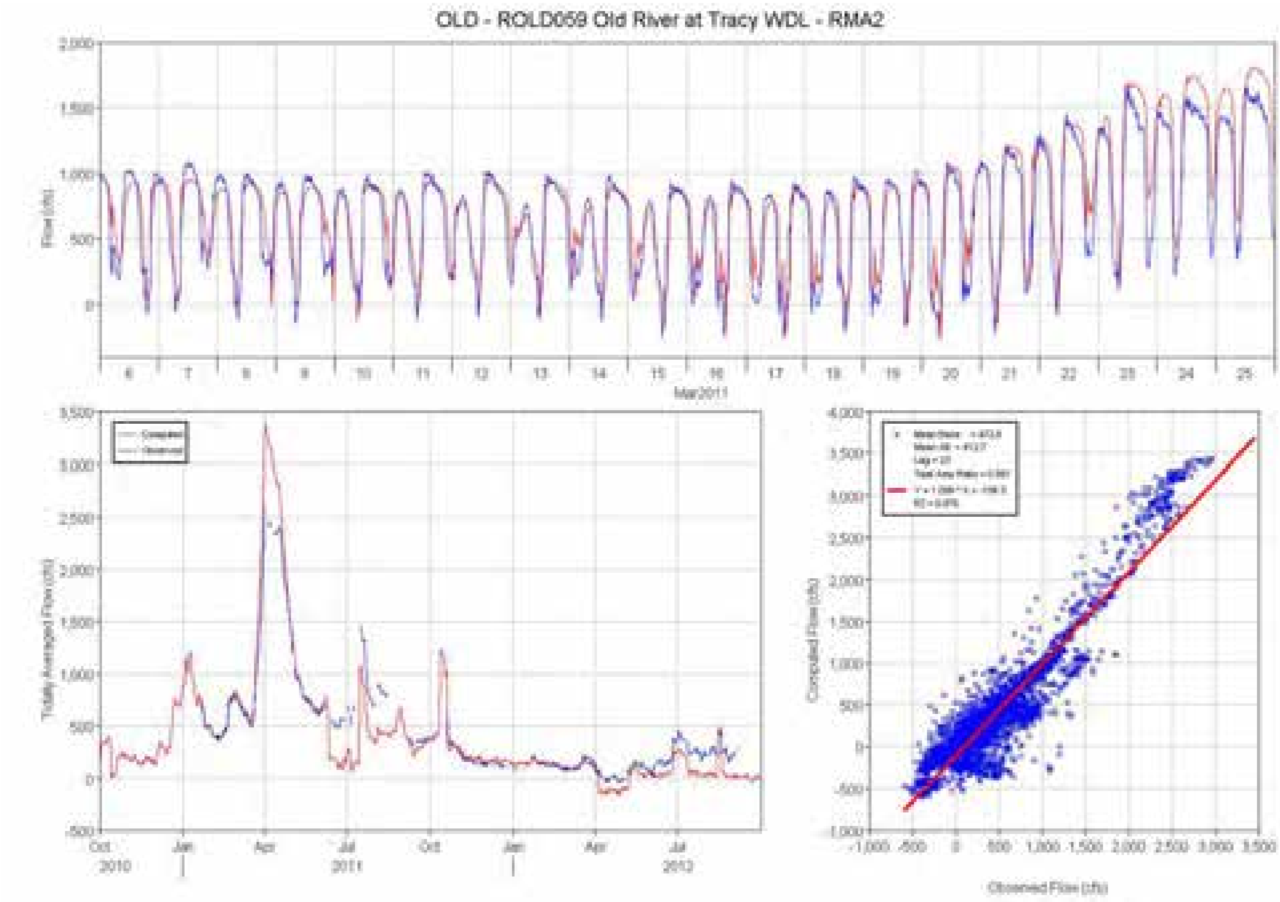


Figure 47 Computed (RMA2) and observed flow comparison plots for Old River at Tracy.

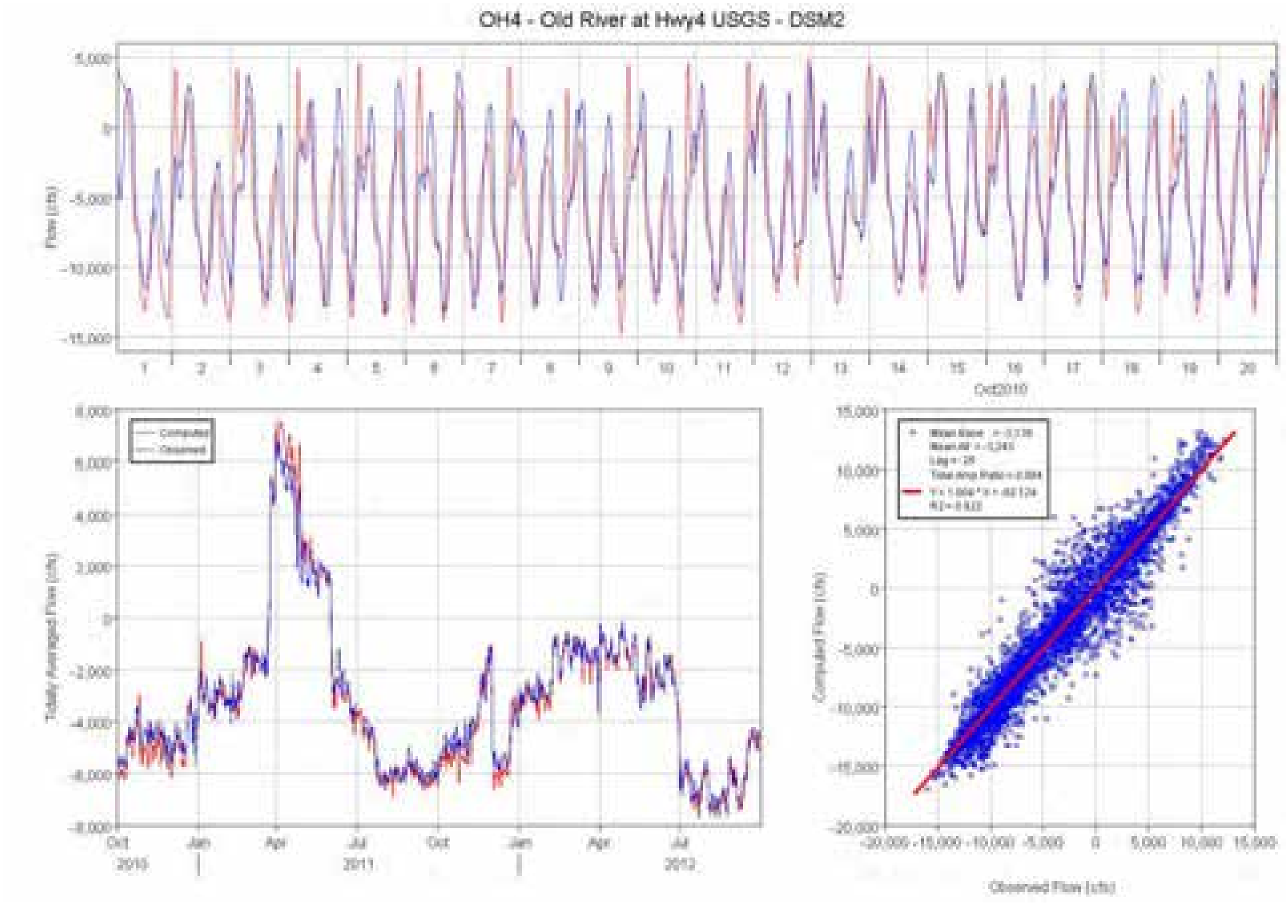


Figure 48 Computed (DSM2) and observed flow comparison plots for Old River at Hwy 4.

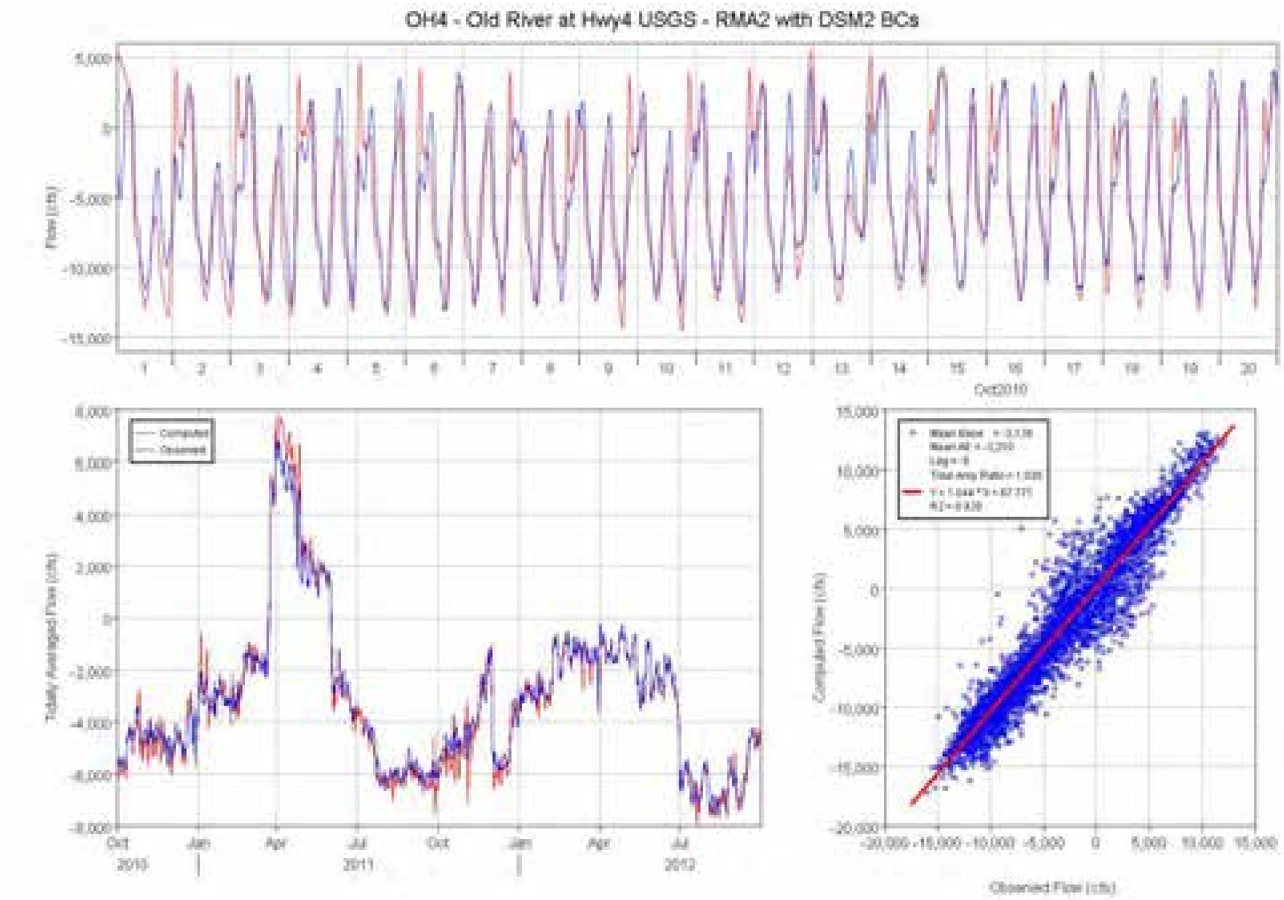


Figure 49 Computed (RMA2 with DSM2 BCs) and observed flow comparison plots for Old River at Hwy 4.

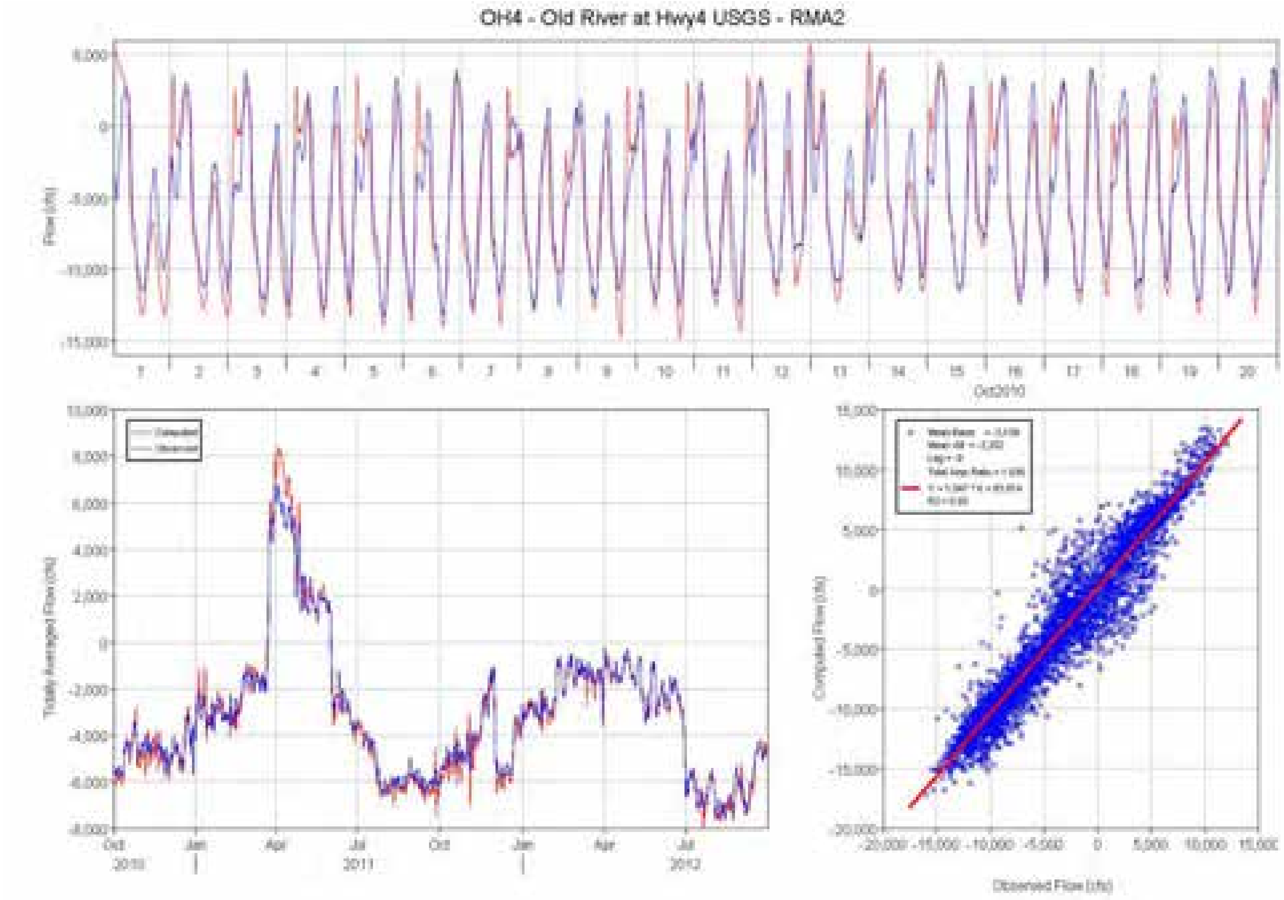


Figure 50 Computed (RMA2) and observed flow comparison plots for Old River at Hwy 4.

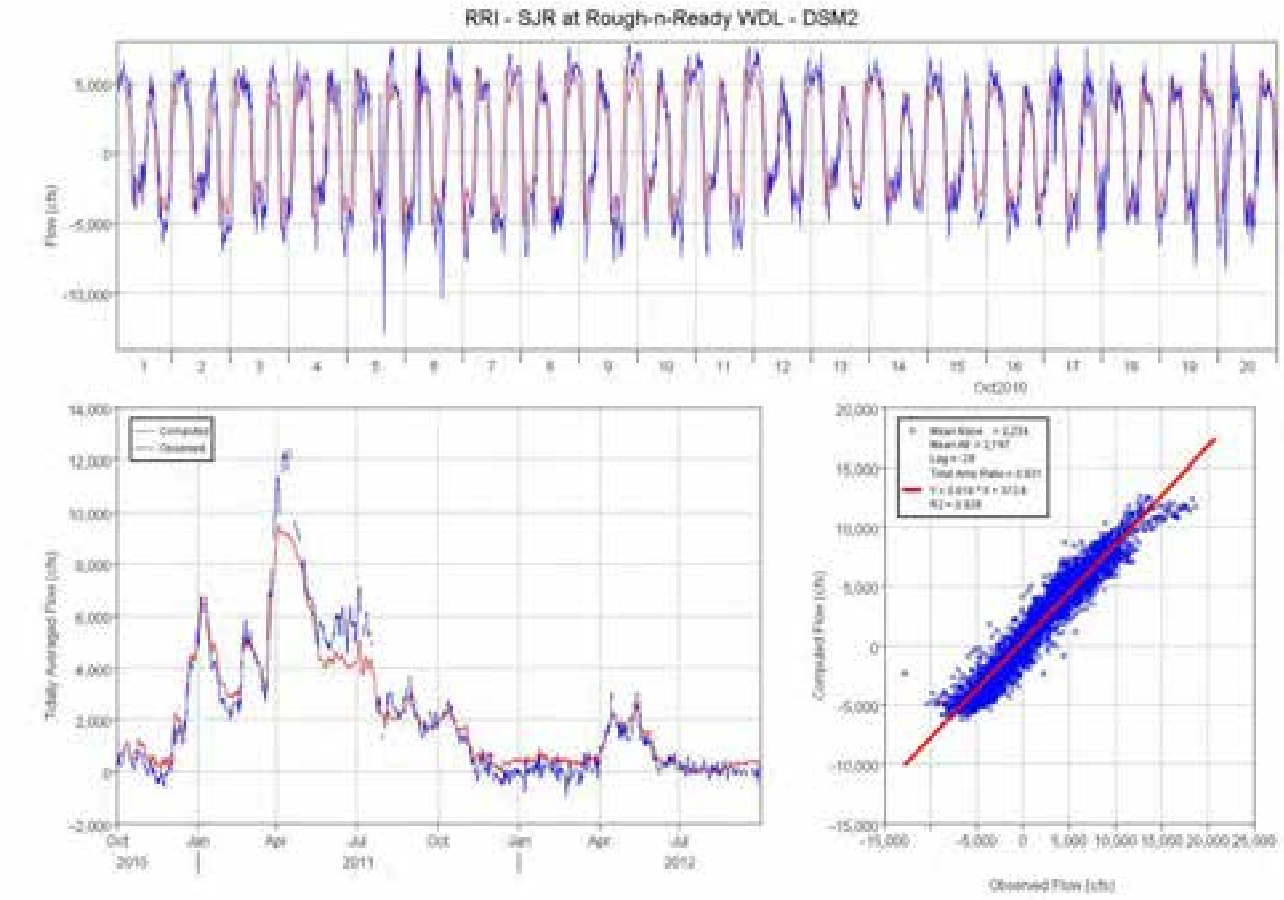


Figure 51 Computed (DSM2) and observed flow comparison plots for SJR at Rough-n-Ready.

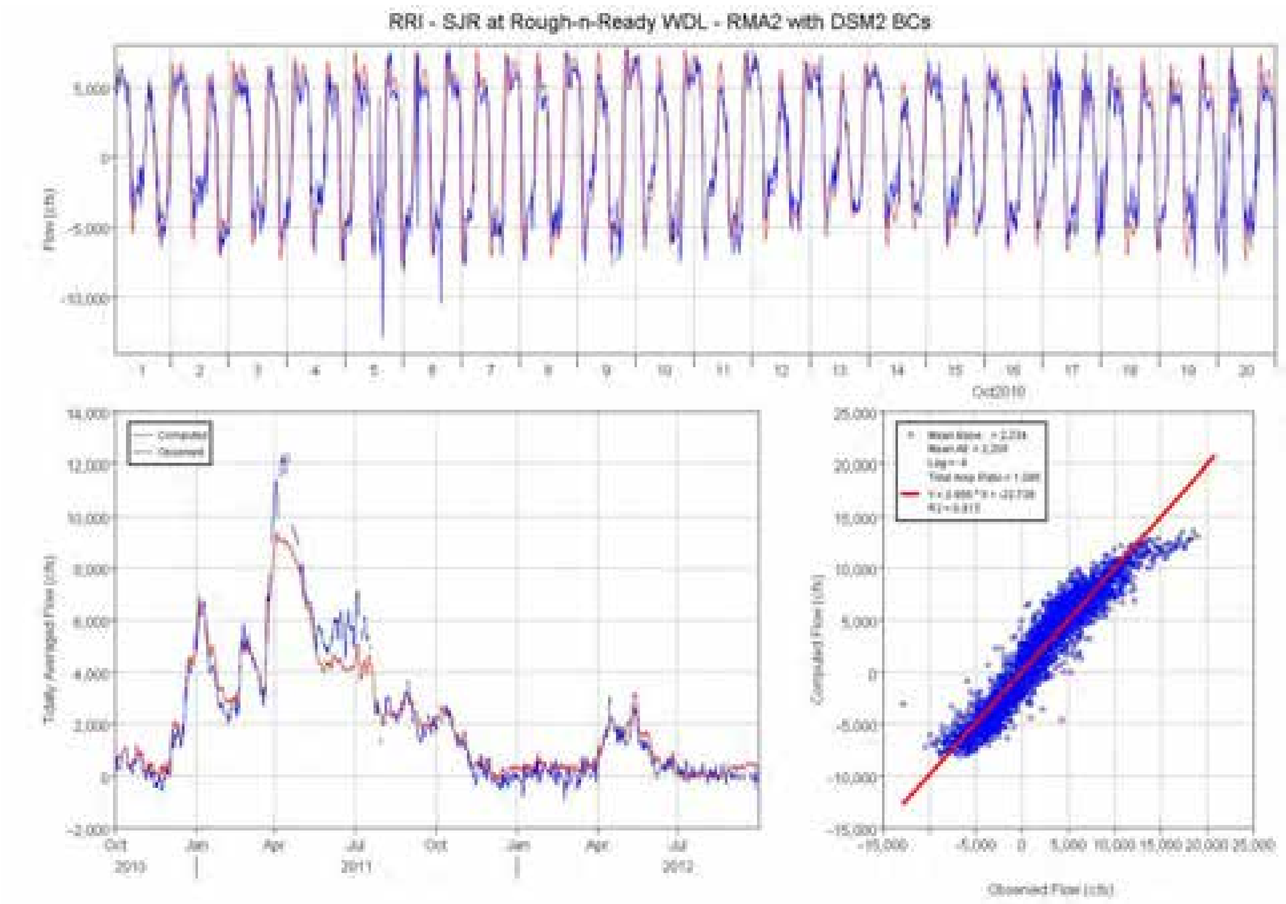


Figure 52 Computed (RMA2 with DSM2 BCs) and observed flow comparison plots for SJR at Rough-n-Ready.

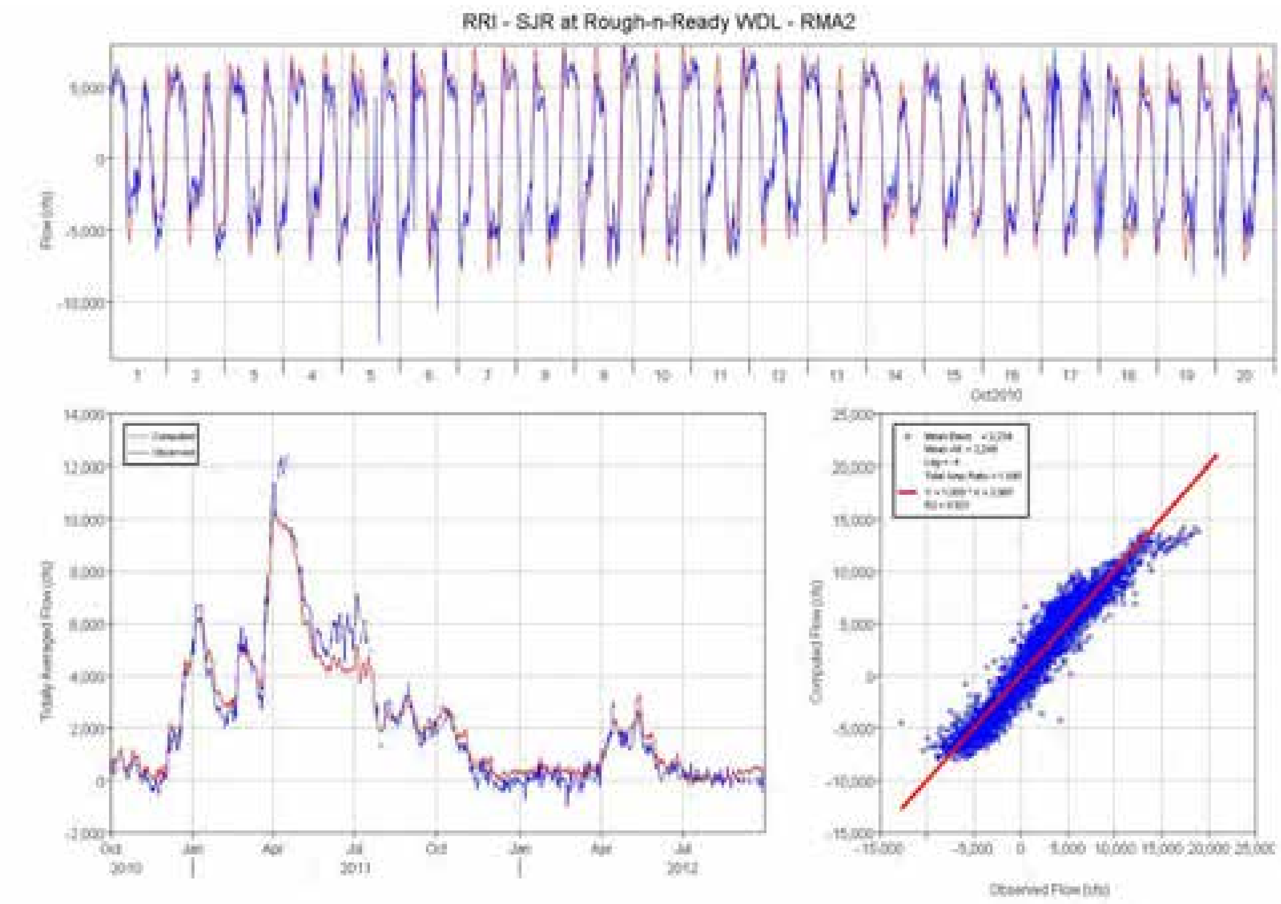


Figure 53 Computed (RMA2) and observed flow comparison plots for SJR at Rough-n-Ready.

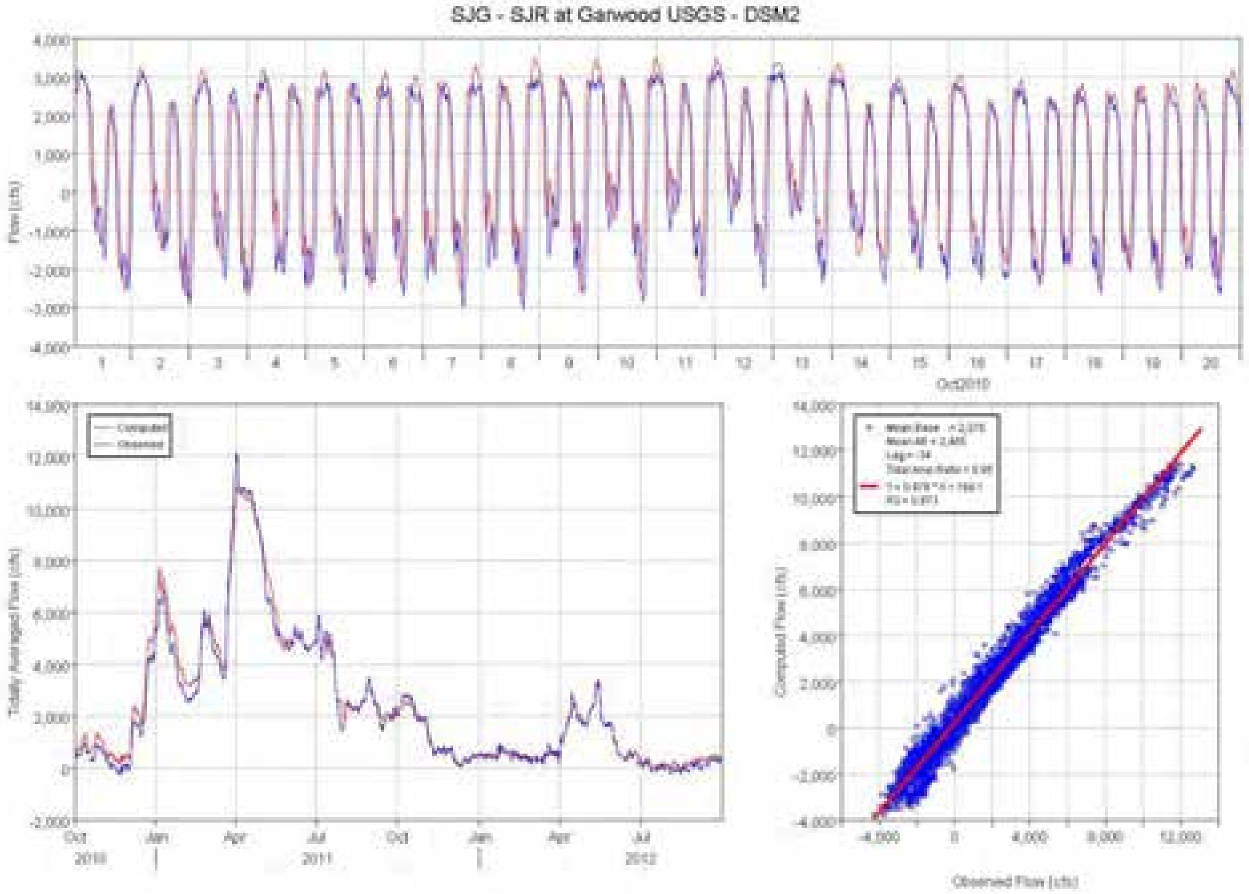


Figure 54 Computed (DSM2) and observed flow comparison plots for SJR at Garwood.

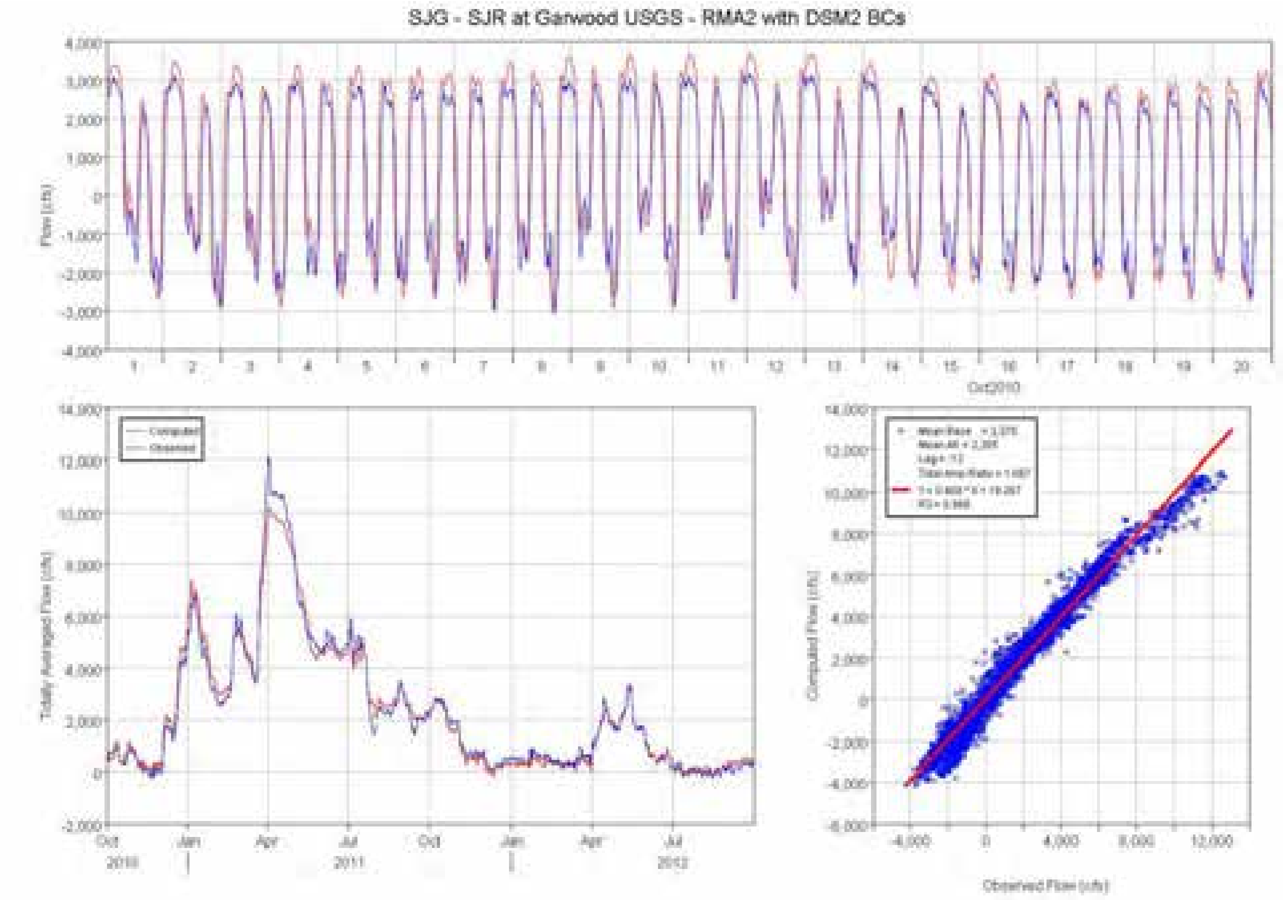


Figure 55 Computed (RMA2 with DSM2 BCs) and observed flow comparison plots for SJR at Garwood.

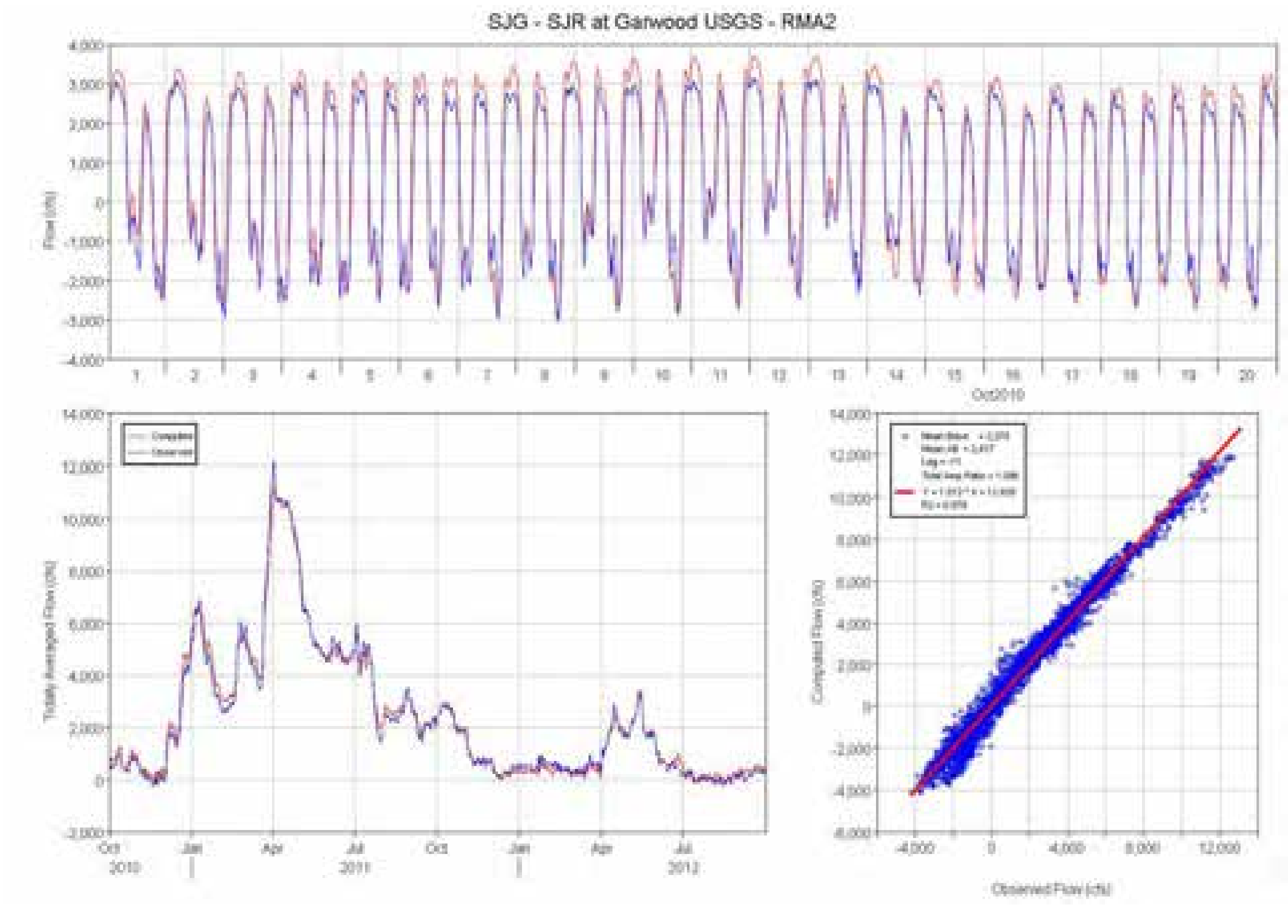


Figure 56 Computed (RMA2) and observed flow comparison plots for SJR at Garwood.

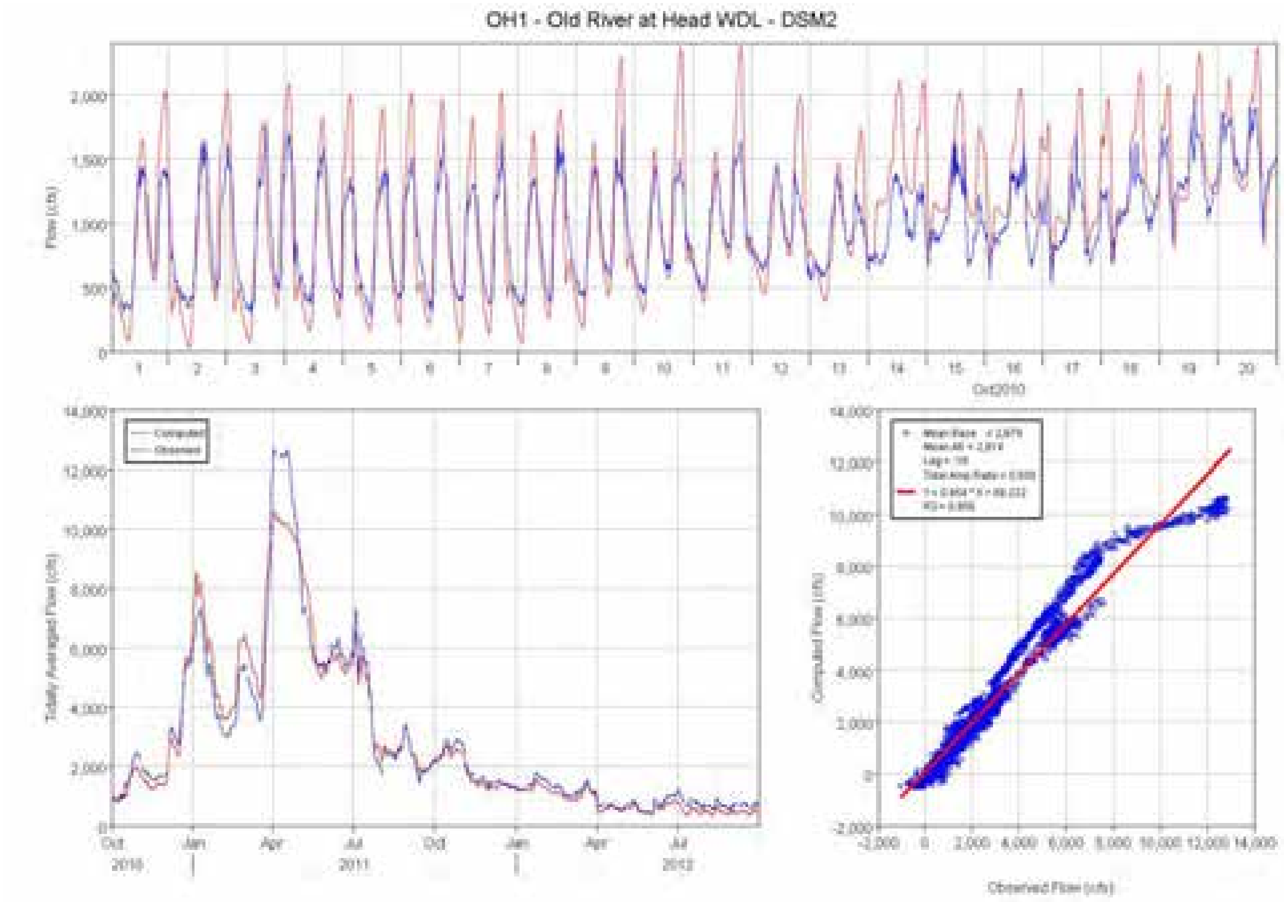


Figure 57 Computed (DSM2) and observed flow comparison plots for Old River at Head.

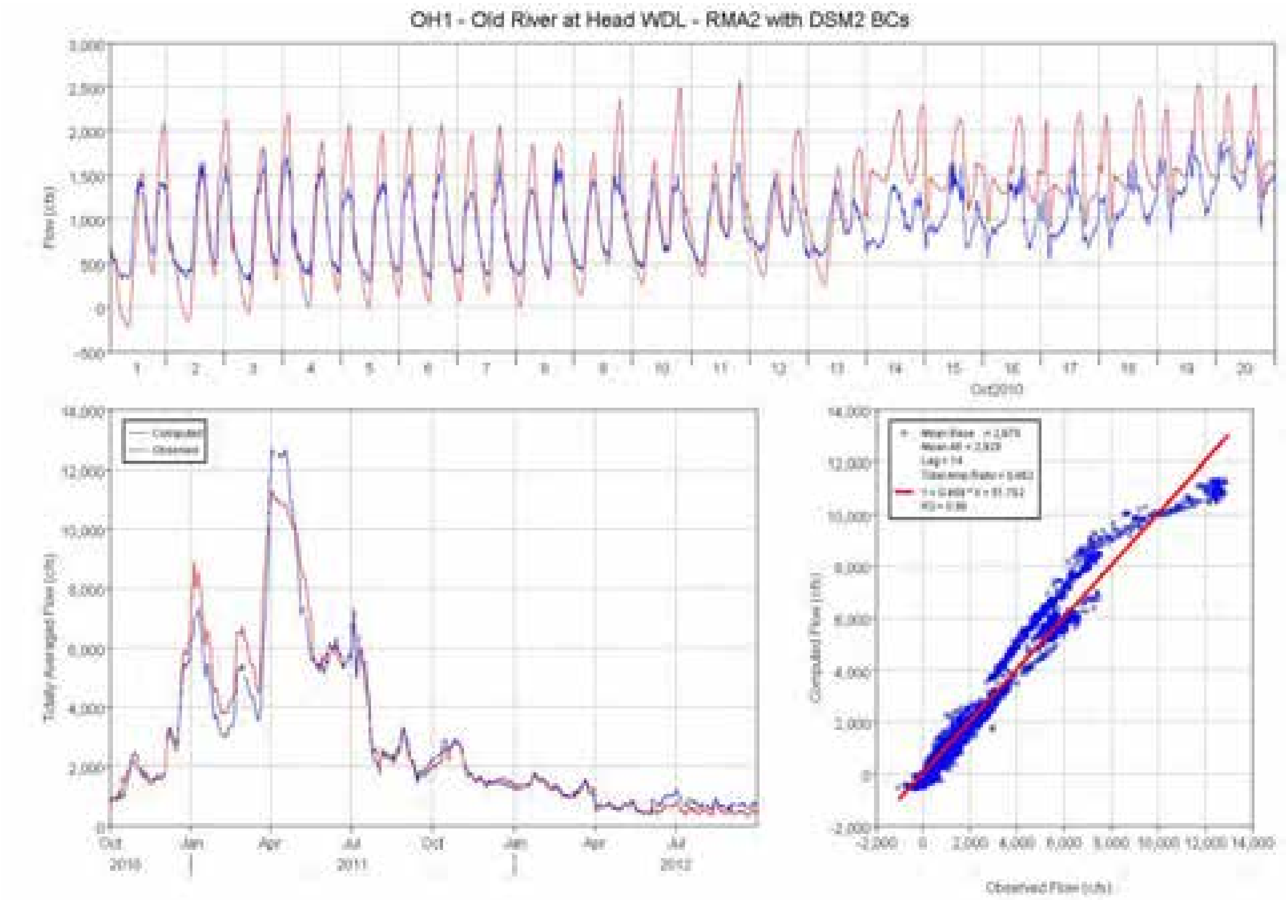


Figure 58 Computed (RMA2 with DSM2 BCs) and observed flow comparison plots for Old River at Head.

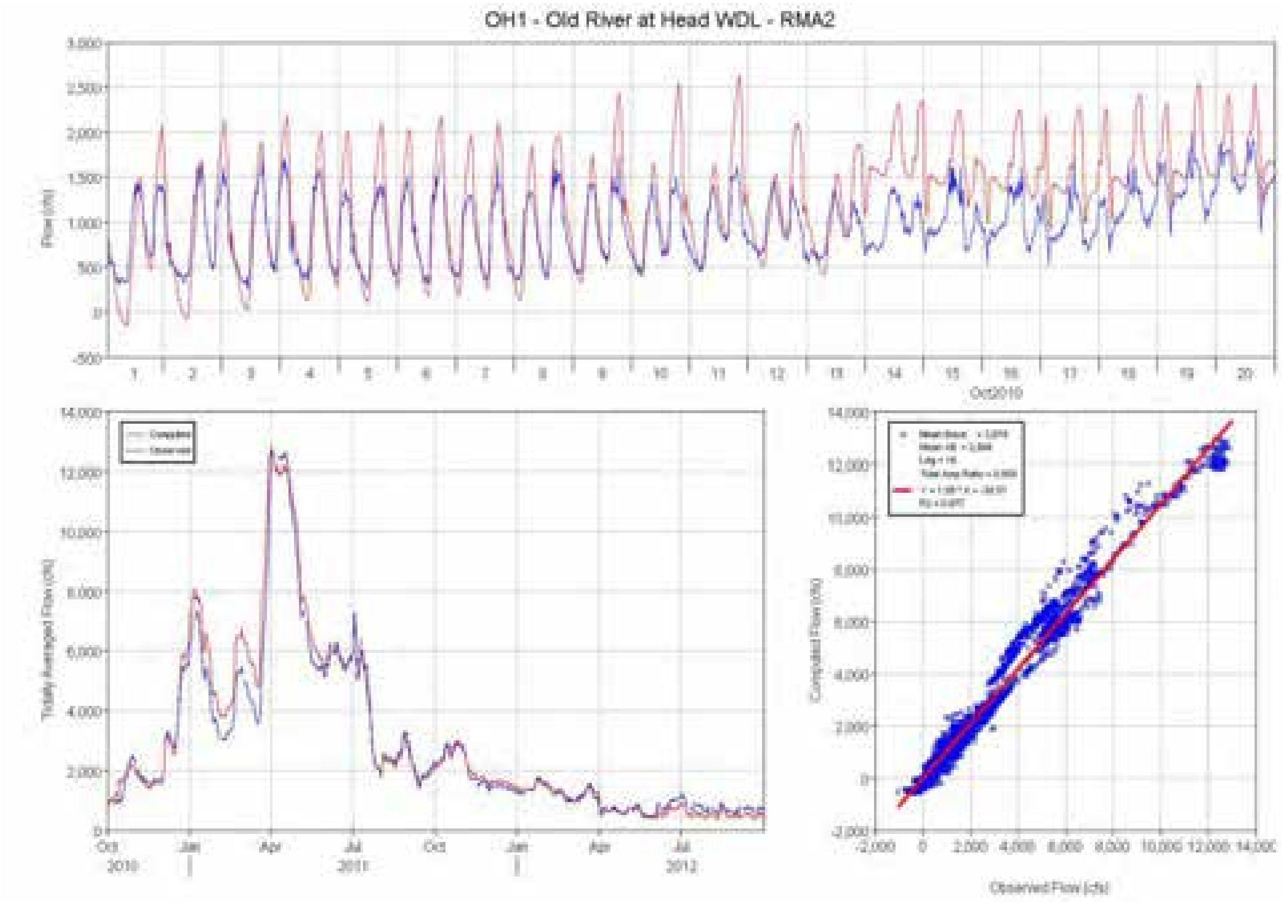


Figure 59 Computed (RMA2) and observed flow comparison plots for Old River at Head.

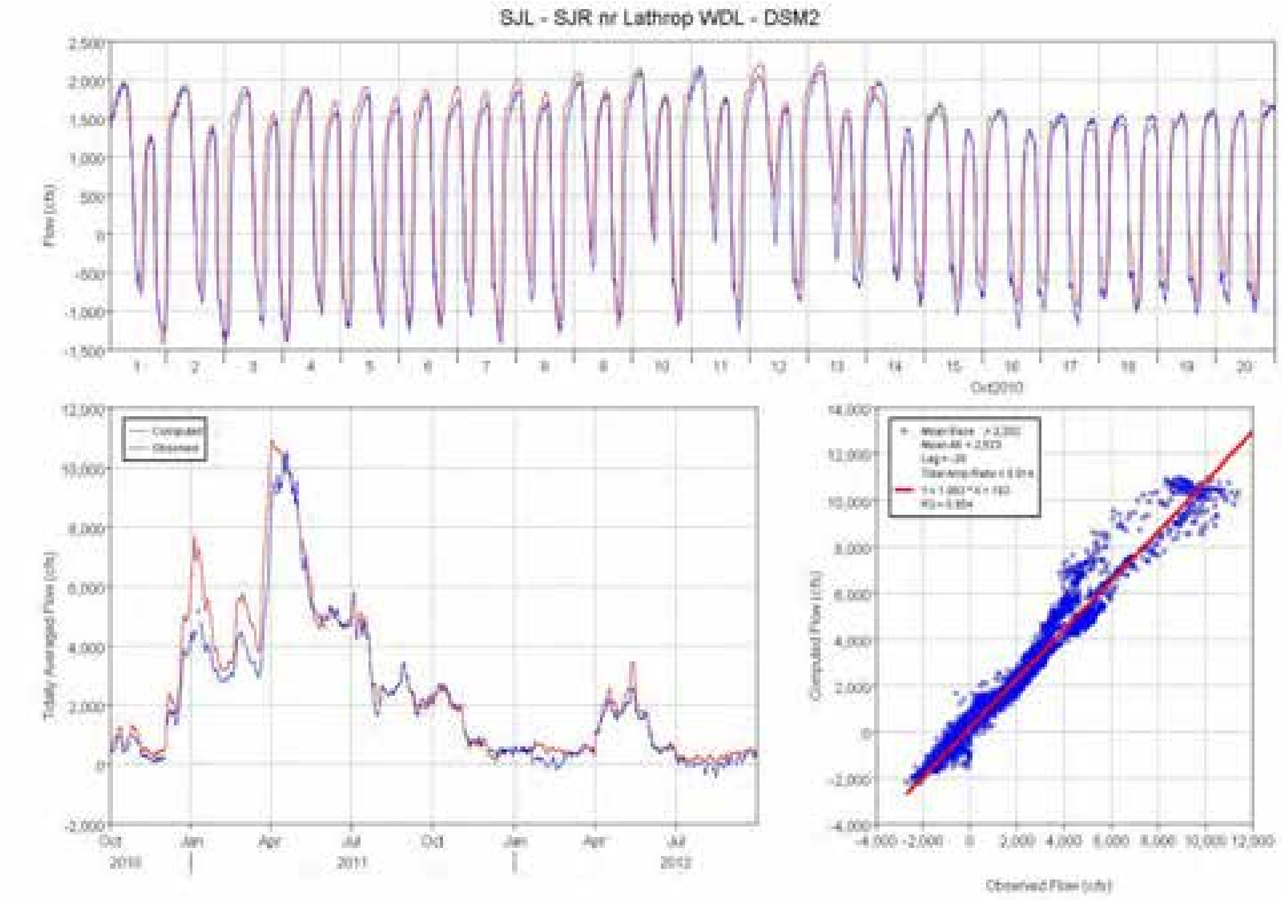


Figure 60 Computed (DSM2) and observed flow comparison plots for SJR near Lathrop.

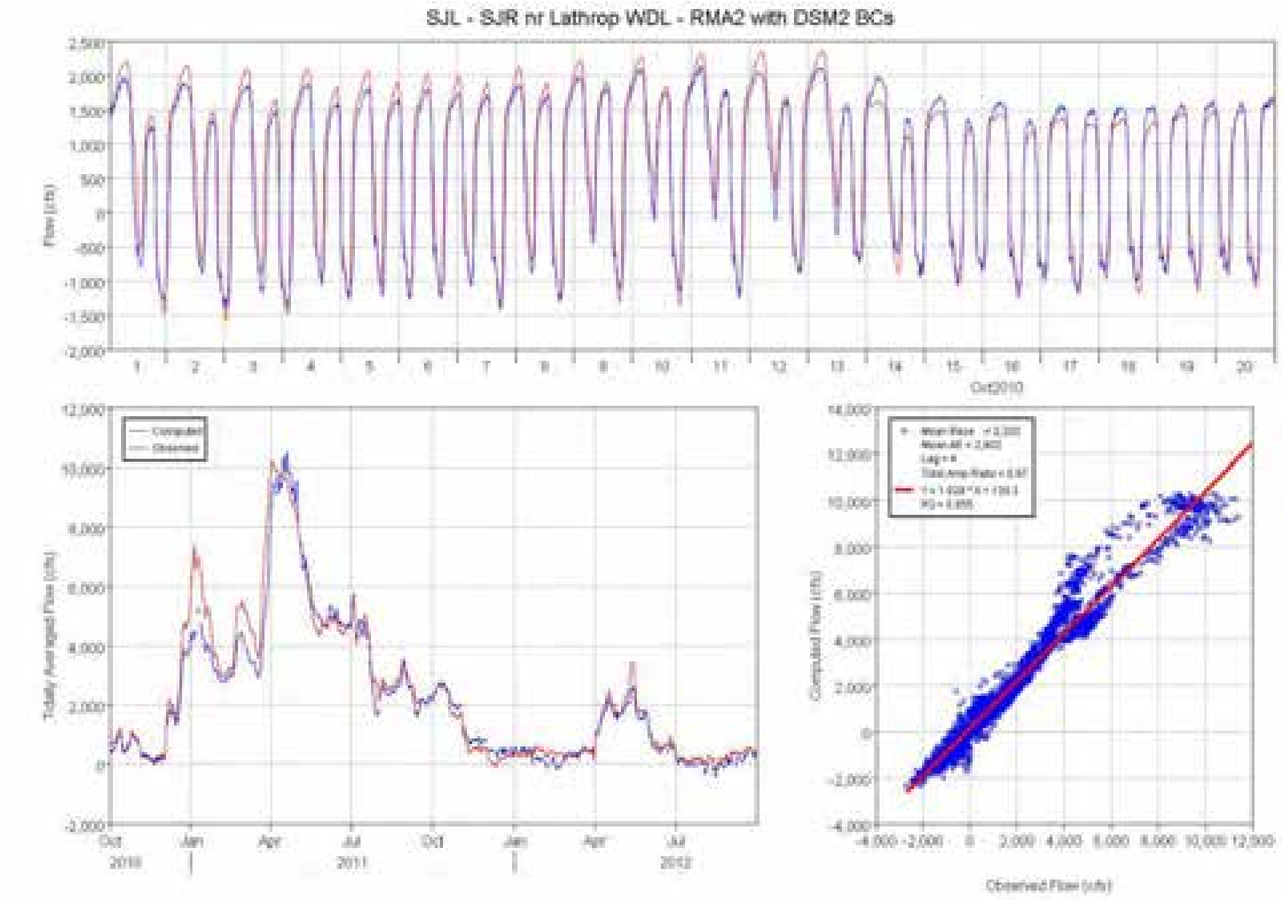


Figure 61 Computed (RMA2 with DSM2 BCs) and observed flow comparison plots for SJR near Lathrop.

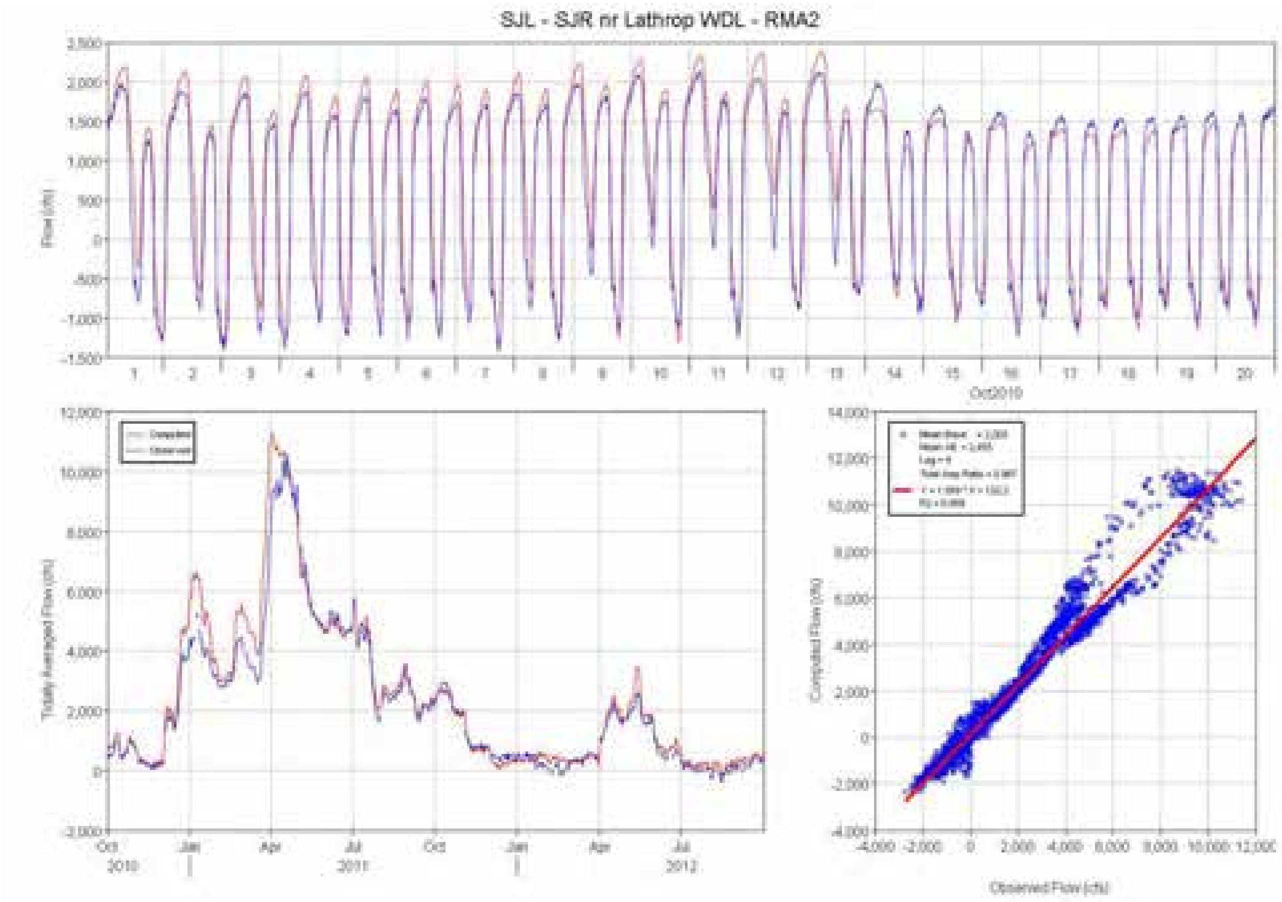


Figure 62 Computed (RMA2) and observed flow comparison plots for SJR near Lathrop.

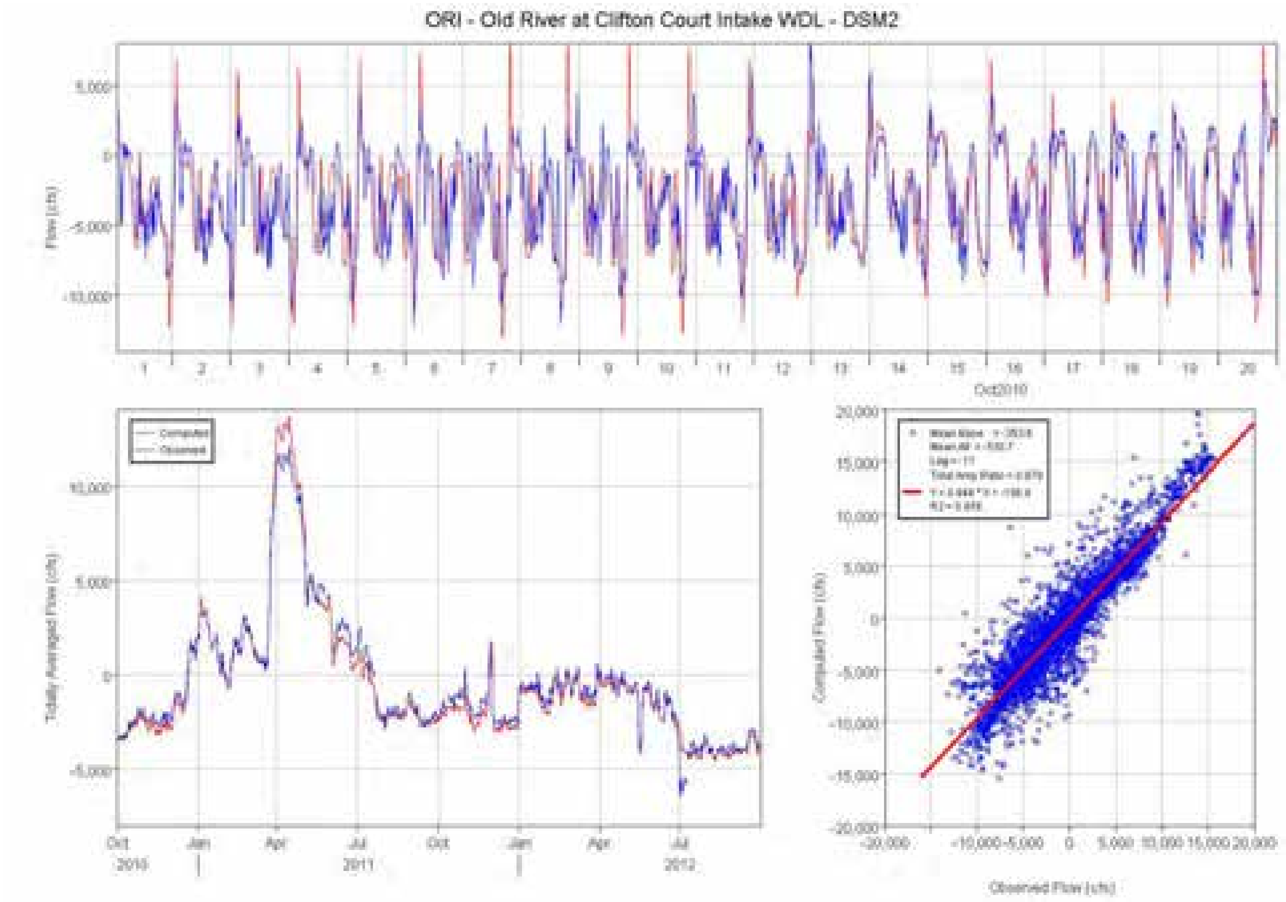


Figure 63 Computed (DSM2) and observed flow comparison plots for Old River at Clifton Court Intake.

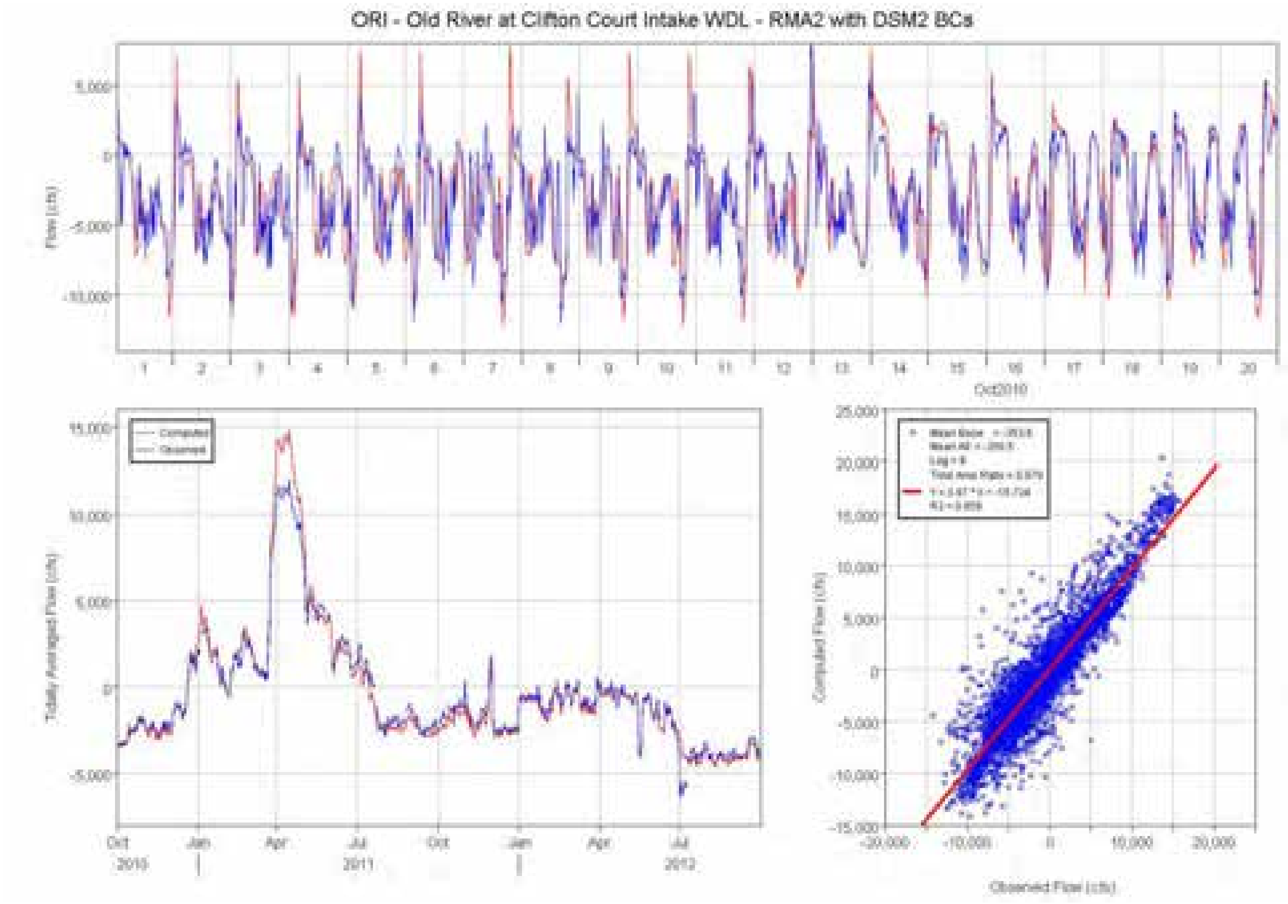


Figure 64 Computed (RMA2 with DSM2 BCs) and observed flow comparison plots for Old River at Clifton Court Intake.

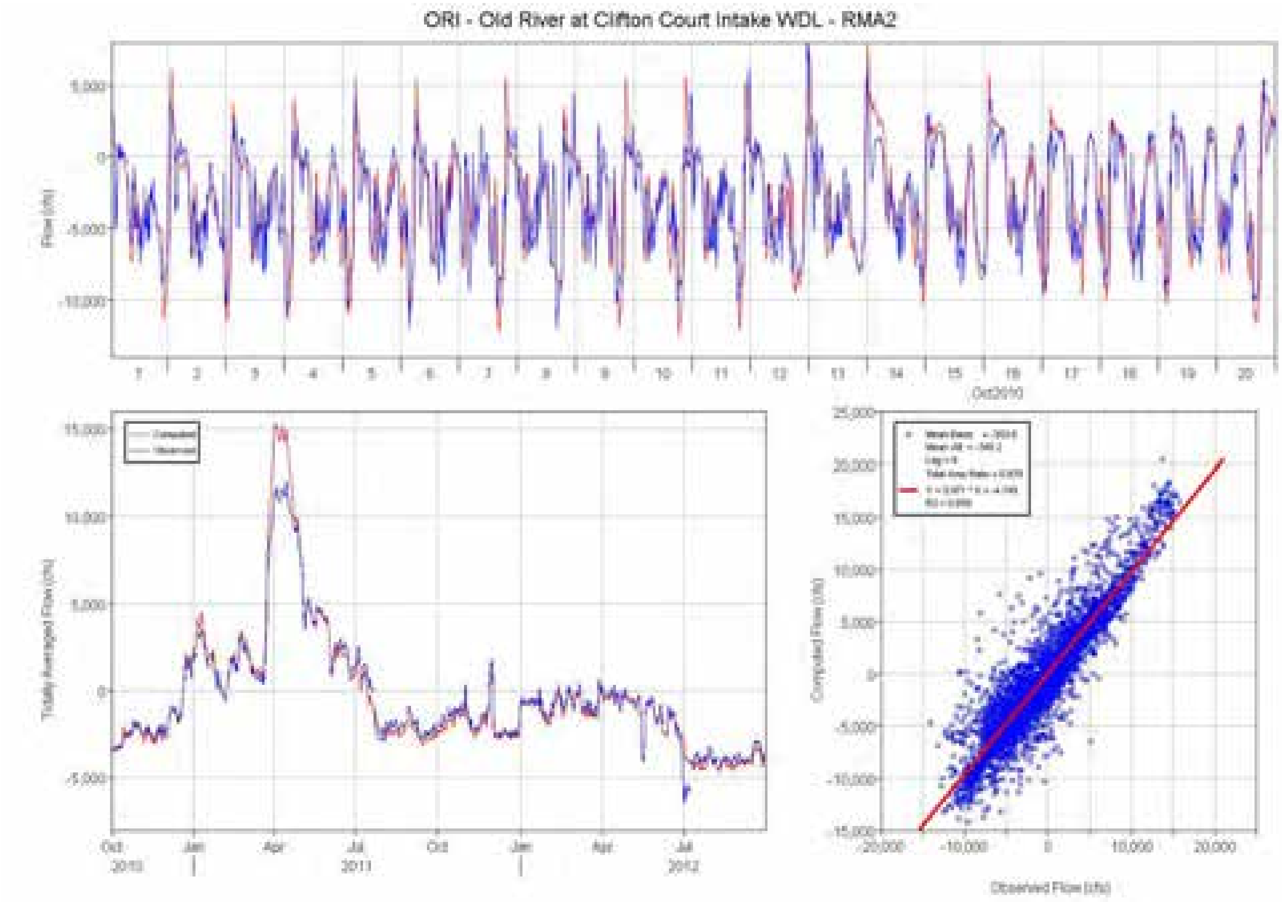


Figure 65 Computed (RMA2) and observed flow comparison plots for Old River at Clifton Court Intake.

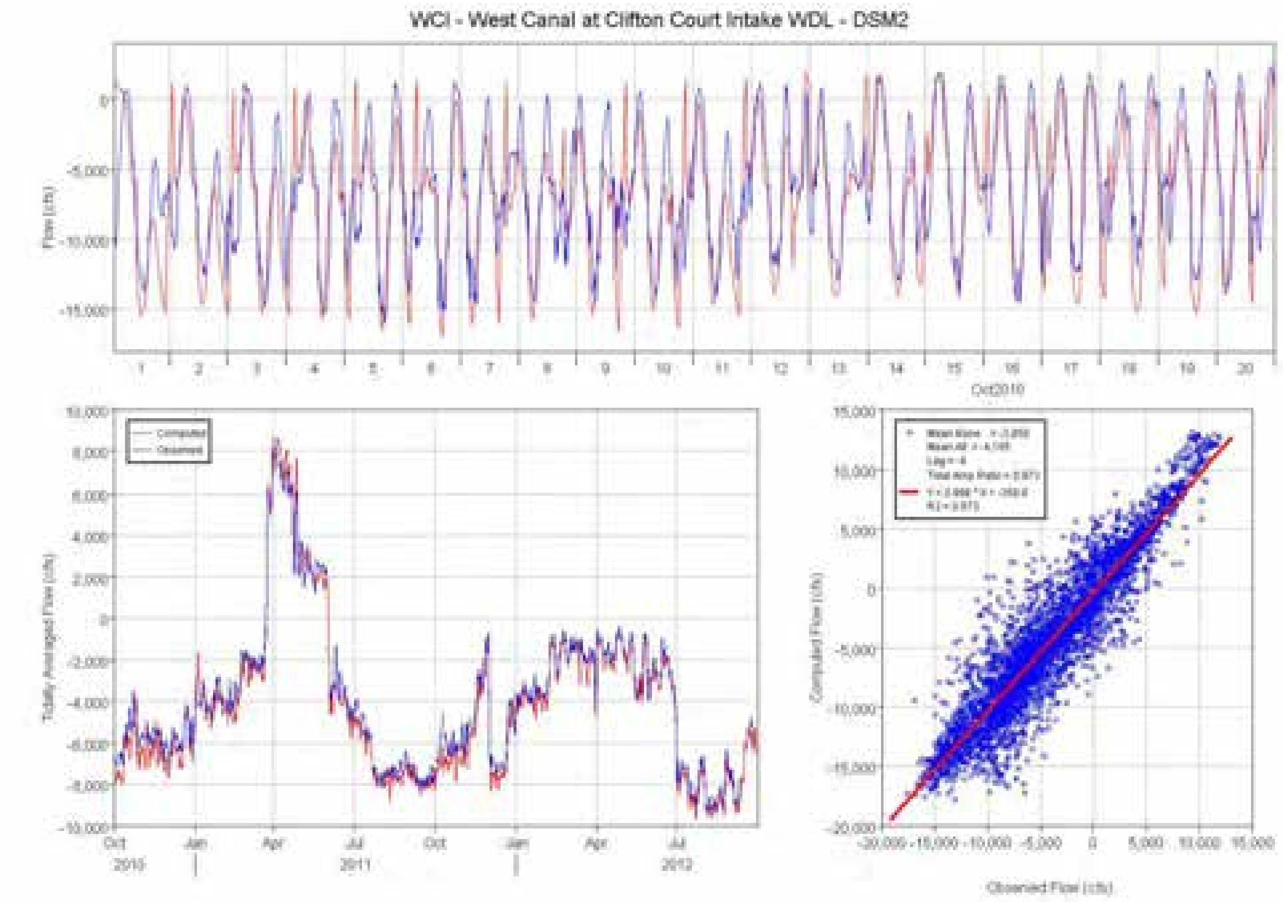


Figure 66 Computed (DSM2) and observed flow comparison plots for West Canal at Clifton Court Intake.

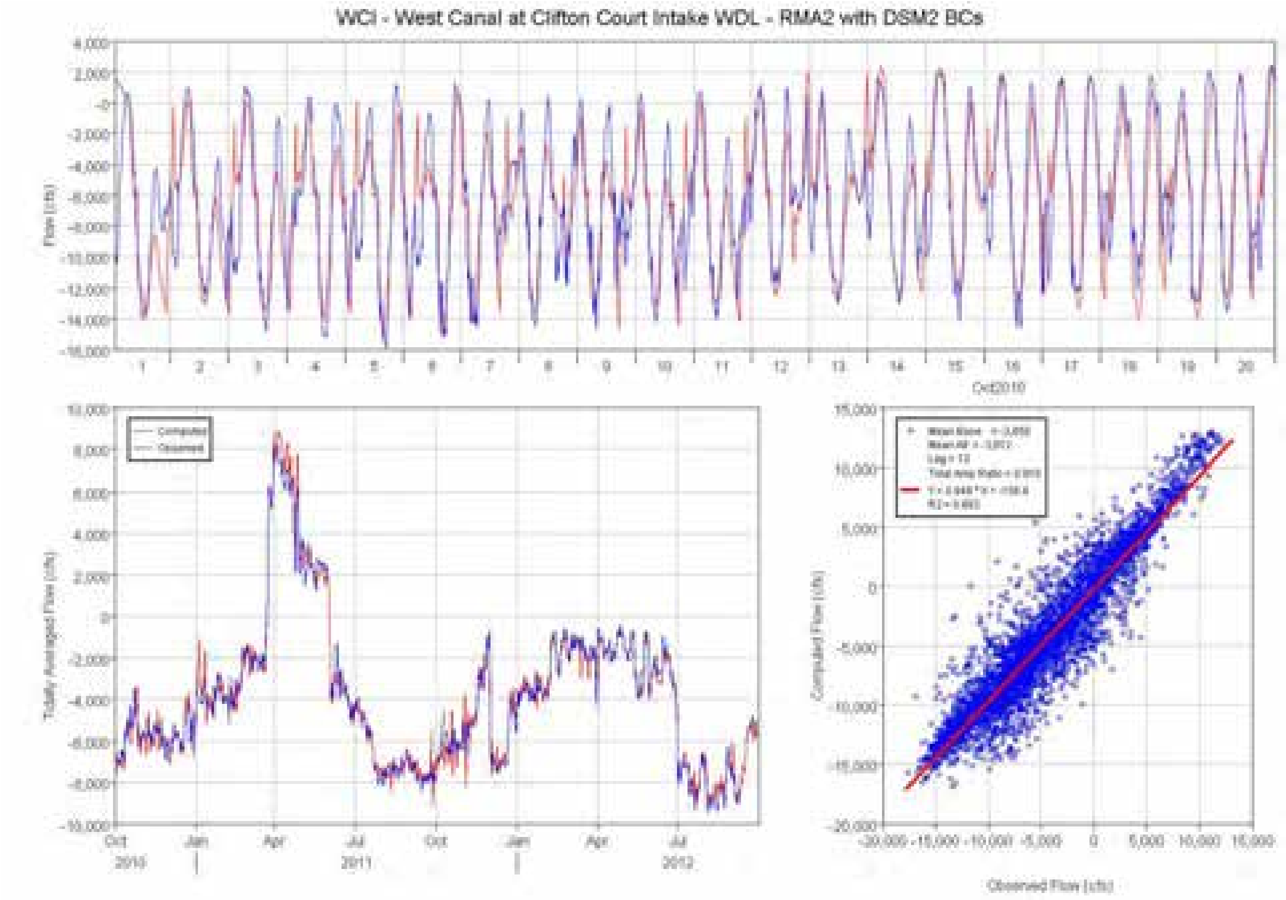


Figure 67 Computed (RMA2 with DSM2 BCs) and observed flow comparison plots for West Canal at Clifton Court Intake.

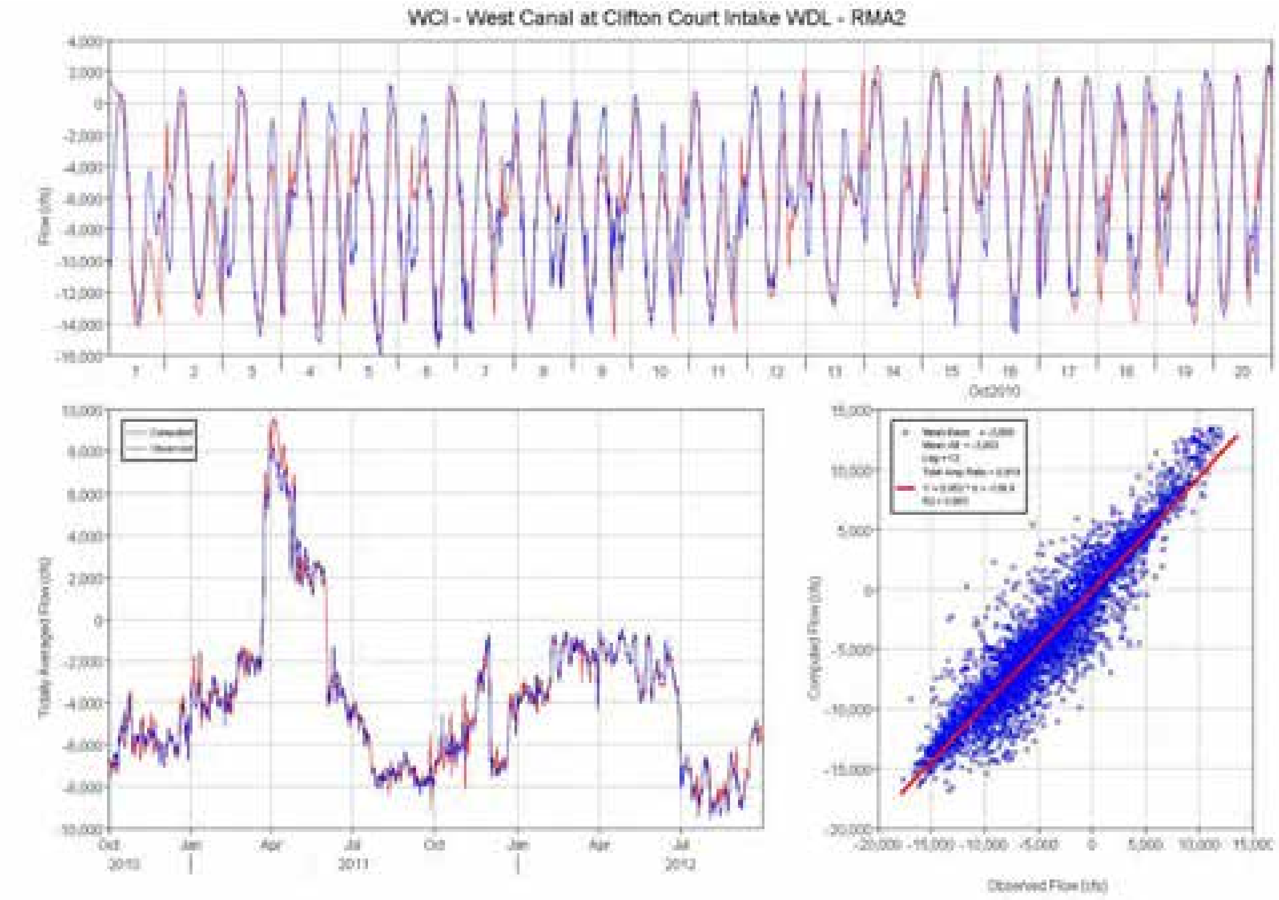


Figure 68 Computed (RMA2) and observed flow comparison plots for West Canal at Clifton Court Intake.

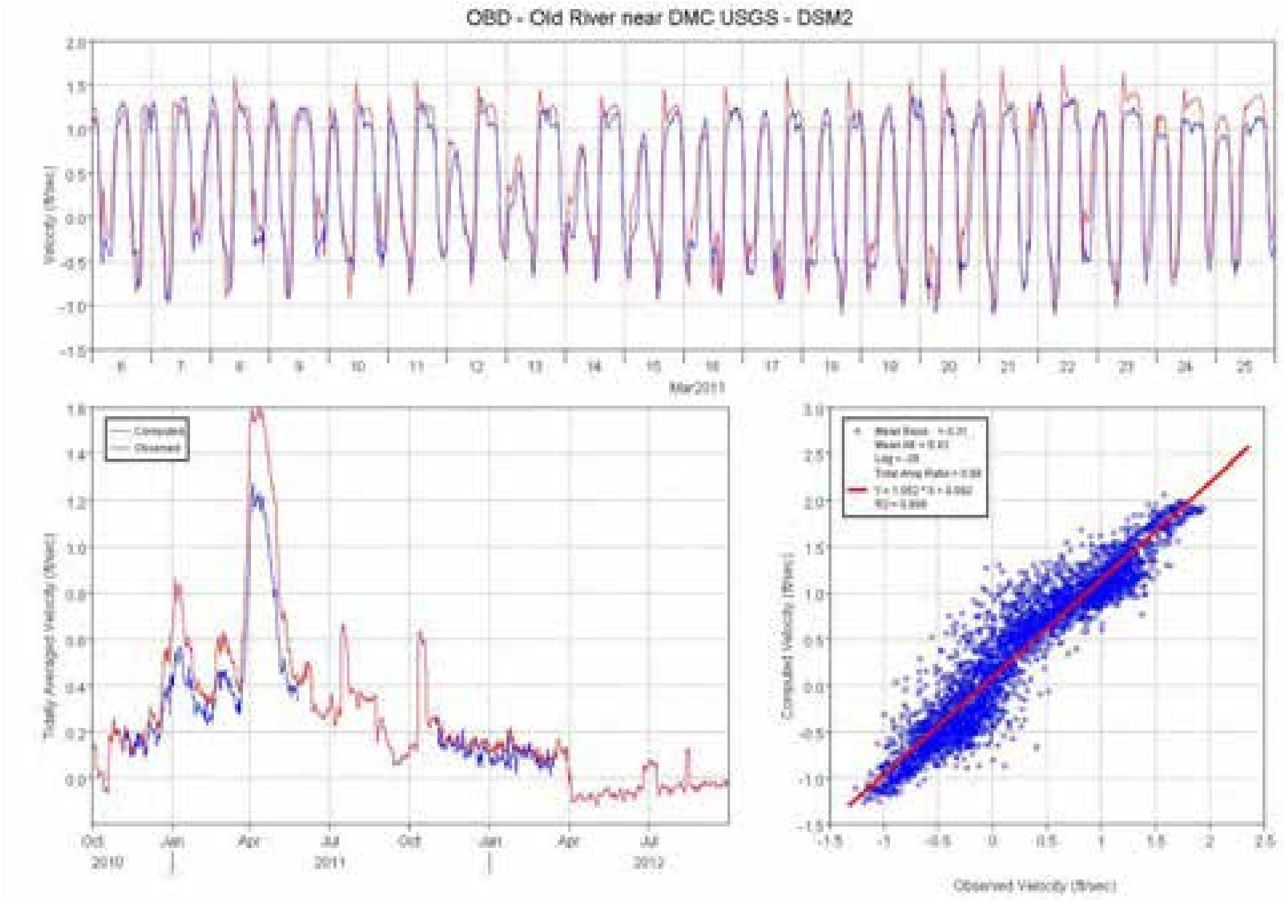


Figure 69 Computed (DSM2) and observed flow comparison plots for Old River near DMC.

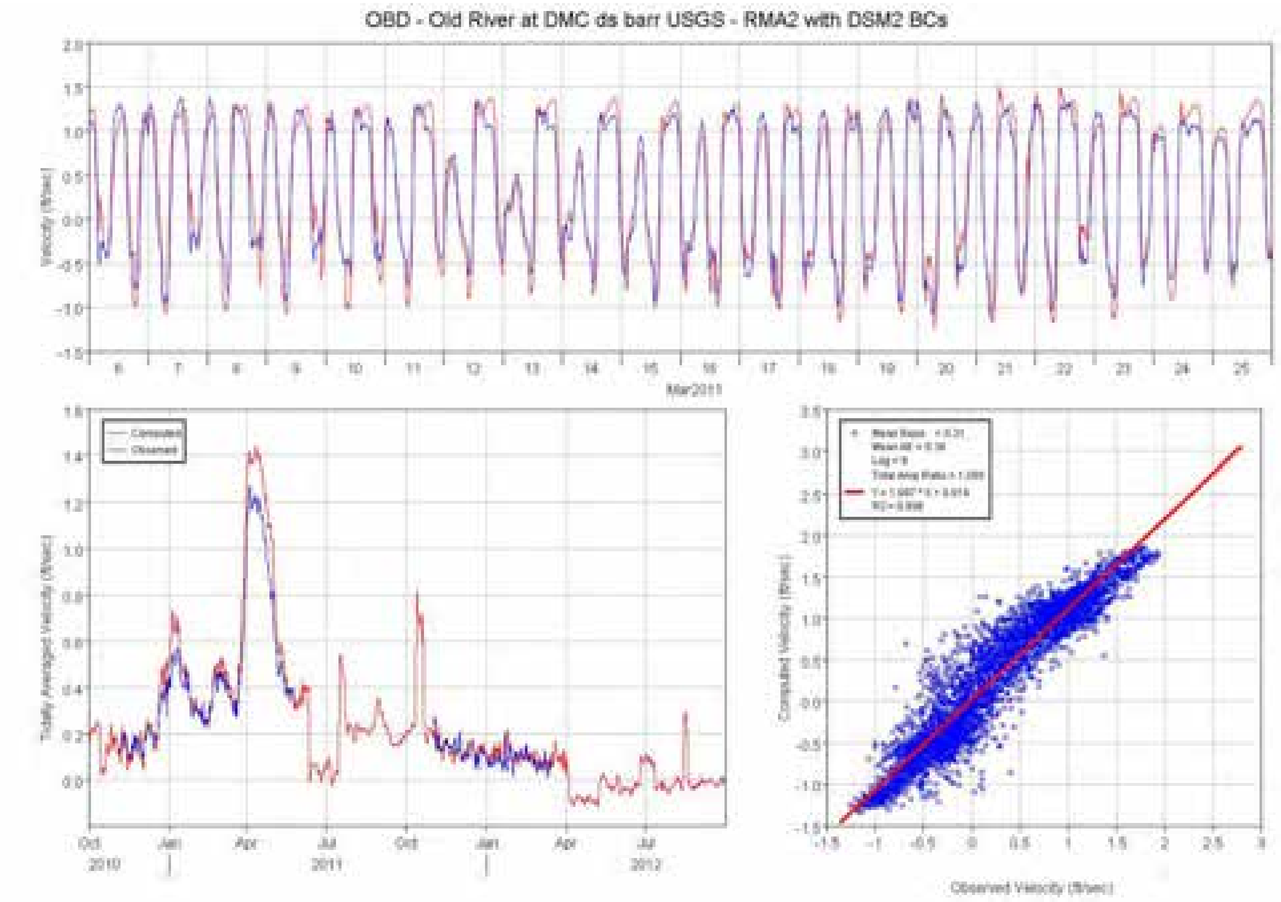


Figure 70 Computed (RMA2 with DSM2 BCs) and observed flow comparison plots for Old River near DMC.

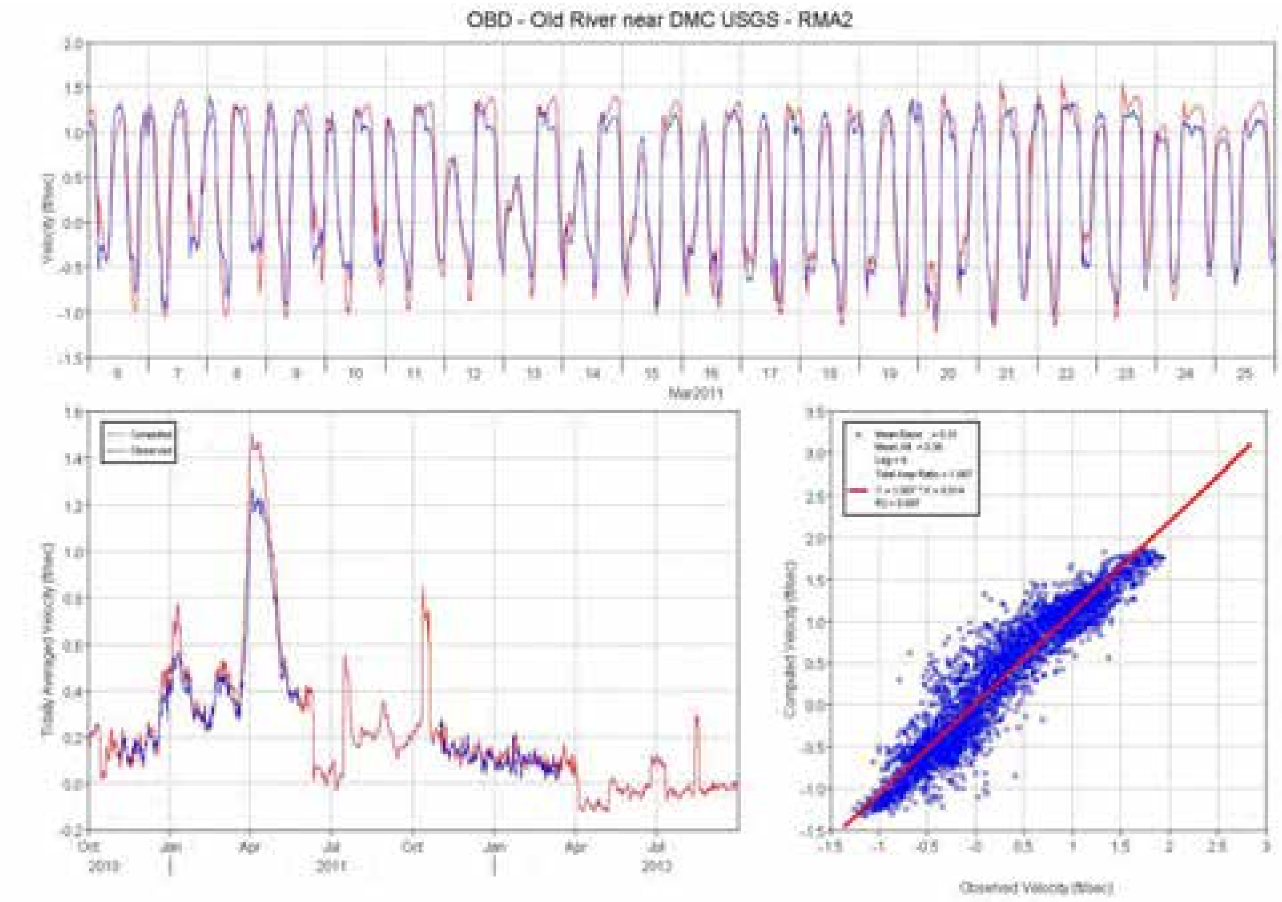


Figure 71 Computed (RMA2) and observed flow comparison plots for Old River near DMC.

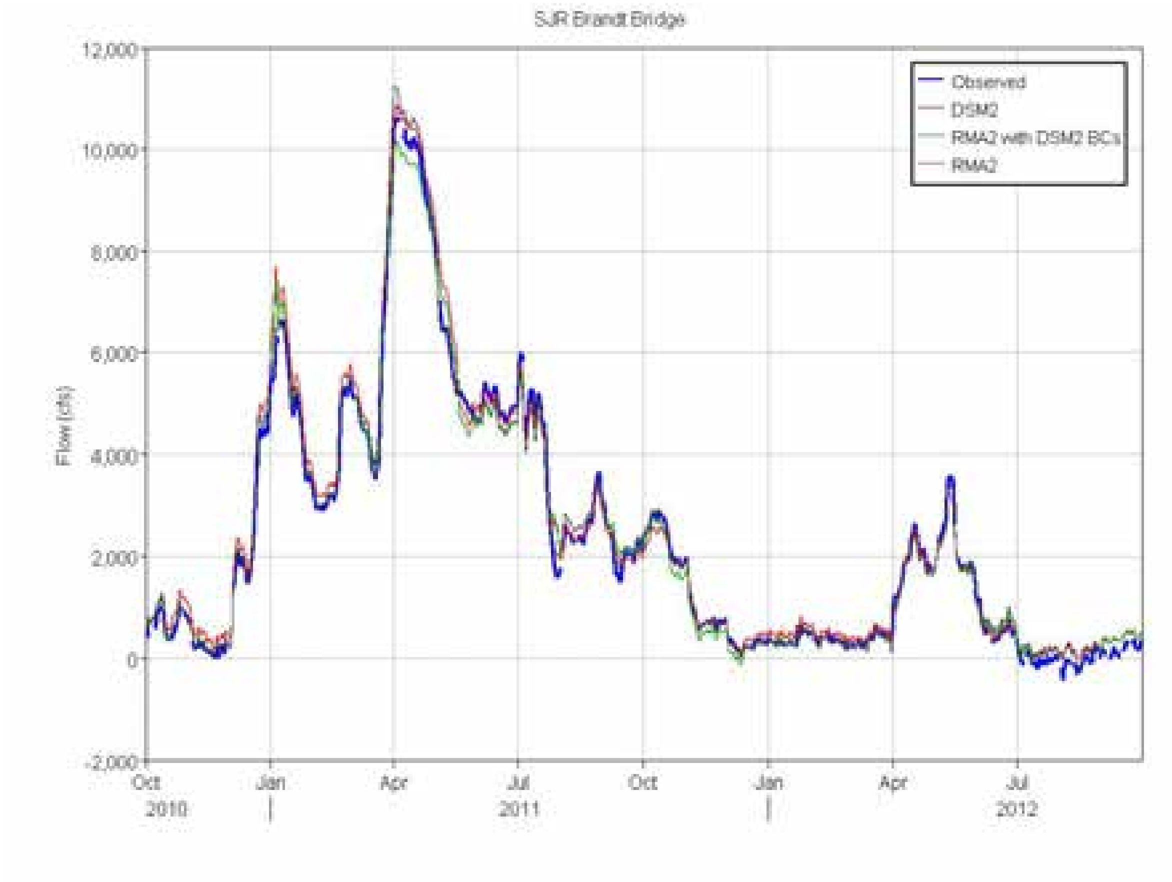


Figure 72 Tidally averaged observed and computed flows for SJR at Brandt Bridge.

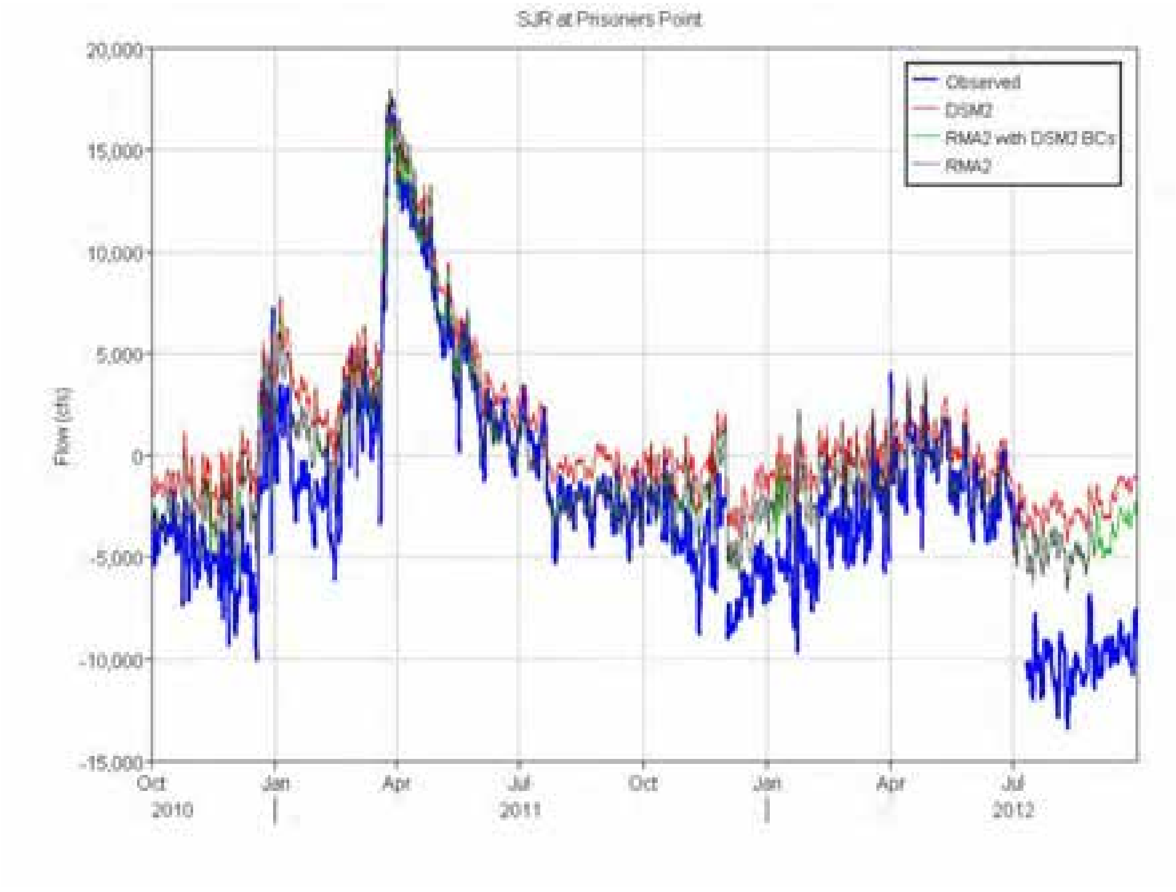


Figure 73 Tidally averaged observed and computed flows for SJR Prisoner Point.

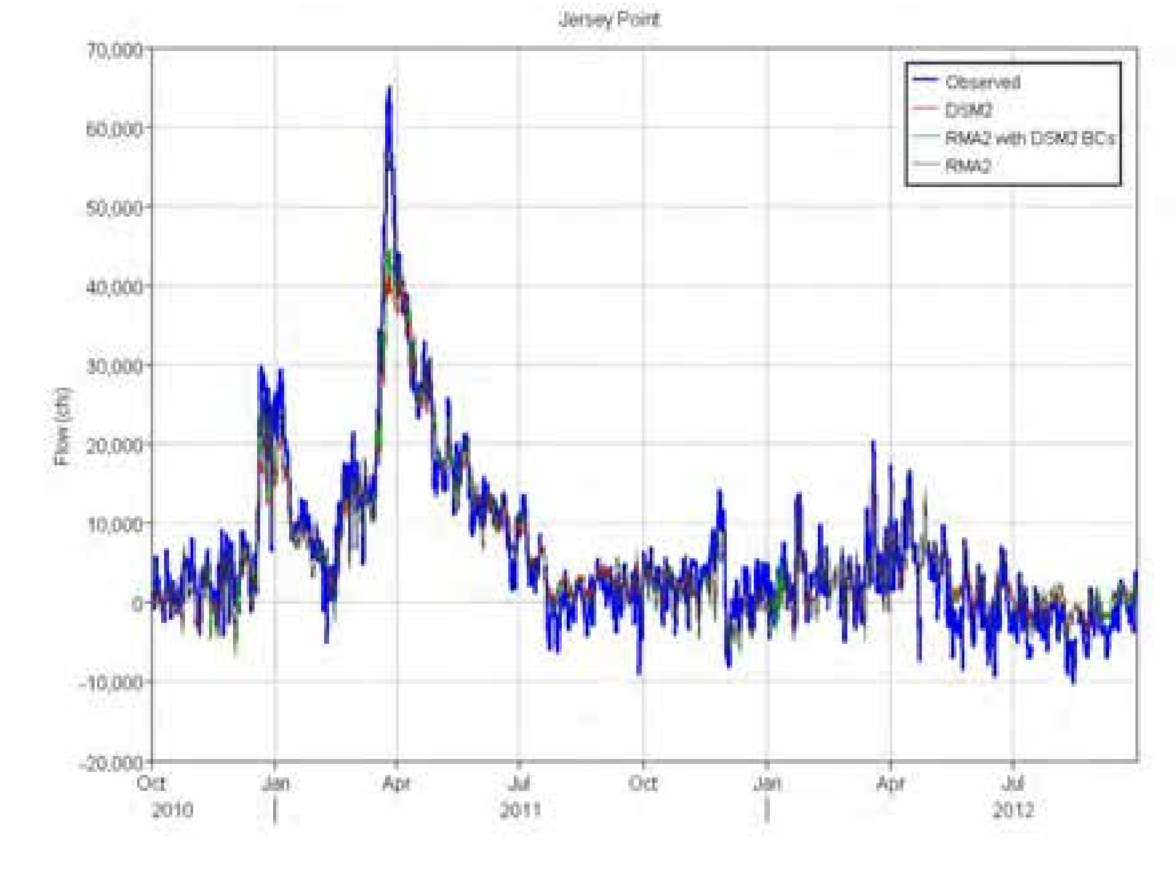


Figure 74 Tidally averaged observed and computed flows for Jersey Point.

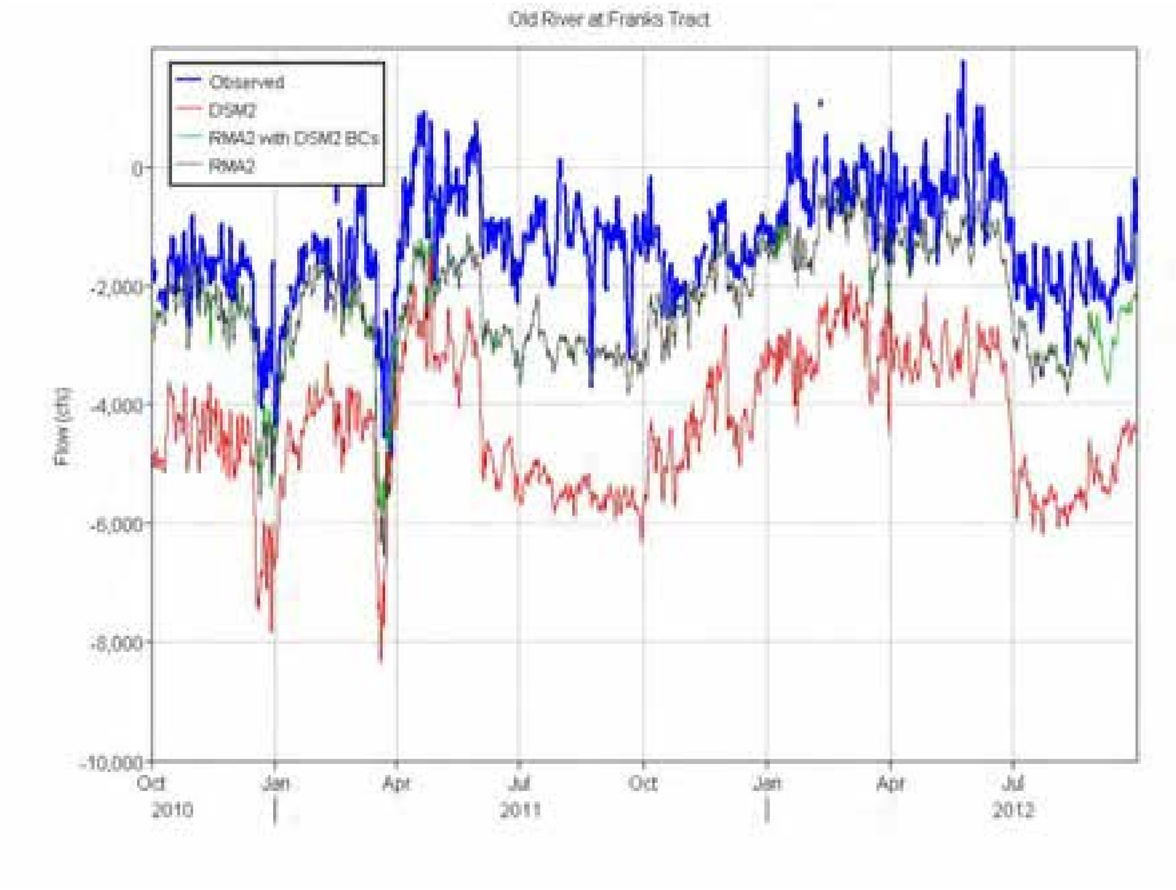


Figure 75 Tidally averaged observed and computed flows for Old River at Franks Tract.

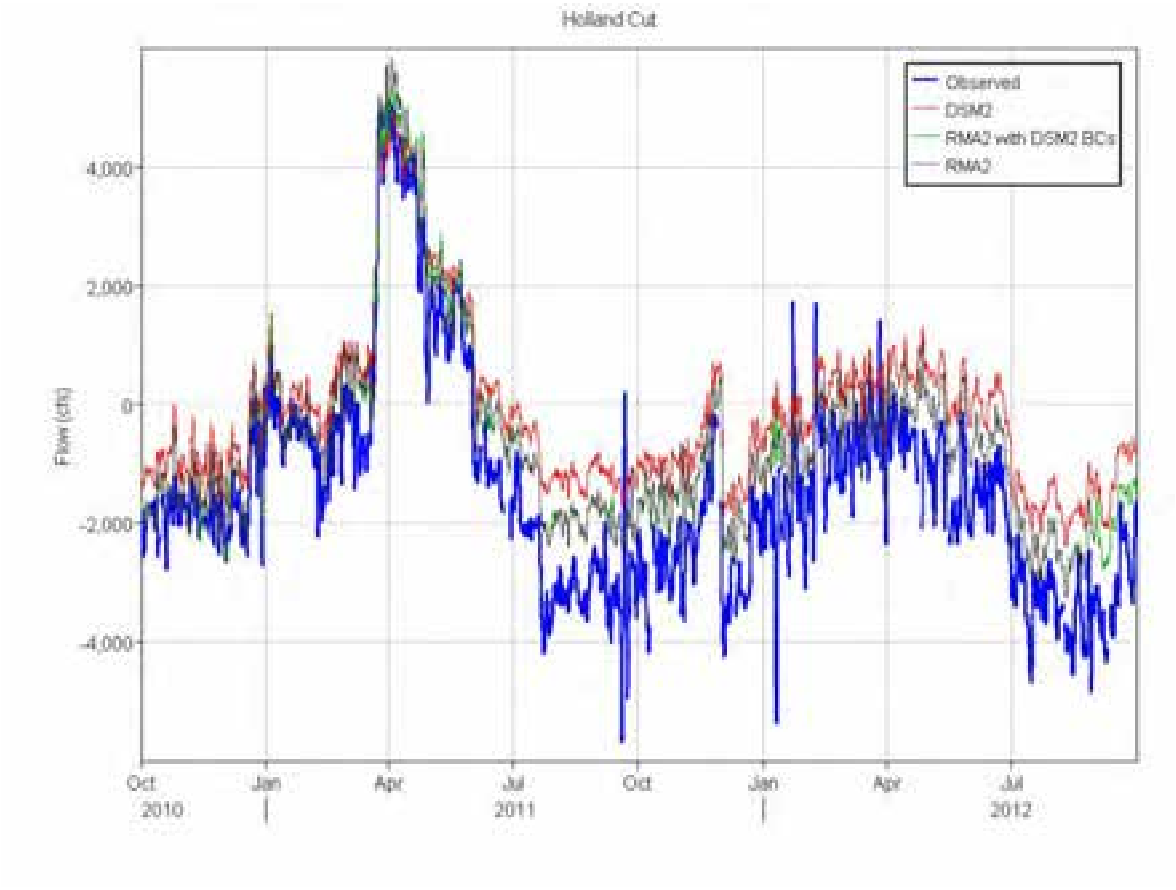


Figure 76 Tidally averaged observed and computed flows for Holland Cut.

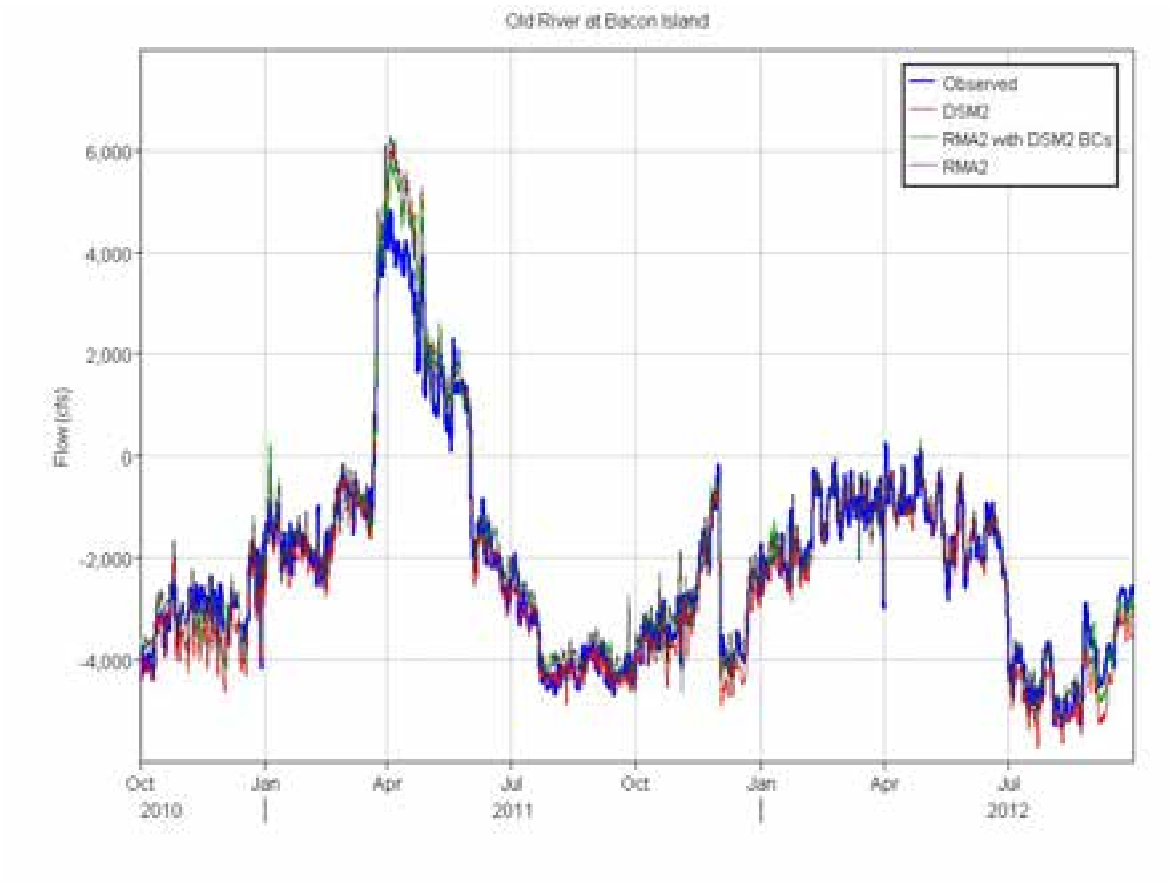


Figure 77 Tidally averaged observed and computed flows for Old River at Bacon Island.

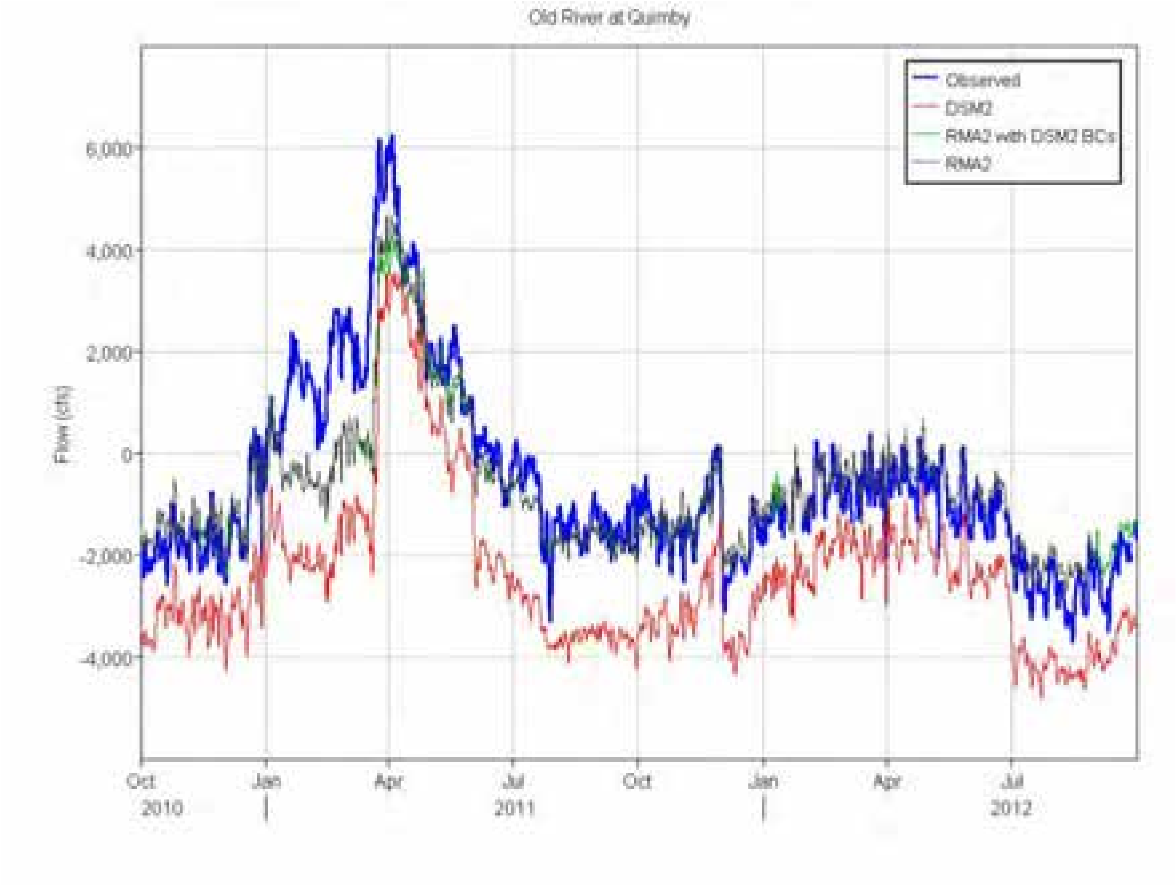


Figure 78 Tidally averaged observed and computed flows for Old River at Quimby.

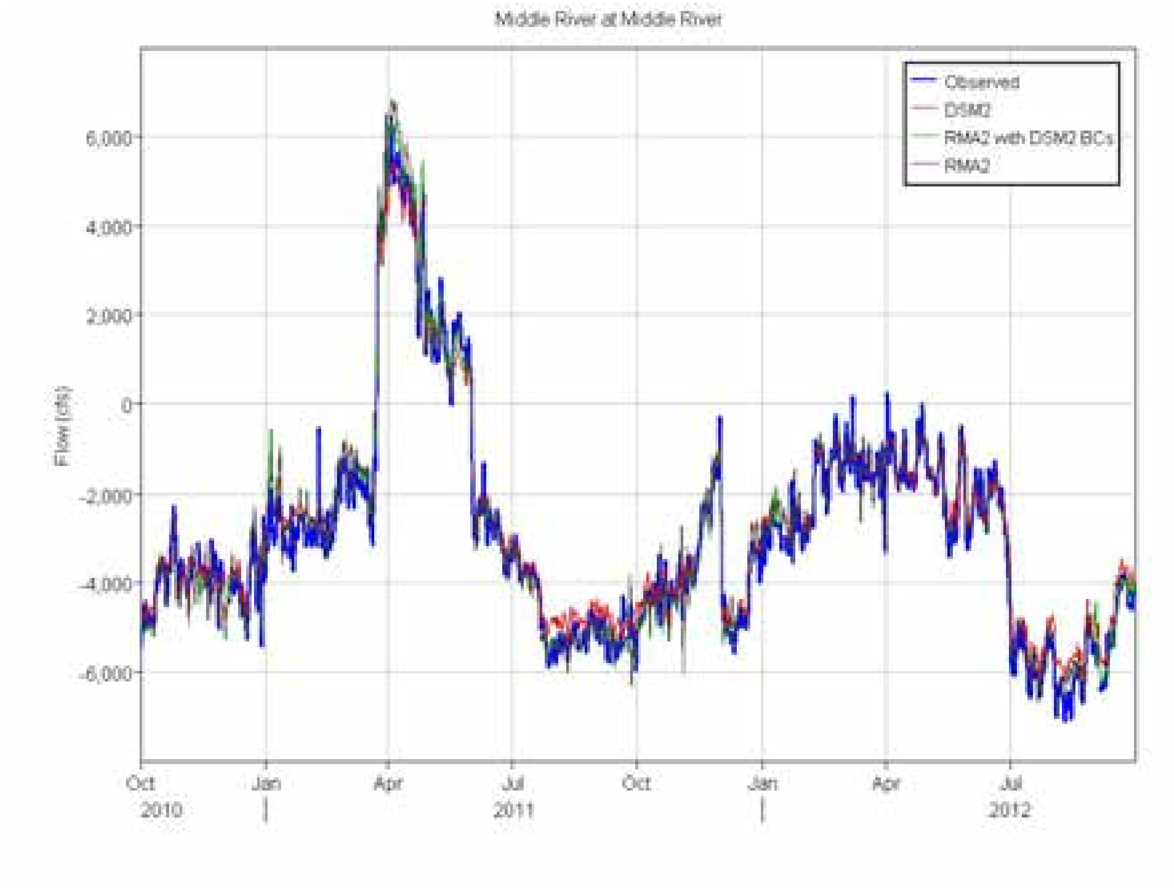


Figure 79 Tidally averaged observed and computed flows for Middle River at Middle River.

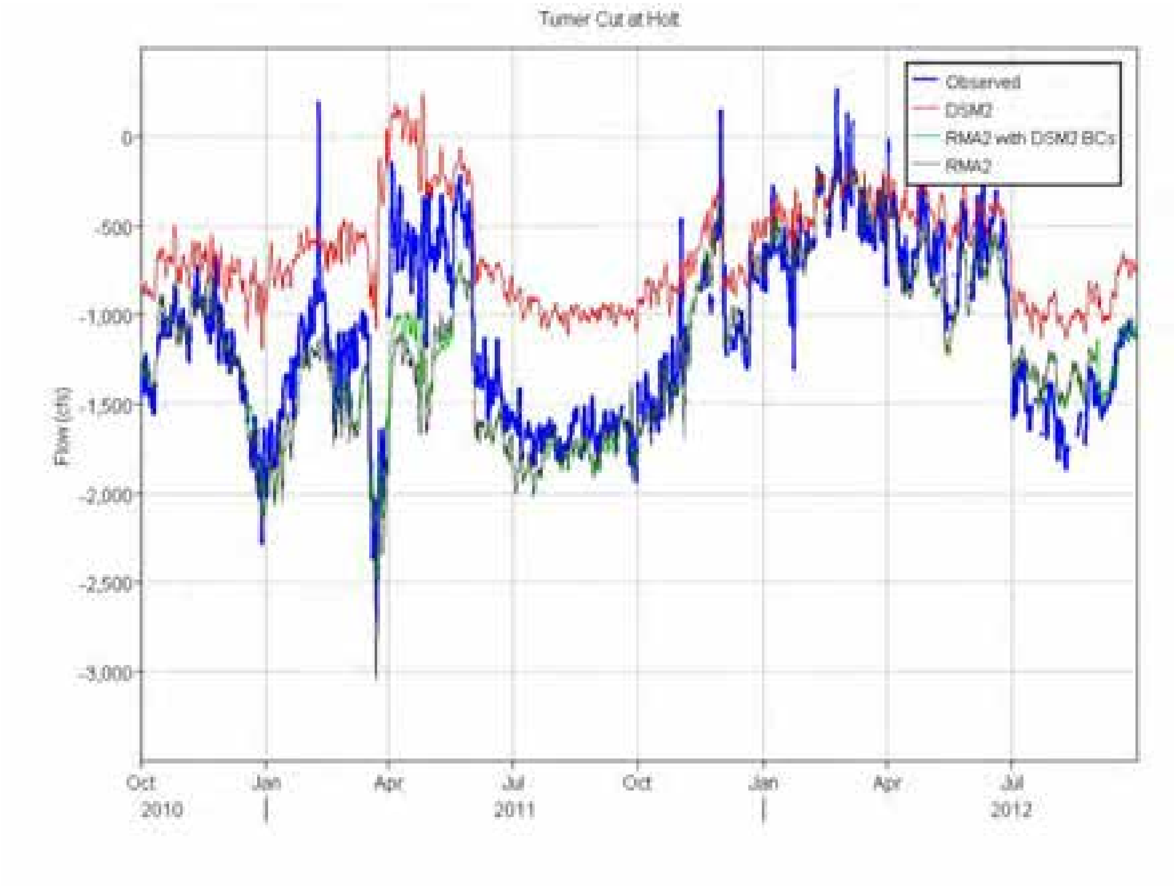


Figure 80 Tidally averaged observed and computed flows for Turner Cut at Holt.

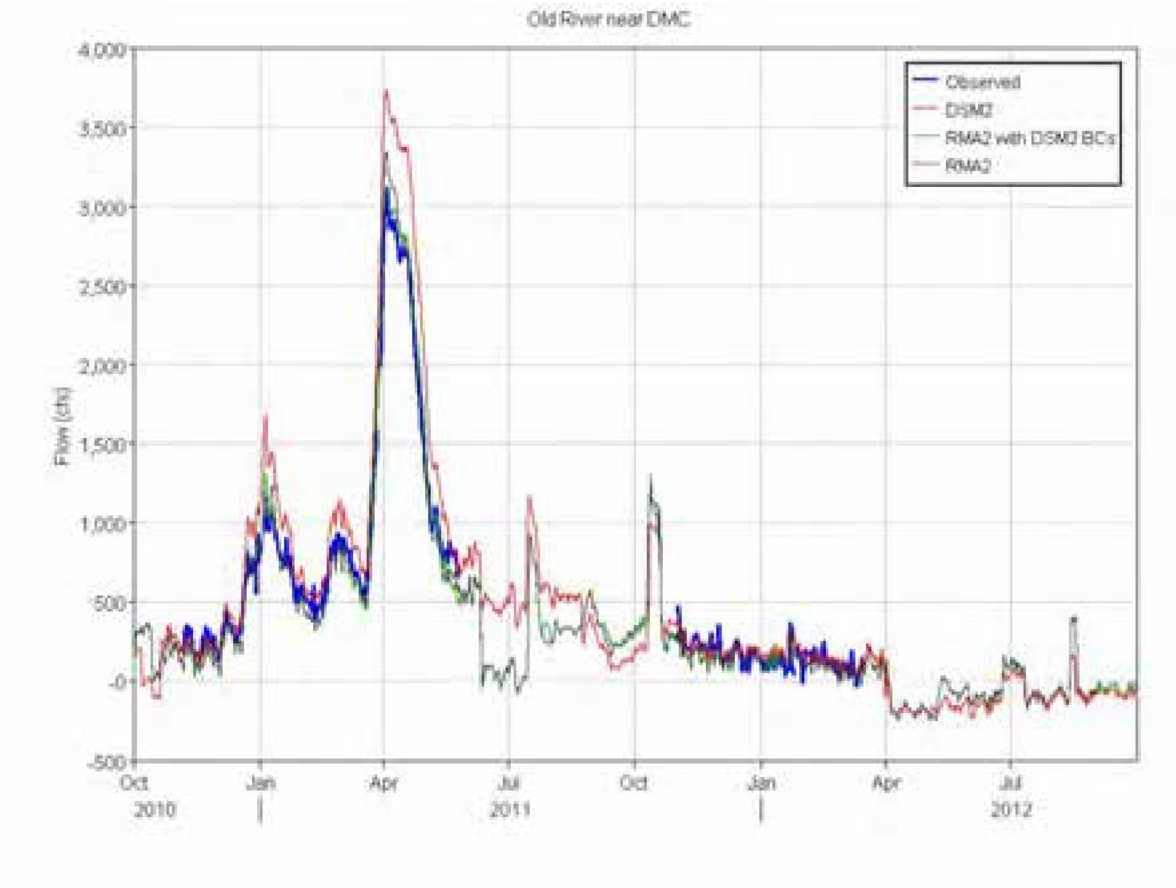


Figure 81 Tidally averaged observed and computed flows for Old River at DMC ds Barrier.

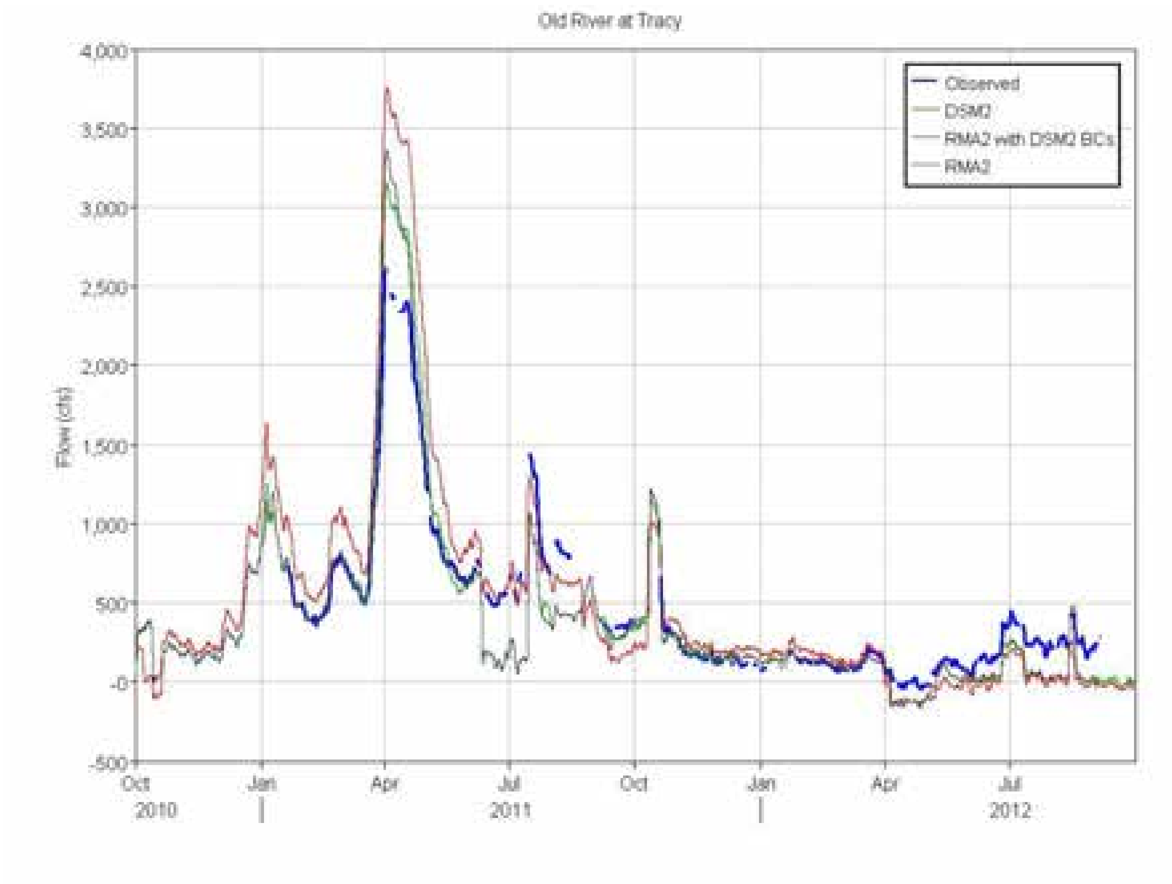


Figure 82 Tidally averaged observed and computed flows for Old River at Tracy.

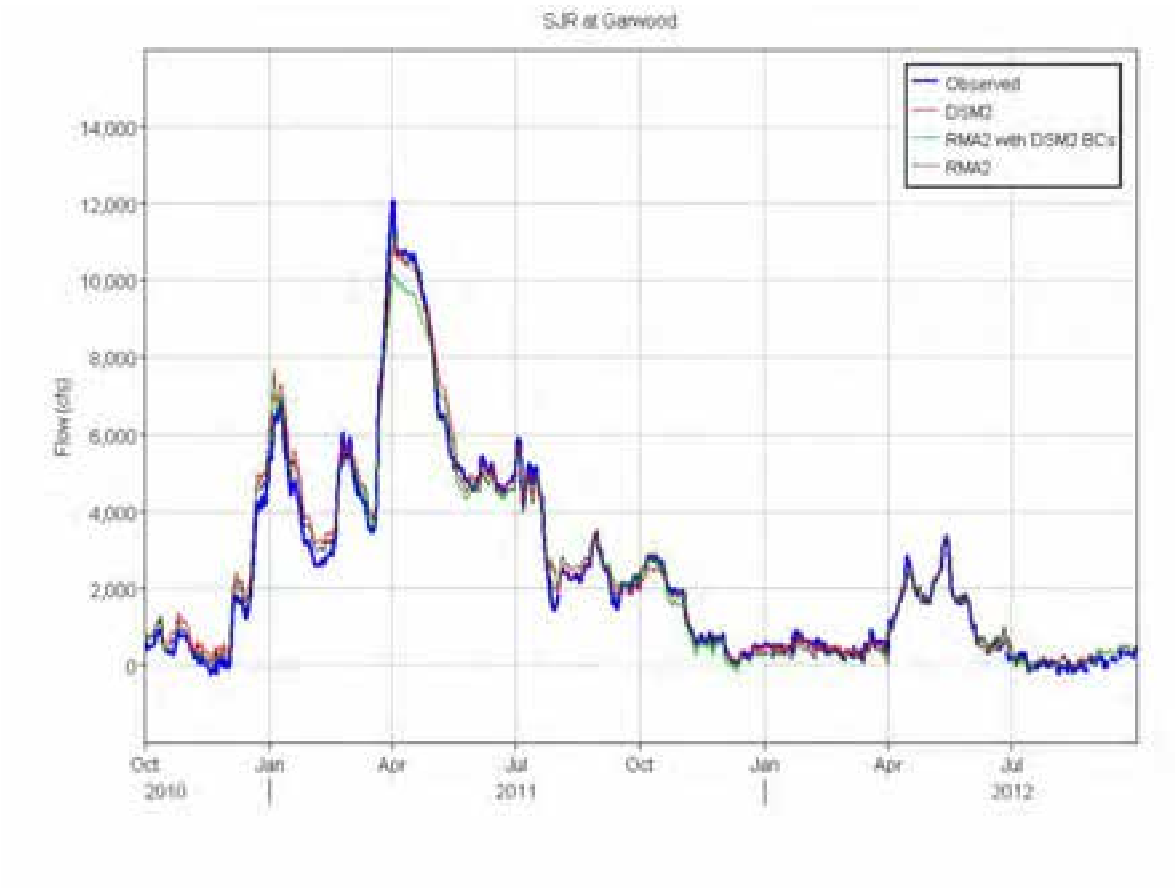


Figure 83 Tidally averaged observed and computed flows for Old River at Hwy 4.

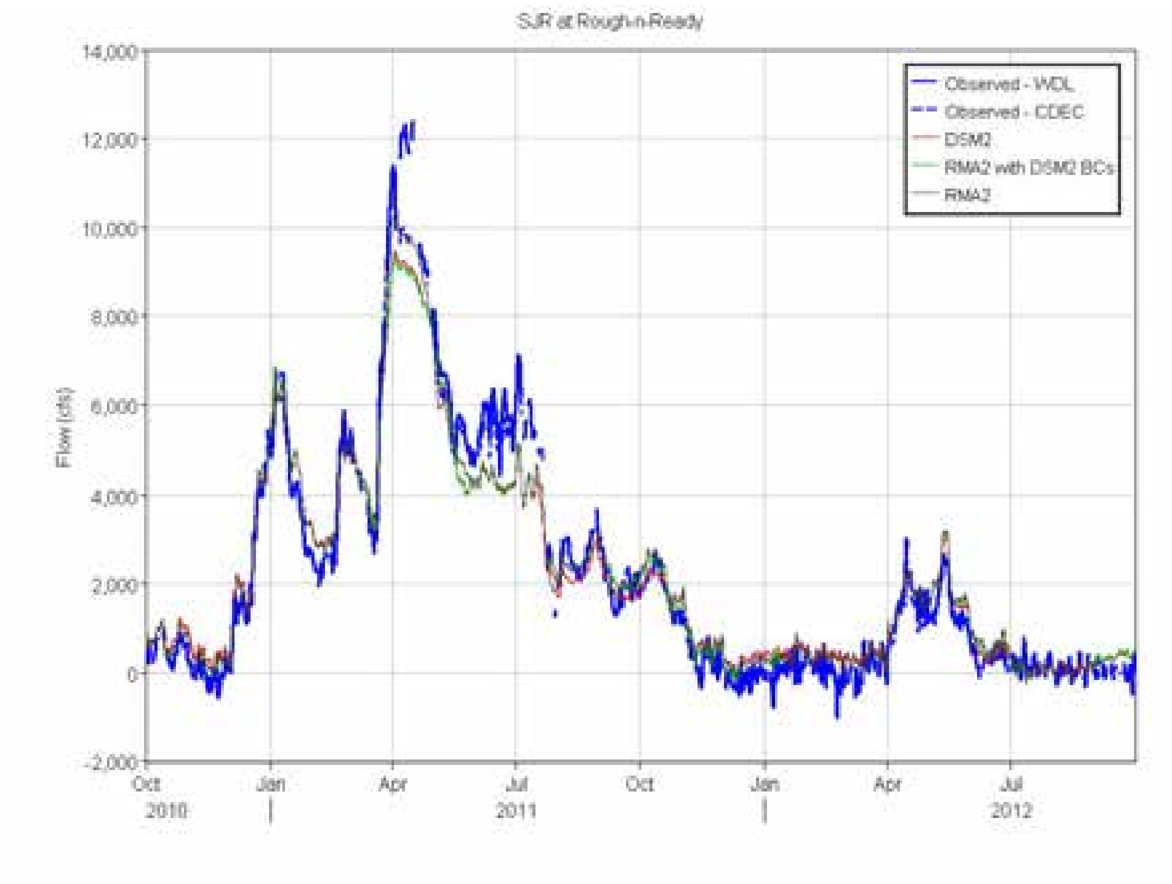


Figure 84 Tidally averaged observed and computed flows for SJR at Rough-n-Ready.

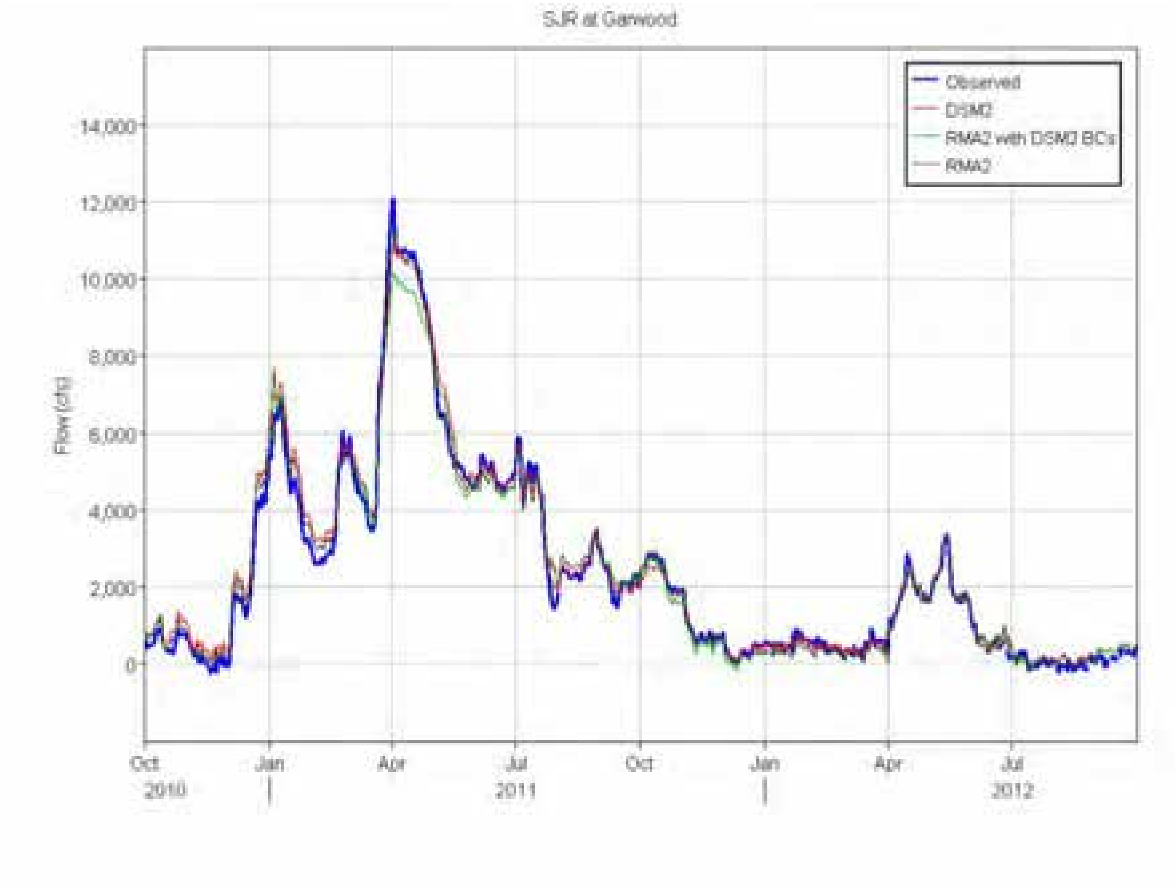


Figure 85 Tidally averaged observed and computed flows for SJR at Garwood.

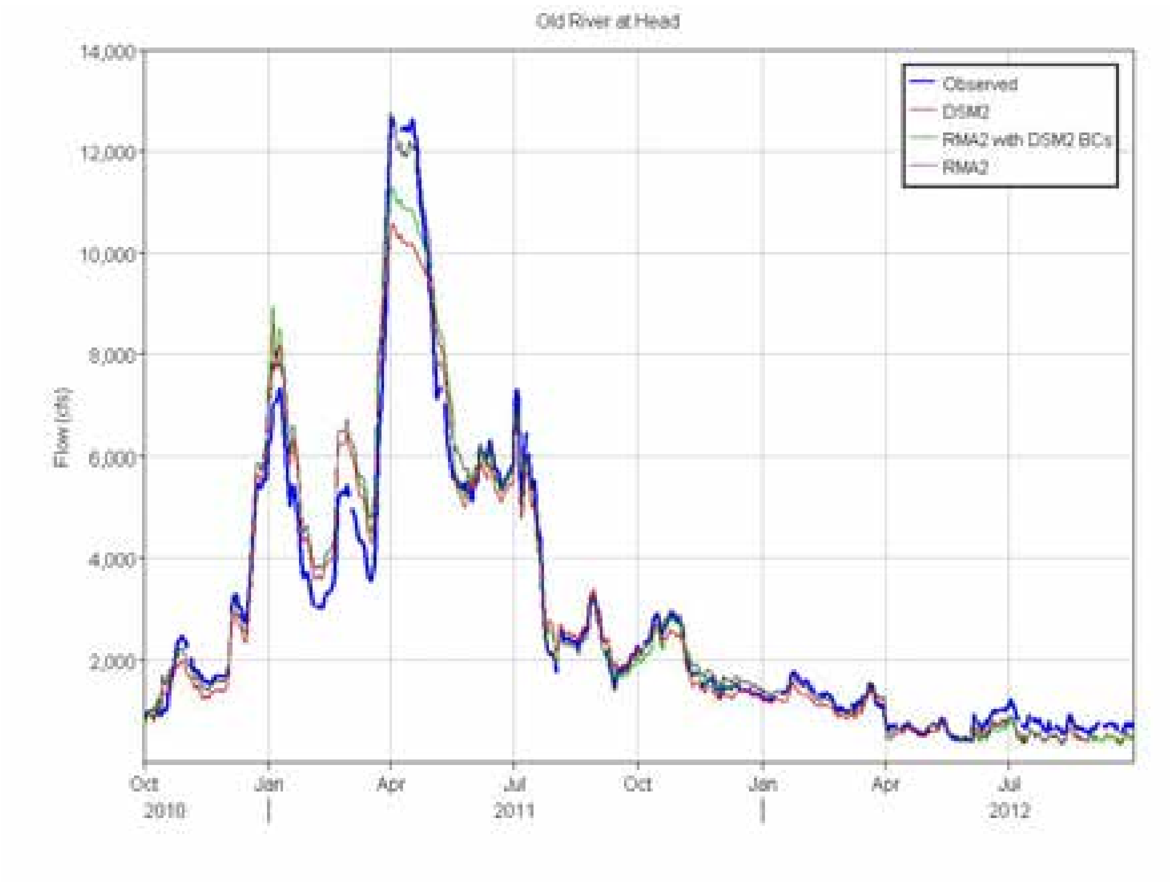


Figure 86 Tidally averaged observed and computed flows for Old River at Head.

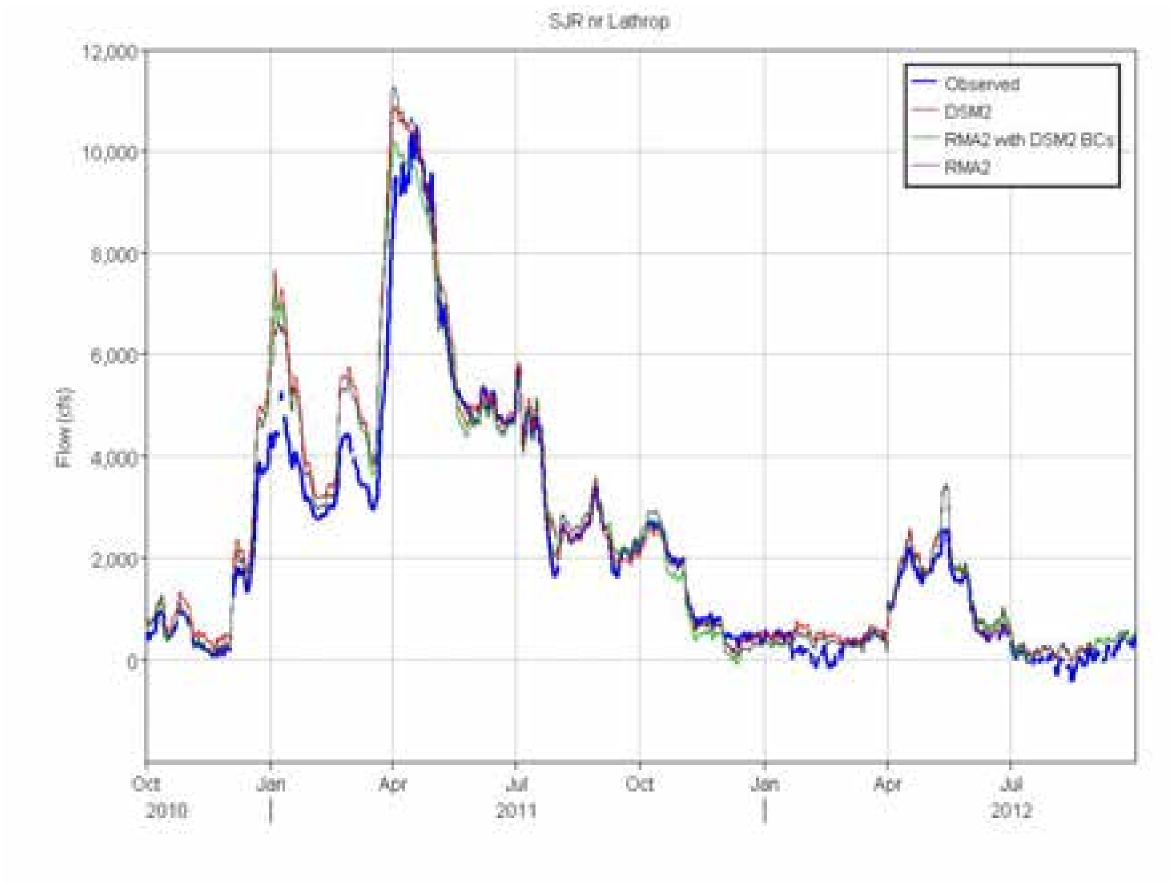


Figure 87 Tidally averaged observed and computed flows for SJR near Lathrop.

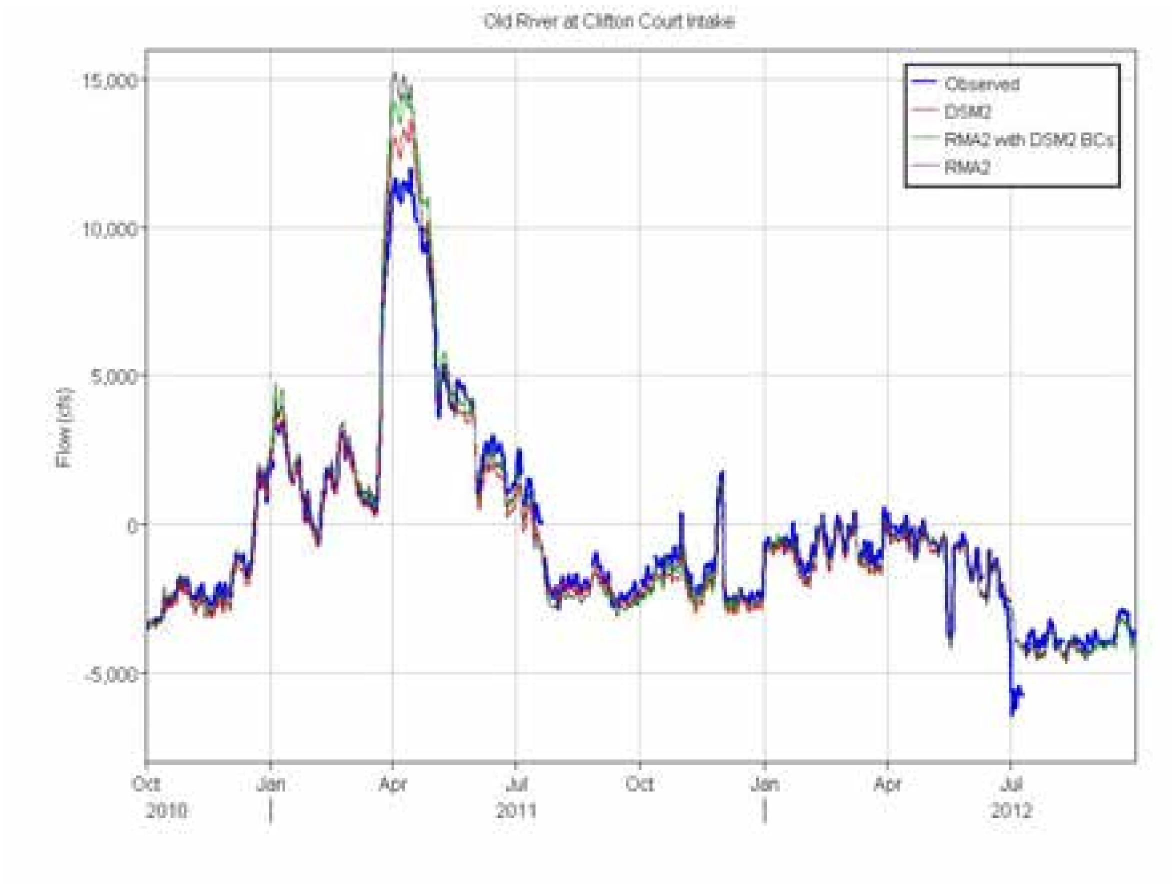


Figure 88 Tidally averaged observed and computed flows for Old River at Clifton Court Intake.

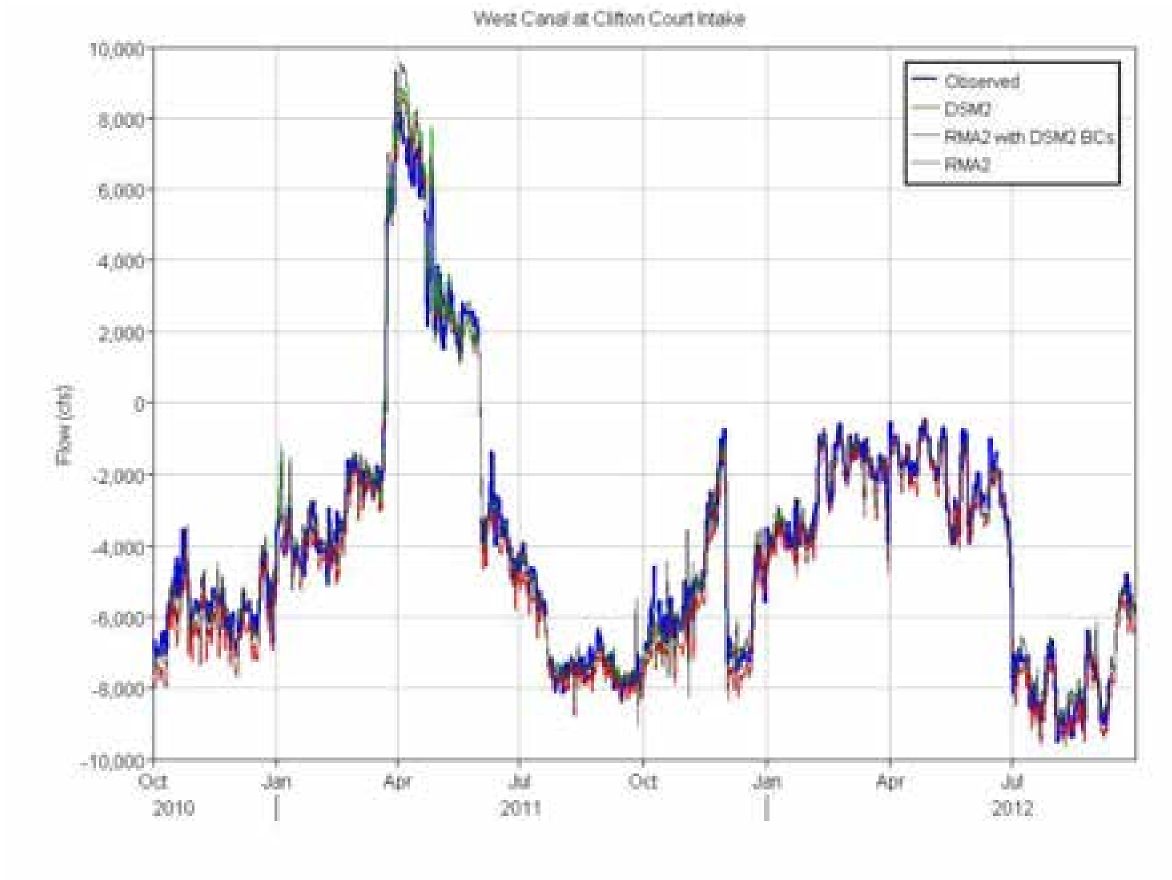


Figure 89 Tidally averaged observed and computed flows for West Canal at Clifton Court Intake.

Velocity Results Comparison

In Figure 91 through Figure 138, computed velocities for the three model simulations are compared with CDEC and USGS observed data (data sources are noted in plot titles). Error metrics from these plots are summarized by location in Table 4. Plot locations are shown in Figure 90. USGS data were used where available. CDEC data are likely to contain uncorrected time shifts which can result in apparent larger lag errors.

Table 5 summarizes velocity results for each model by error metric (percent difference from observed, lag, amplitude ratio and R^2) and model skill. Table cells are color coded for a quick assessment of goodness of fit with observed data, ranging from green for better fit to red for worse fit. Relative to the flow error metrics, the DSM2 and RMA velocity error metrics indicate worse agreement with observed data. However, for both models, the model skill is within the accurate range on average and for most individual stations. For velocity, a skill accuracy greater than 0.9 is considered accurate, 0.8-0.9 is considered acceptable and a skill accuracy below 0.8 is considered poor agreement. The average model skill for velocity is 0.940 for DSM2 and 0.945 for RMA2.

Comparison of velocity results among the model simulations and with observed data generally shows the same trends as flow data. Where there are disparities between flow and velocity comparison, this indicates either model geometry issues or problems with calculation of observed flow from observed velocity.

In Old River at Bacon, tidally averaged RMA2 results more closely match flow data than velocity data during periods of net flow greater than about +/-2000 cfs, which may indicate problems with the RMA2 model geometry.

For both models, tidal and tidally averaged flows are in reasonably good agreement with observed data in Old River at Hwy 4 (model skill = 0.970 for DSM2 and 0.979 for RMA2), whereas the matches with observed tidal and tidally averaged velocities are poor (model skill = 0.778 for DSM2 and 0.786 for RMA2). It is not clear whether this issue affects both models because they both use the same inaccurate bathymetry data to set model geometry, or whether there is an issue with the velocity observations.

Table 4 Velocity error metrics summary. Asterisks after station names indicate that observed data are from CDEC, which can contain time shift errors.

	DSM2	RMA2 w DSM2 BC	RMA2	DSM2	RMA2 w DSM2 BC	RMA2	DSM2	RMA2 w DSM2 BC	RMA2
	SJR at Brandt Bridge*			Old River at Quimby			SJR at Garwood		
mean diff (ft/s)	-0.08	-0.10	-0.09	-0.13	-0.01	-0.01	0.06	0.02	0.04
lag (minutes)	1	27	27	-12	-15	-14	-32	-10	-10
ampRatio	0.861	0.918	0.915	0.899	0.910	0.911	0.989	1.110	1.110
slope	0.873	0.889	0.892	0.895	0.901	0.902	1.004	1.026	1.043
intercept	0.1	0.0	0.0	-0.1	0.0	0.0	0.1	0.0	0.0
R2	0.957	0.956	0.960	0.967	0.968	0.969	0.973	0.971	0.978
	SJR at Prisoners Point			Turner Cut at Holt			Old River at Head		
mean diff (ft/s)	0.07	0.03	0.03	0.10	-0.01	-0.01	-0.13	-0.20	-0.18
lag (minutes)	-43	-26	-26	-90	-8	-7	18	40	41
ampRatio	0.904	0.927	0.927	0.896	0.504	0.505	0.748	0.625	0.619
slope	0.902	0.924	0.924	0.867	0.517	0.517	1.063	1.018	1.027
intercept	0.1	0.0	0.0	0.1	-0.1	-0.1	-0.2	-0.2	-0.2
R2	0.975	0.972	0.973	0.898	0.794	0.794	0.922	0.922	0.921
	SJR at Jersey Pt			Old River near DMC*			SJR nr Lathrop		
mean diff (ft/s)	-0.05	-0.01	-0.01	0.11	0.04	0.04	-0.14	-0.16	-0.15
lag (minutes)	-27	-13	-13	-26	9	9	21	43	44
ampRatio	0.652	0.953	0.953	0.990	1.065	1.067	0.584	0.655	0.656
slope	0.651	0.951	0.952	1.052	1.087	1.087	0.796	0.862	0.858
intercept	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.0
R2	0.987	0.987	0.989	0.899	0.896	0.897	0.804	0.838	0.854
	Old River at Franks Tr			Old River at Tracy			Old R at Clifton Court Intake		
mean diff (ft/s)	-0.14	-0.04	-0.04	-0.07	-0.07	-0.07	-0.06	-0.01	-0.01
lag (minutes)	-22	6	6	0	47	47	10	37	37
ampRatio	0.993	0.592	0.593	0.822	0.741	0.743	1.043	0.947	0.946
slope	0.990	0.593	0.593	1.010	0.990	0.984	1.142	1.057	1.059
intercept	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	0.0	0.0	0.0
R2	0.936	0.917	0.918	0.806	0.736	0.734	0.849	0.848	0.849
	Holland Cut			Old River at Hwy 4			West Canal at Clifton Ct*		
mean diff (ft/s)	0.10	0.07	0.07	0.69	0.71	0.71	-0.10	-0.05	-0.05
lag (minutes)	-27	-20	-20	-24	-8	-8	28	40	40
ampRatio	0.973	0.900	0.900	0.395	0.403	0.404	1.006	0.973	0.974
slope	0.974	0.898	0.898	0.406	0.409	0.410	1.036	1.009	1.011
intercept	0.1	0.1	0.1	0.0	0.0	0.0	-0.1	0.0	0.0
R2	0.974	0.973	0.974	0.920	0.927	0.928	0.860	0.860	0.861
	Old River at Bacon			SJR at Rough-n-Ready*					
mean diff (ft/s)	0.00	0.04	0.04	0.01	-0.01	-0.01			
lag (minutes)	-17	-17	-17	-9	14	15			
ampRatio	0.879	0.909	0.909	0.878	1.018	1.018			
slope	0.888	0.909	0.910	0.881	0.947	0.955			
intercept	0.0	0.0	0.0	0.0	0.0	0.0			
R2	0.972	0.977	0.979	0.849	0.832	0.839			

Table 5 Summary of velocity error metrics and model skill with shading ranging from green for better fit to red for worse fit. Asterisks after station names indicate that observed data are from CDEC, which can contain time shift errors.

	% diff from observed			lag (minutes)			ampRatio			R2			Model Skill		
Station	**DSM2**	**RMA2 w DSM2 BC**	**RMA2**	**DSM2**	**RMA2 w DSM2 BC**	**RMA2**	**DSM2**	**RMA2 w DSM2 BC**	**RMA2**	**DSM2**	**RMA2 w DSM2 BC**	**RMA2**	**DSM2**	**RMA2 w DSM2 BC**	**RMA2**
SJR at Brandt Bridge*	-6.6%	-8.8%	-7.4%	1	27	27	0.861	0.918	0.915	0.957	0.956	0.960	0.984	0.980	0.982
SJR at Prisoners Point	187.5%	97.7%	99.7%	-43	-26	-26	0.904	0.927	0.927	0.975	0.972	0.973	0.954	0.978	0.978
SJR at Jersey Pt	-33.2%	-8.9%	-6.5%	-27	-13	-13	0.652	0.953	0.953	0.987	0.987	0.989	0.940	0.993	0.993
Old River at Franks Tr	-253.3%	-69.1%	-70.9%	-22	6	6	0.993	0.592	0.593	0.936	0.917	0.918	0.956	0.920	0.920
Holland Cut	93.2%	64.7%	65.2%	-27	-20	-20	0.973	0.900	0.900	0.974	0.973	0.974	0.975	0.981	0.982
Old River at Bacon	2.3%	21.4%	21.8%	-17	-17	-17	0.879	0.909	0.909	0.972	0.977	0.979	0.985	0.986	0.987
Old River at Quimby	-394.6%	-18.0%	-16.5%	-12	-15	-14	0.899	0.910	0.911	0.967	0.968	0.969	0.979	0.985	0.986
Turner Cut at Holt	55.0%	-5.2%	-5.4%	-90	-8	-7	0.896	0.504	0.505	0.898	0.794	0.794	0.805	0.871	0.871
Old River near DMC	34.7%	13.2%	13.1%	-26	9	9	0.990	1.065	1.067	0.899	0.896	0.897	0.952	0.966	0.966
Old River at Tracy*	-18.6%	-18.3%	-17.8%	0	47	47	0.822	0.741	0.743	0.806	0.736	0.734	0.937	0.902	0.902
Old River at Hwy 4	58.9%	60.6%	60.7%	-24	-8	-8	0.395	0.403	0.404	0.920	0.927	0.928	0.778	0.785	0.786
SJR at Rough-n-Ready*	4.6%	-7.1%	-5.2%	-9	14	15	0.878	1.018	1.018	0.849	0.832	0.839	0.957	0.949	0.951
SJR at Garwood	8.4%	3.1%	5.1%	-32	-10	-10	0.989	1.110	1.110	0.973	0.971	0.978	0.983	0.991	0.993
Old River at Head*	-10.2%	-15.7%	-14.5%	18	40	41	0.748	0.625	0.619	0.922	0.922	0.921	0.969	0.958	0.960
SJR nr Lathrop*	-12.4%	-14.2%	-13.1%	21	43	44	0.584	0.655	0.656	0.804	0.838	0.854	0.931	0.932	0.937
Old R at Clifton Court Intake*	-95.2%	-23.8%	-21.4%	10	37	37	1.043	0.947	0.946	0.849	0.848	0.849	0.945	0.936	0.936
West Canal at Clifton Ct Intake*	-14.3%	-7.4%	-7.2%	28	40	40	1.006	0.973	0.974	0.860	0.860	0.861	0.949	0.940	0.940
Average of absolute values	72.8%	25.6%	25.3%	24	22	22	0.854	0.832	0.832	0.915	0.904	0.907	0.940	0.944	0.945

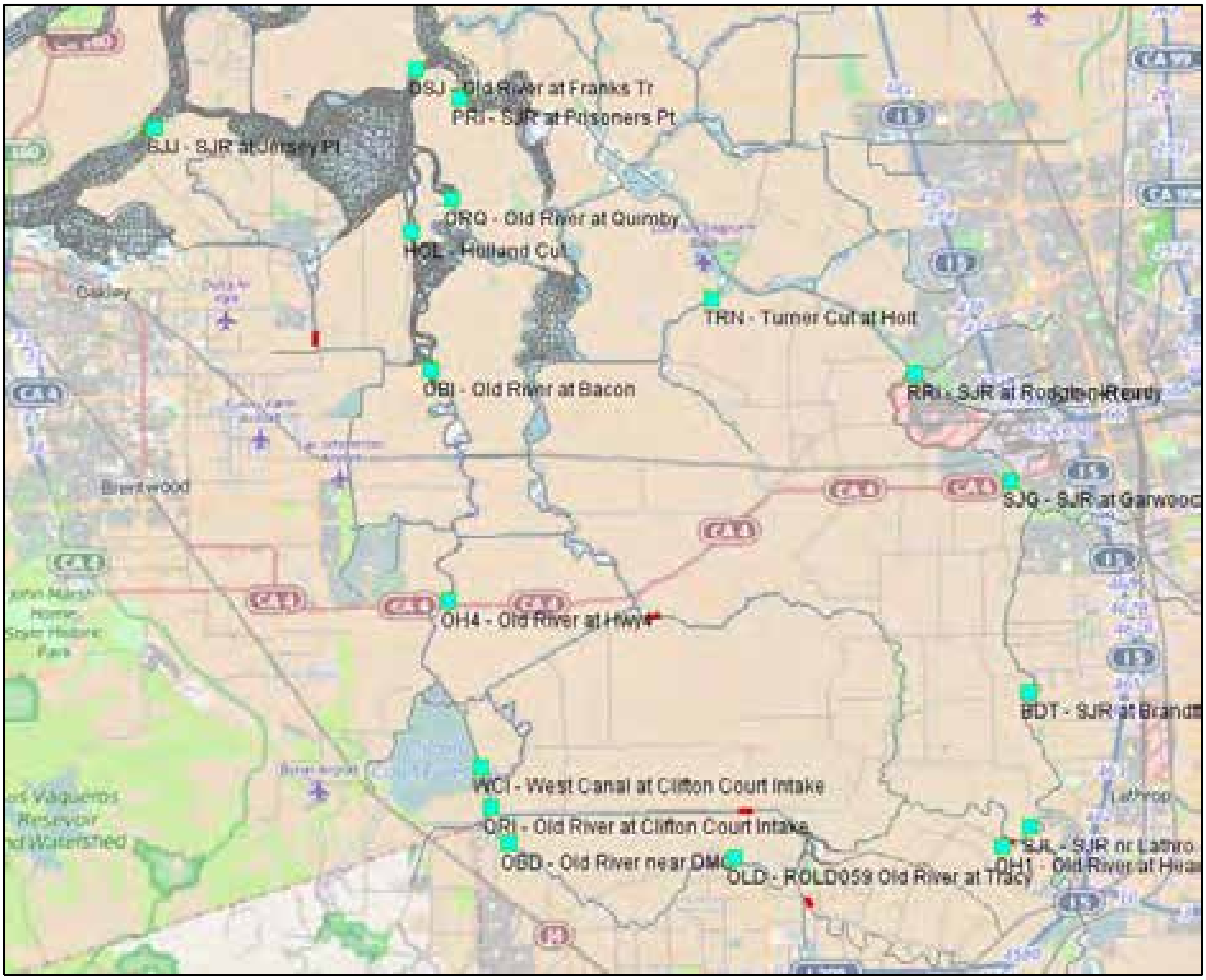


Figure 90 Velocity comparison plot locations.

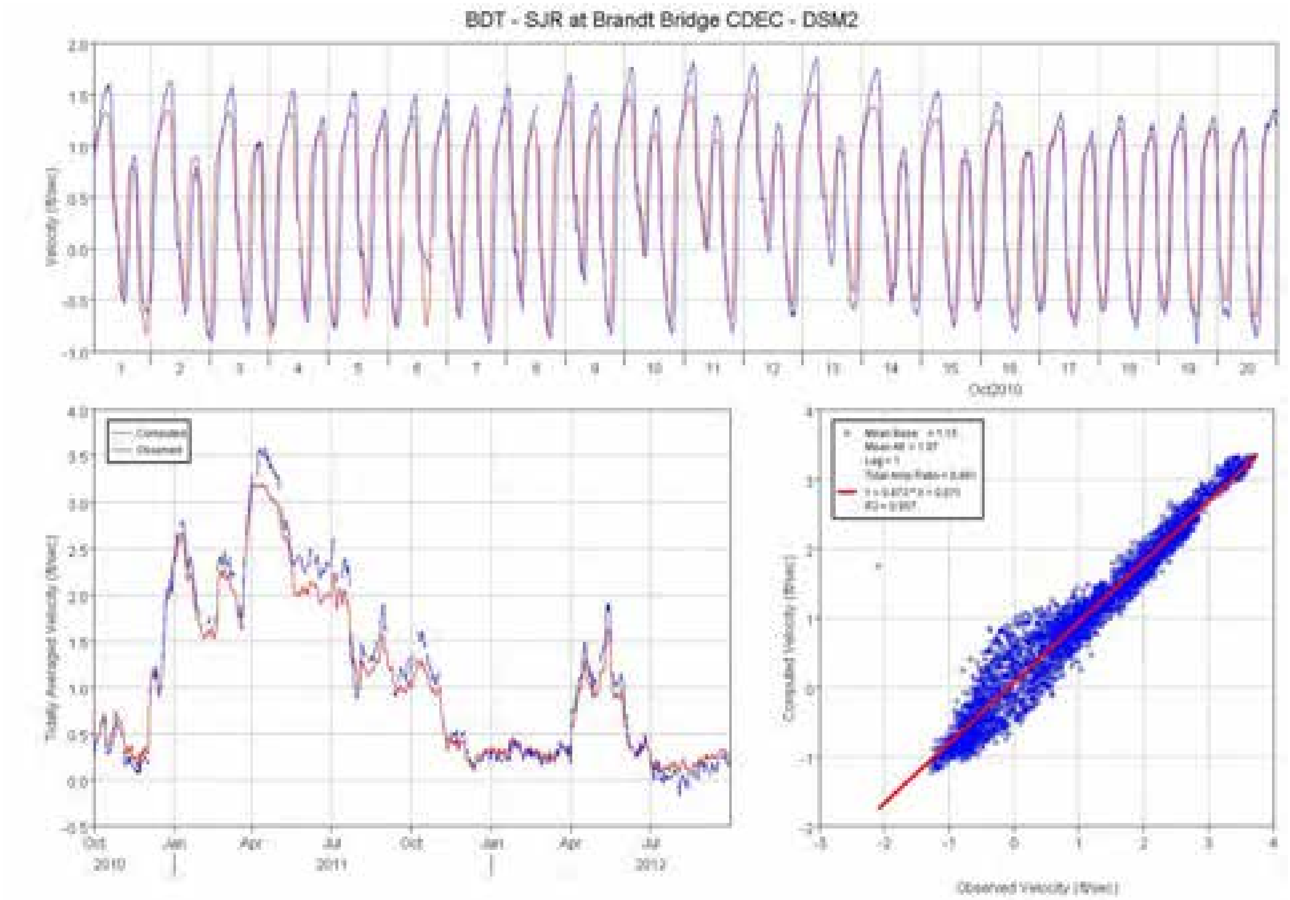


Figure 91 Computed (DSM2) and observed velocity comparison plots for San Joaquin River at Brandt Bridge.

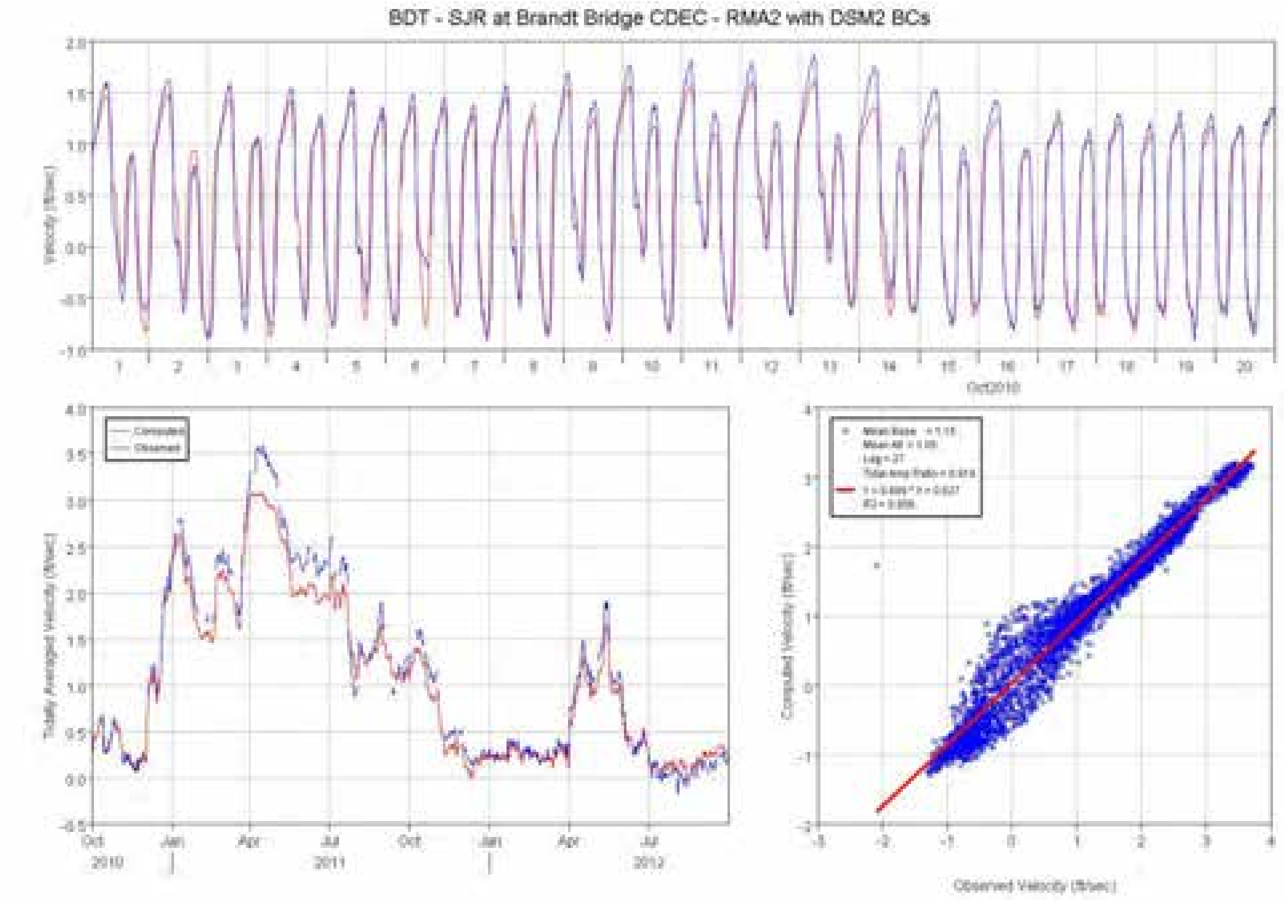


Figure 92 Computed (RMA2 with DSM2 BCs) and observed velocity comparison plots for San Joaquin River at Brandt Bridge.

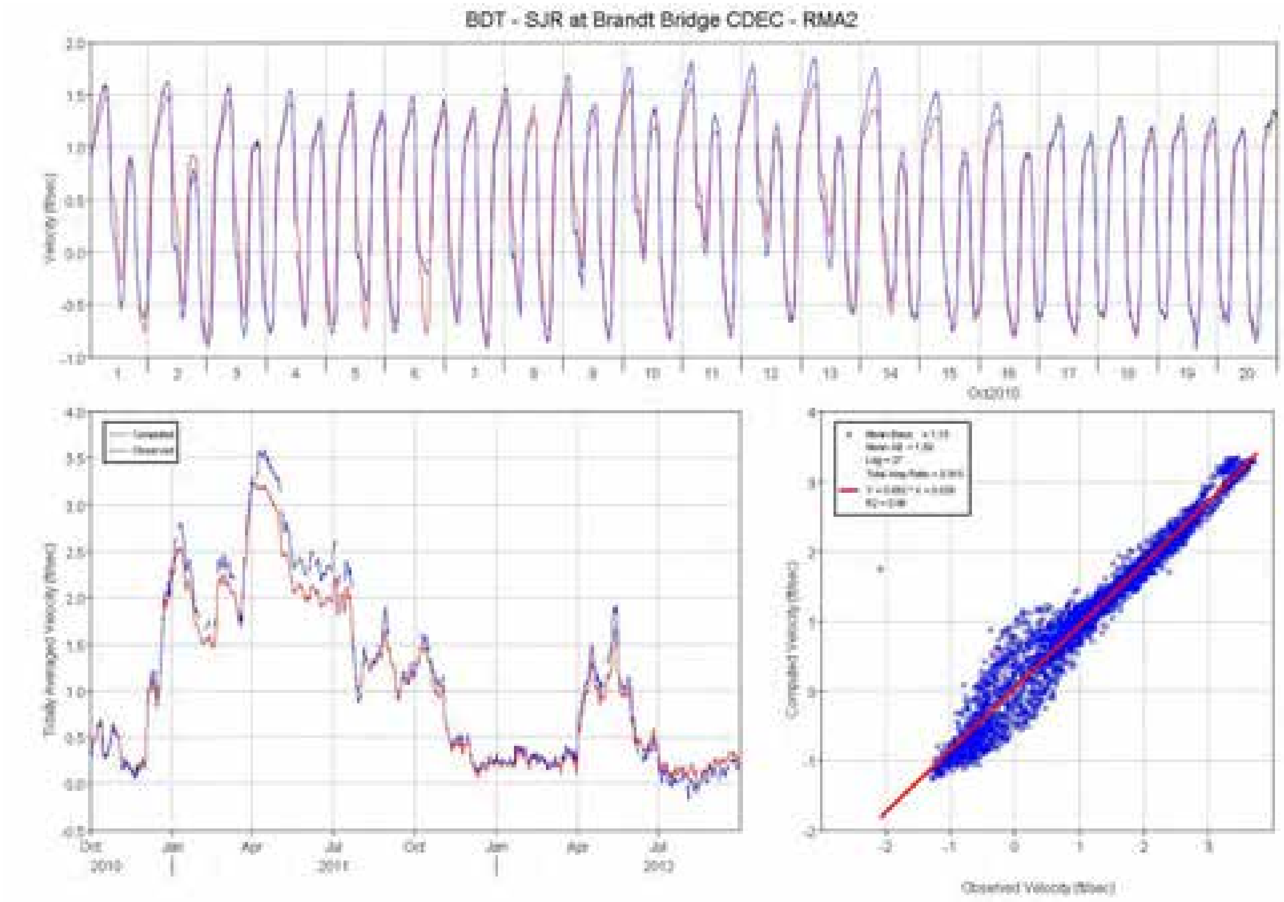


Figure 93 Computed (RMA2) and observed velocity comparison plots for San Joaquin River at Brandt Bridge.

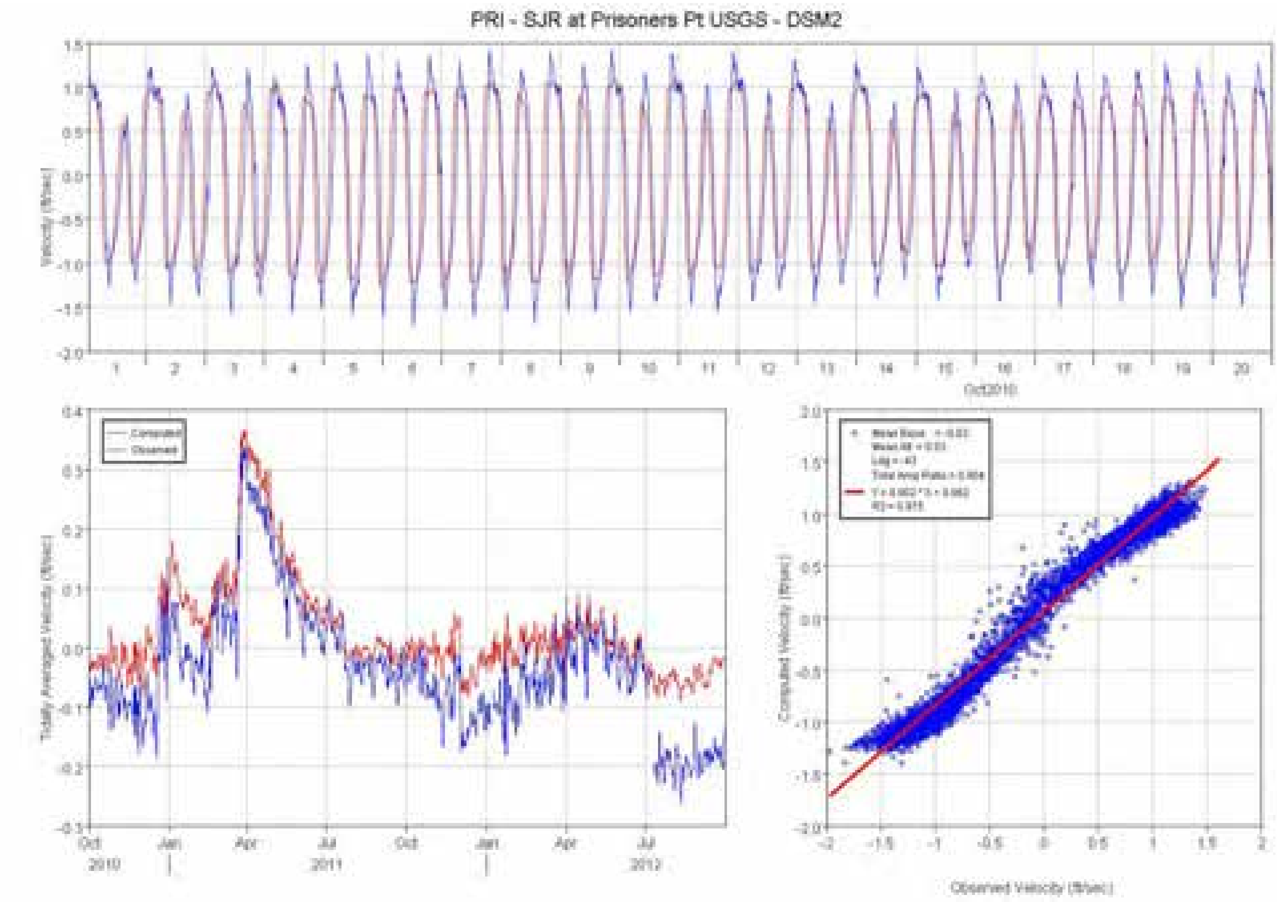


Figure 94 Computed (DSM2) and observed velocity comparison plots for San Joaquin River at Prisoners Point.

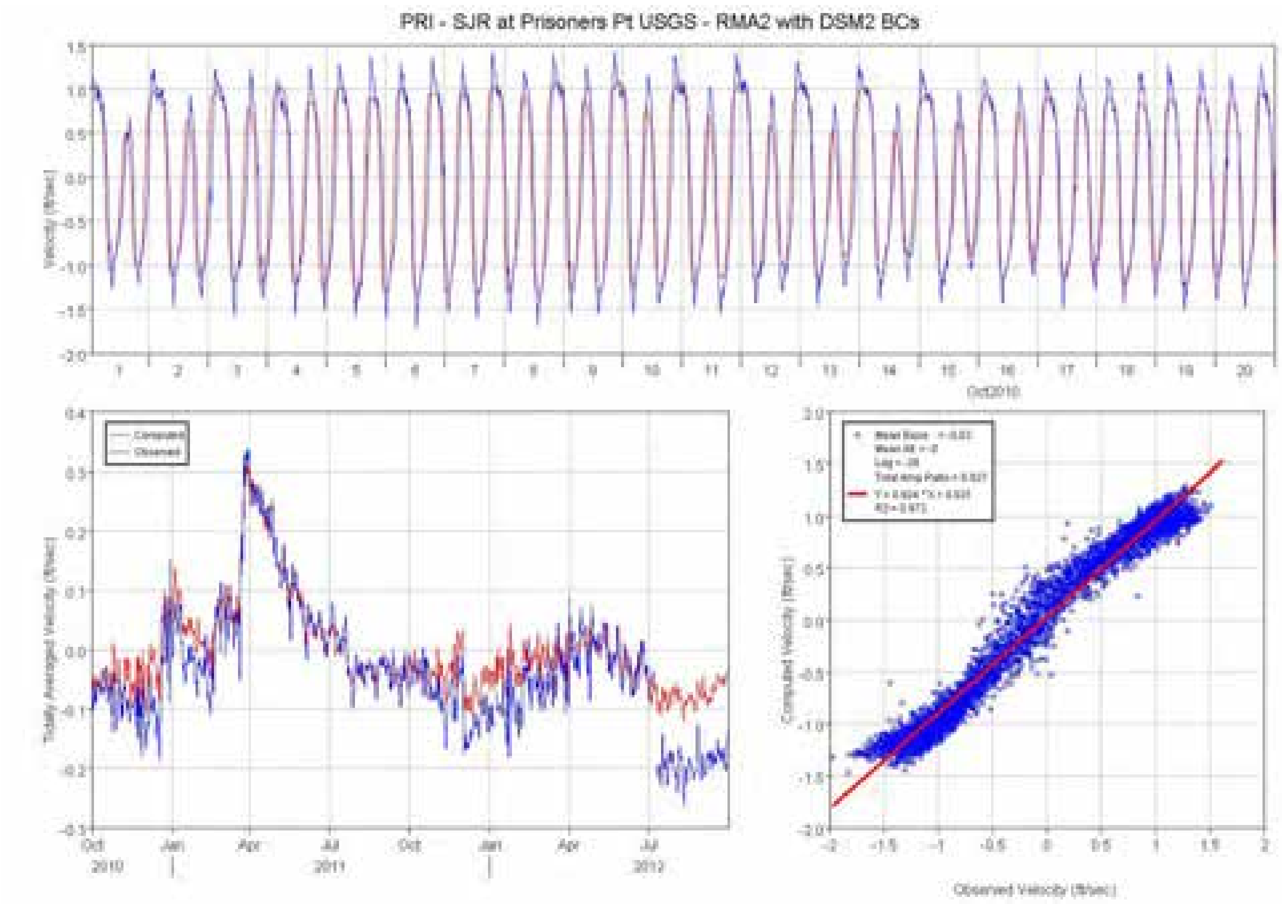


Figure 95 Computed (RMA2 with DSM2 BCs) and observed velocity comparison plots for San Joaquin River at Prisoners Point.

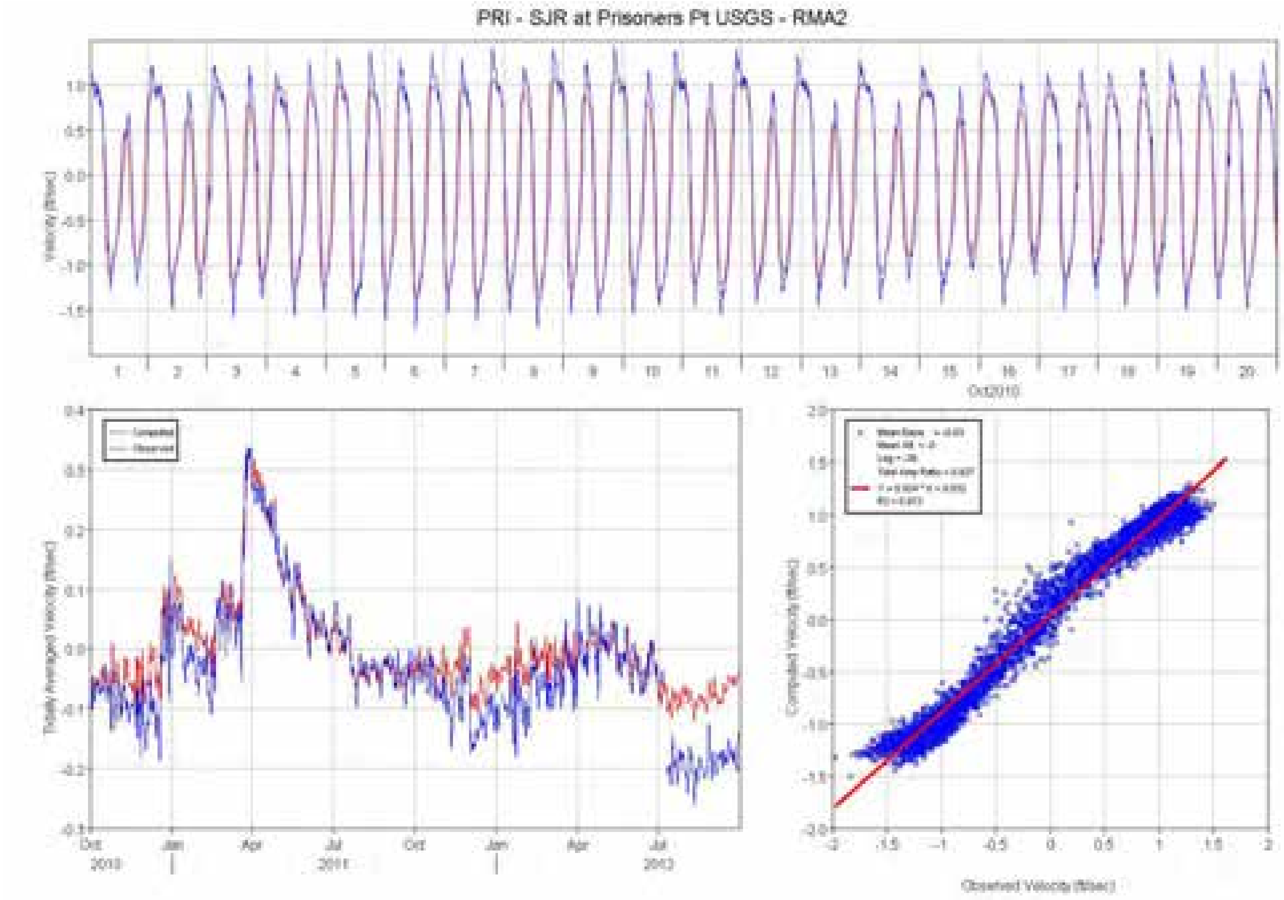


Figure 96 Computed (RMA2) and observed velocity comparison plots for San Joaquin River at Prisoners Point.

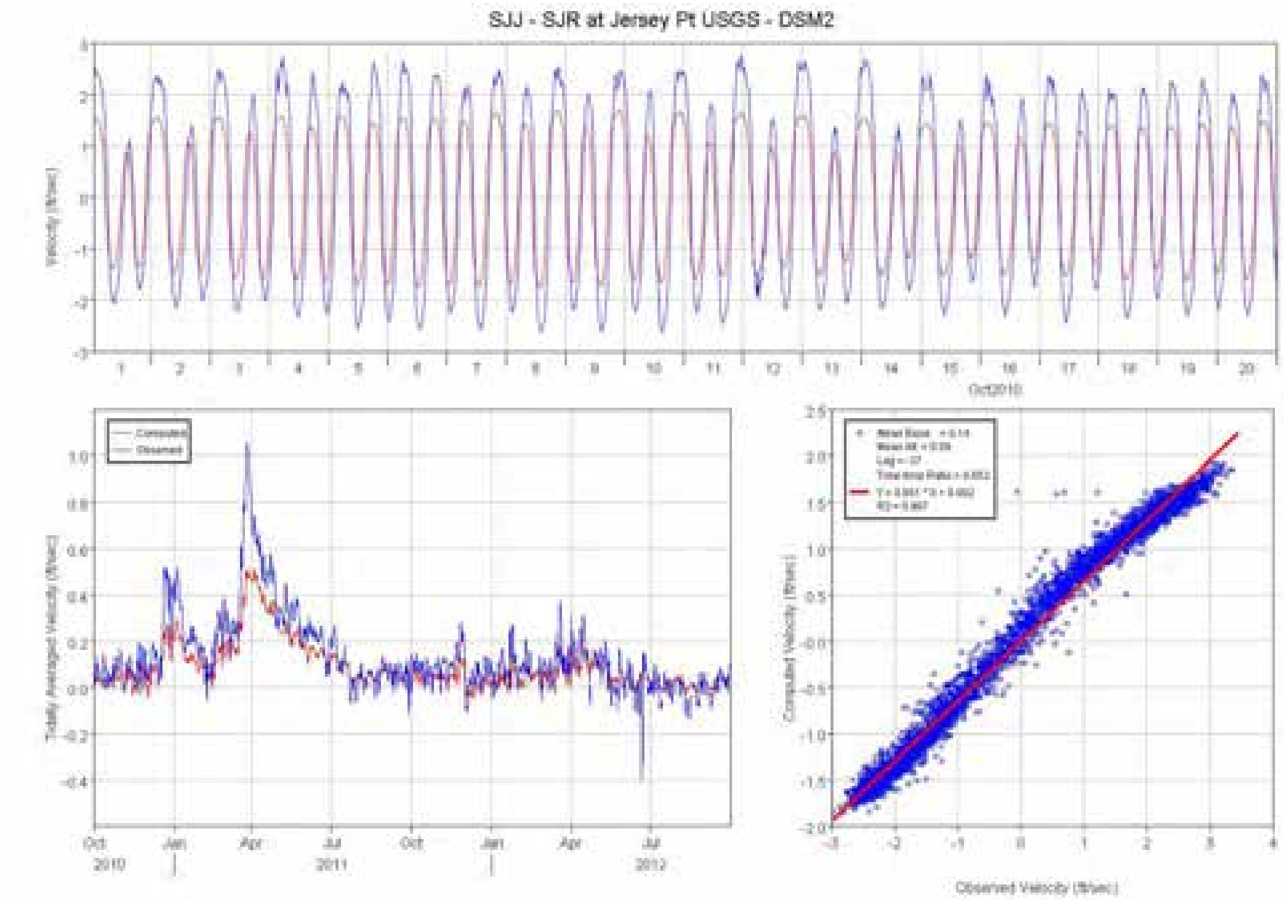


Figure 97 Computed (DSM2) and observed velocity comparison plots for San Joaquin River at Jersey Point.

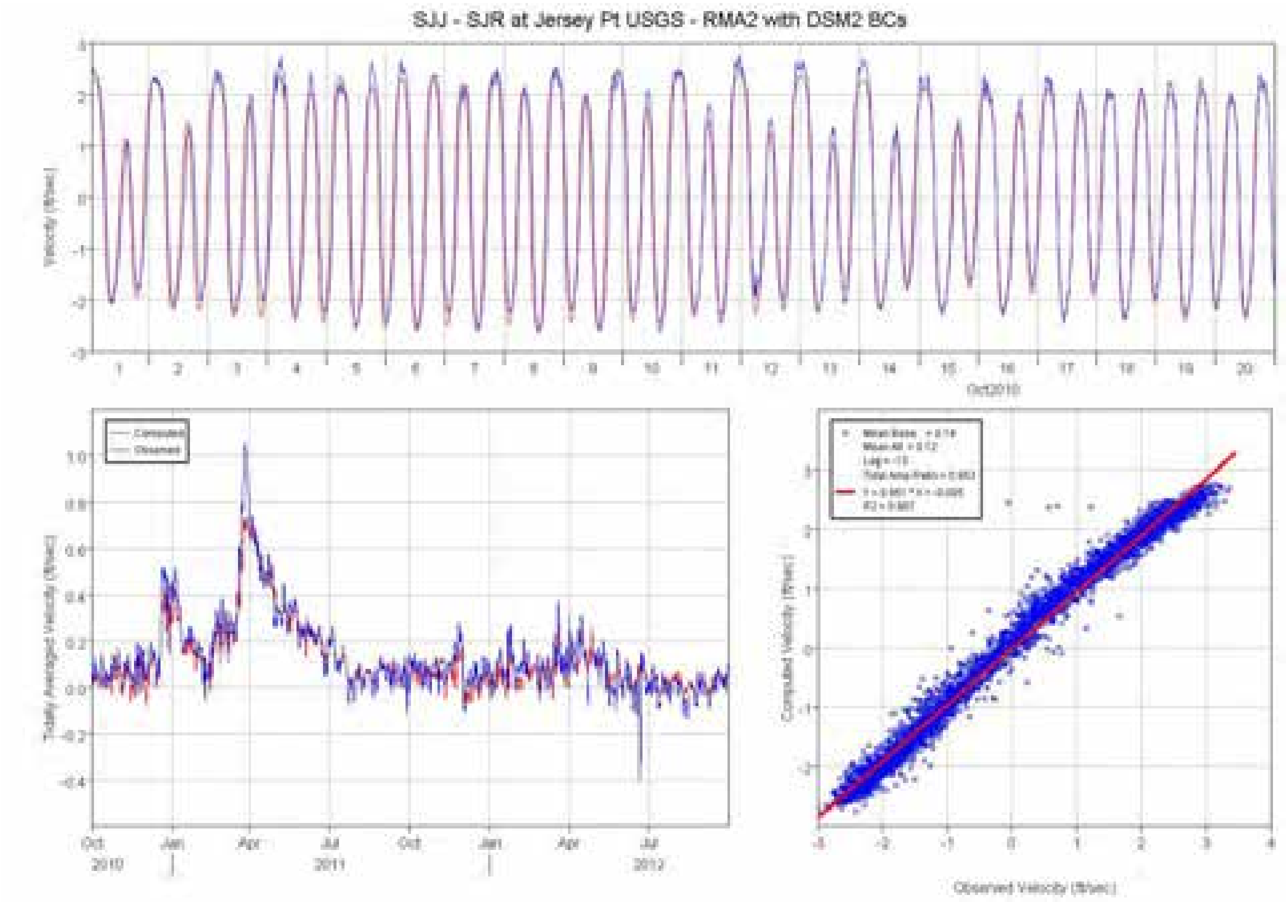


Figure 98 Computed (RMA2 with DSM2 BCs) and observed velocity comparison plots for San Joaquin River at Jersey Point.

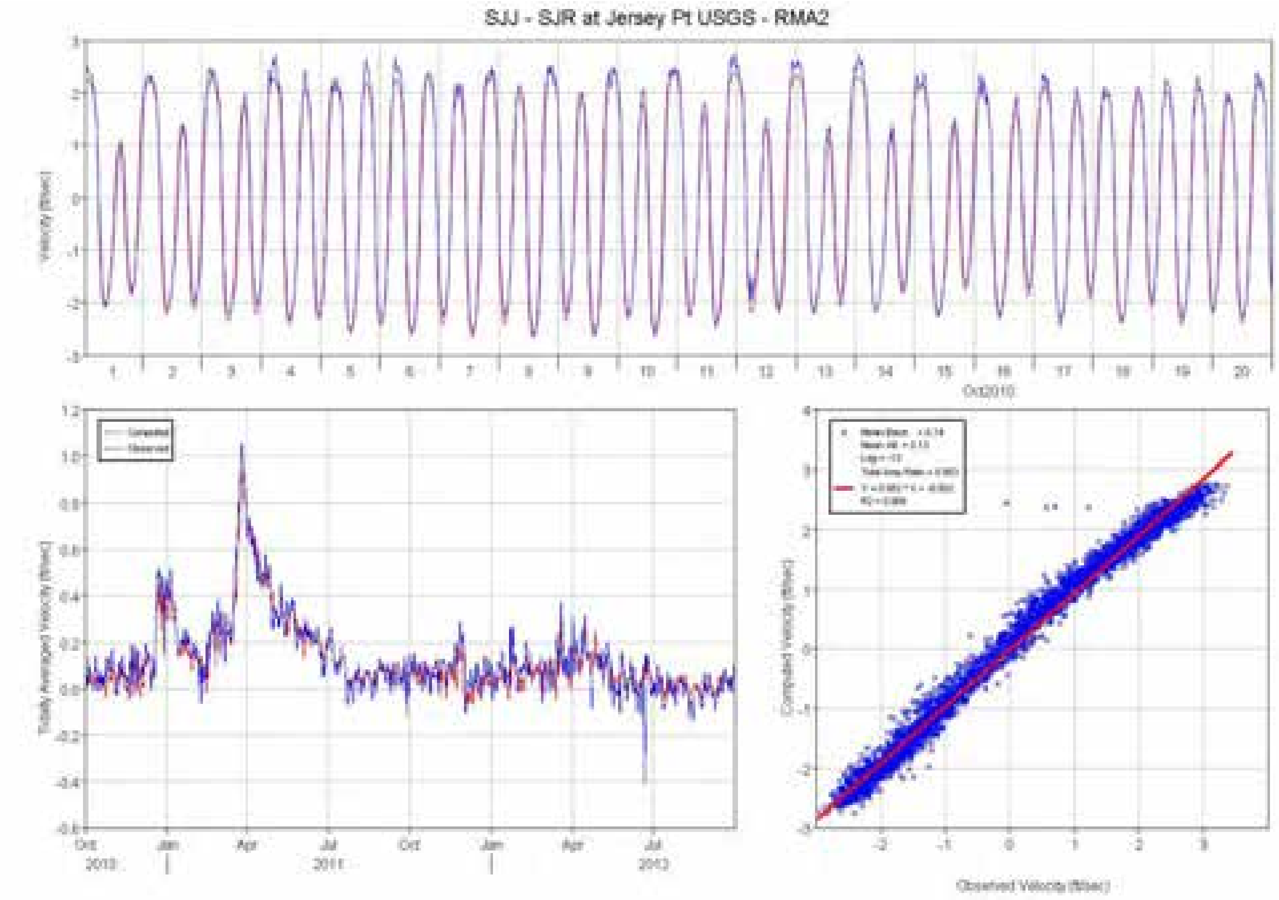


Figure 99 Computed (RMA2) and observed velocity comparison plots for San Joaquin River at Jersey Point.

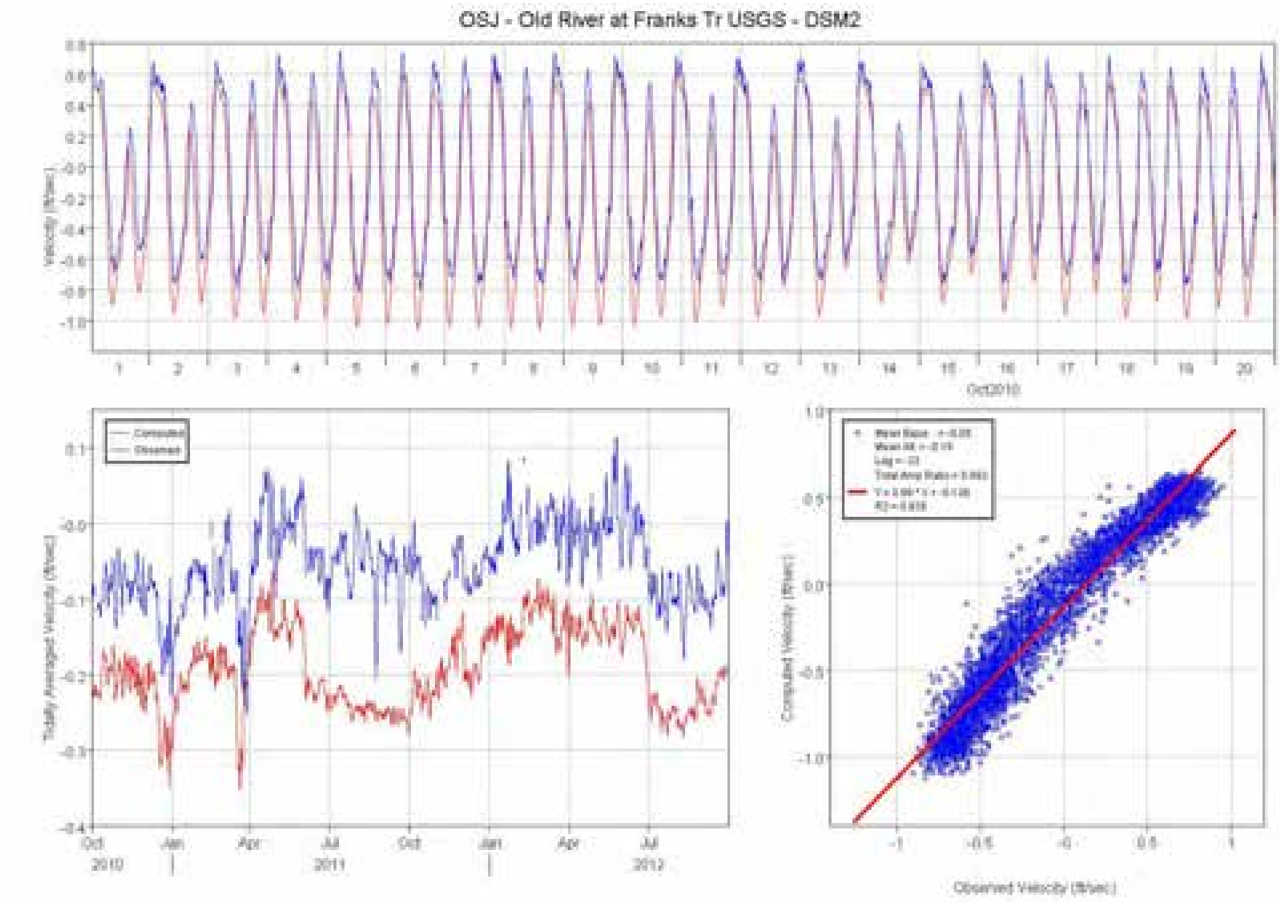


Figure 100 Computed (DSM2) and observed velocity comparison plots for Old River at Franks Tract.

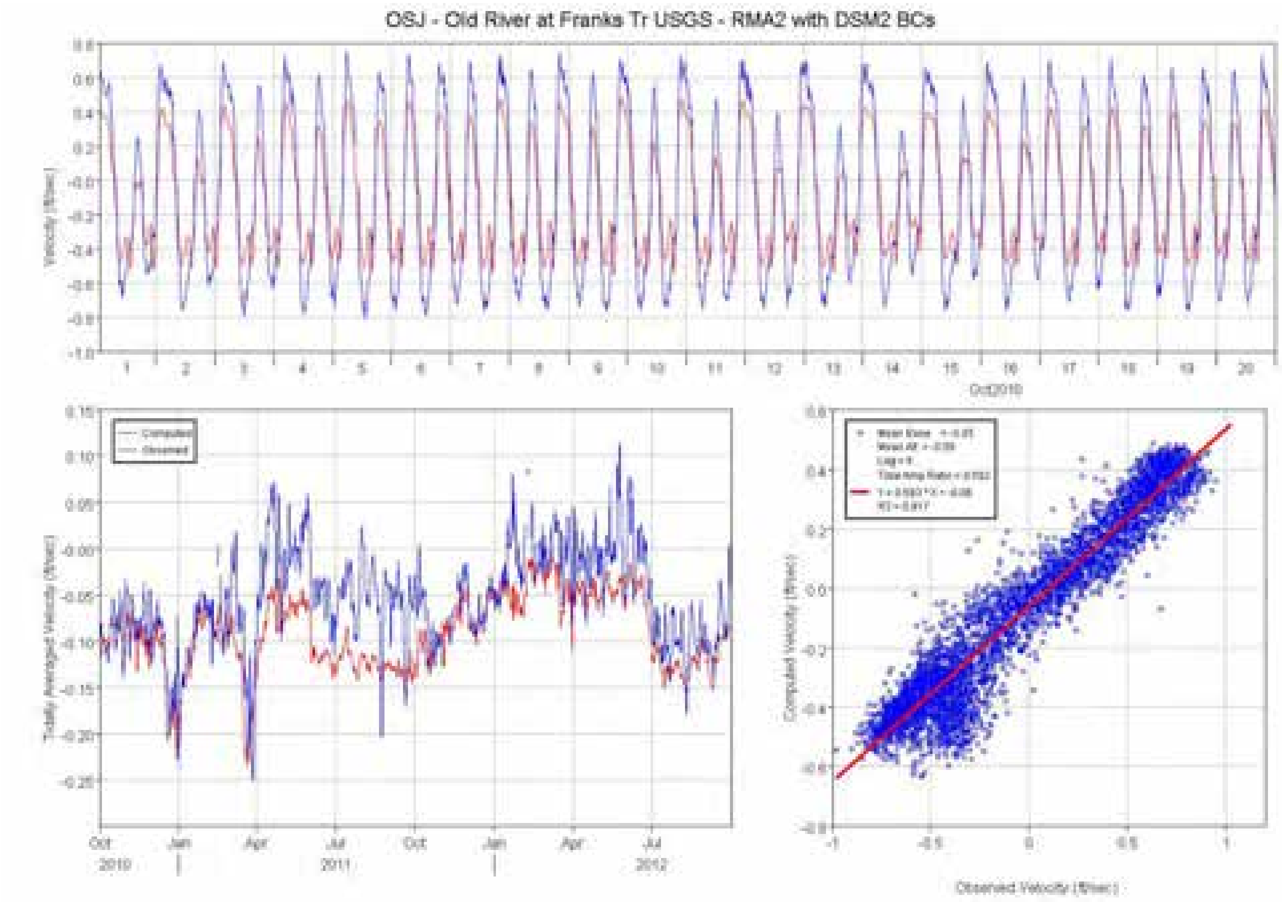


Figure 101 Computed (RMA2 with DSM2 BCs) and observed velocity comparison plots for Old River at Franks Tract.

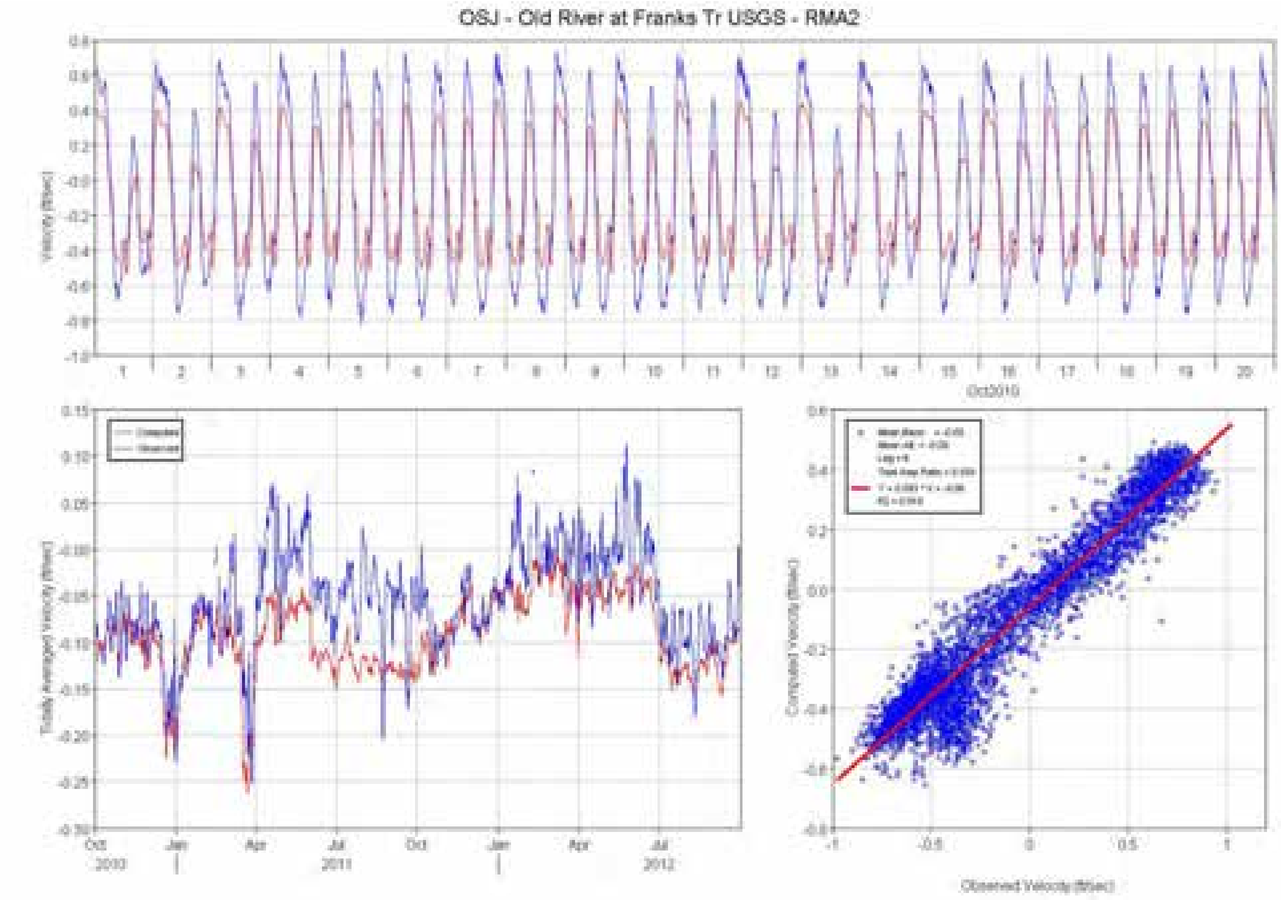


Figure 102 Computed (RMA2) and observed velocity comparison plots for Old River at Franks Tract.

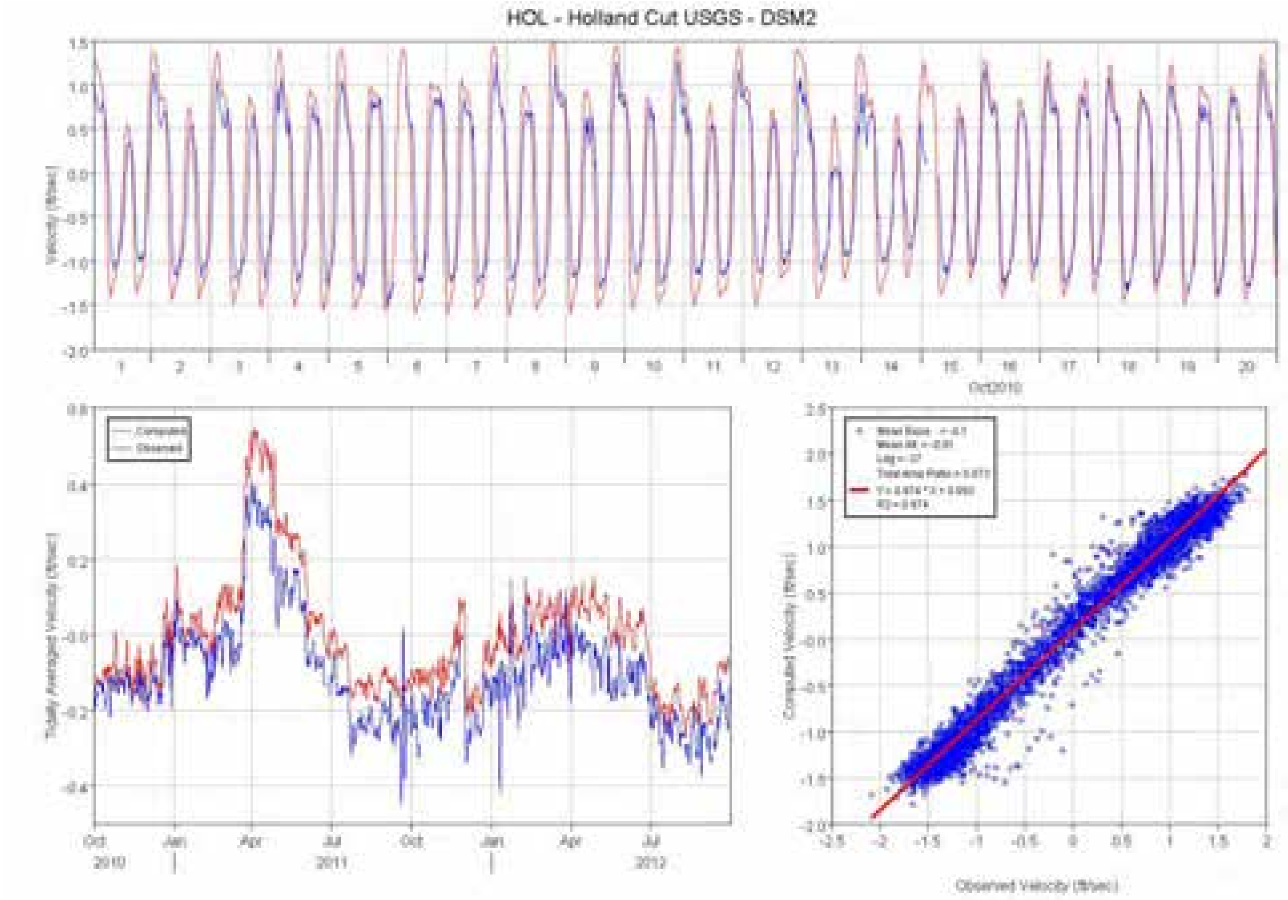


Figure 103 Computed (DSM2) and observed velocity comparison plots for Holland Tract.

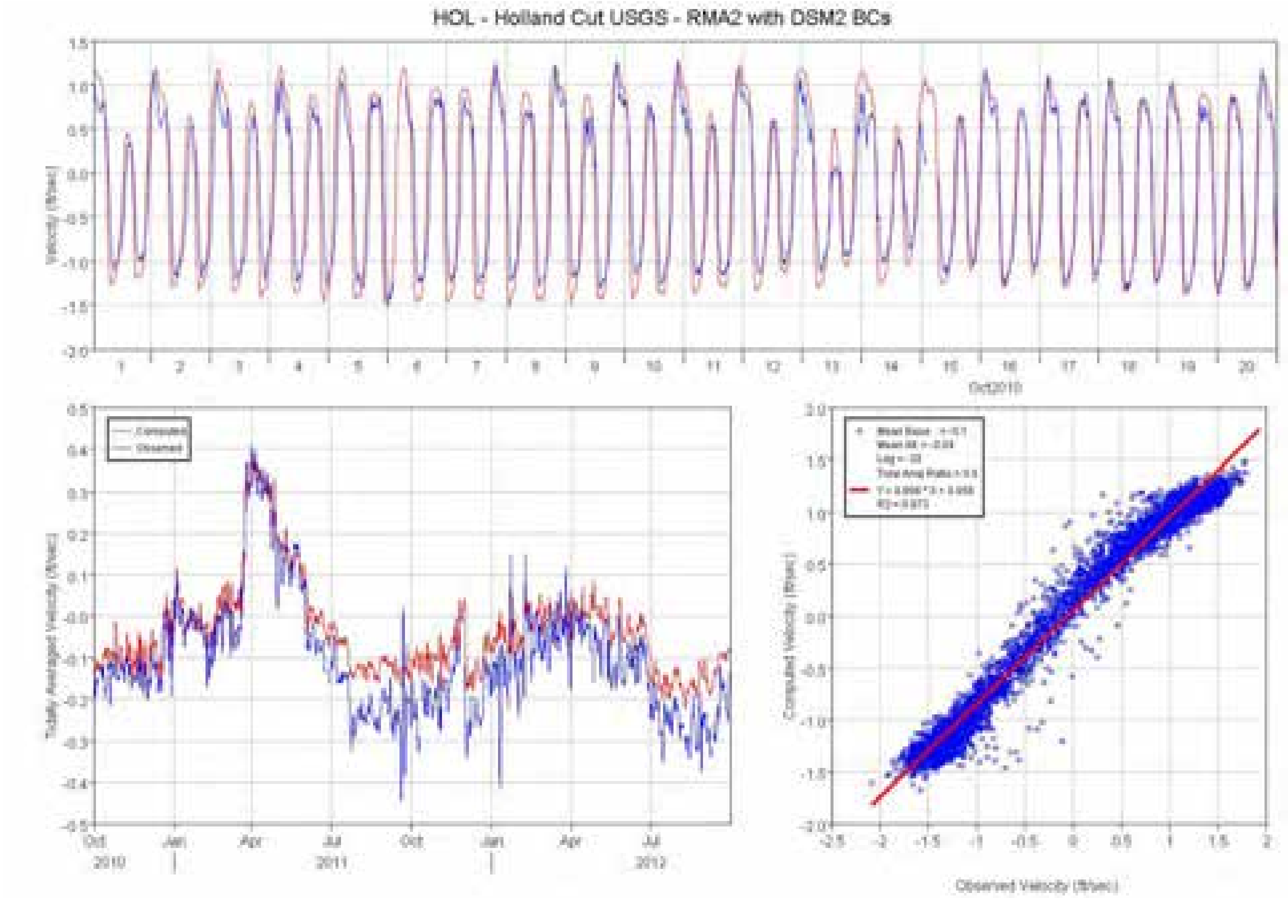


Figure 104 Computed (RMA2 with DSM2 BCs) and observed velocity comparison plots for Holland Tract.

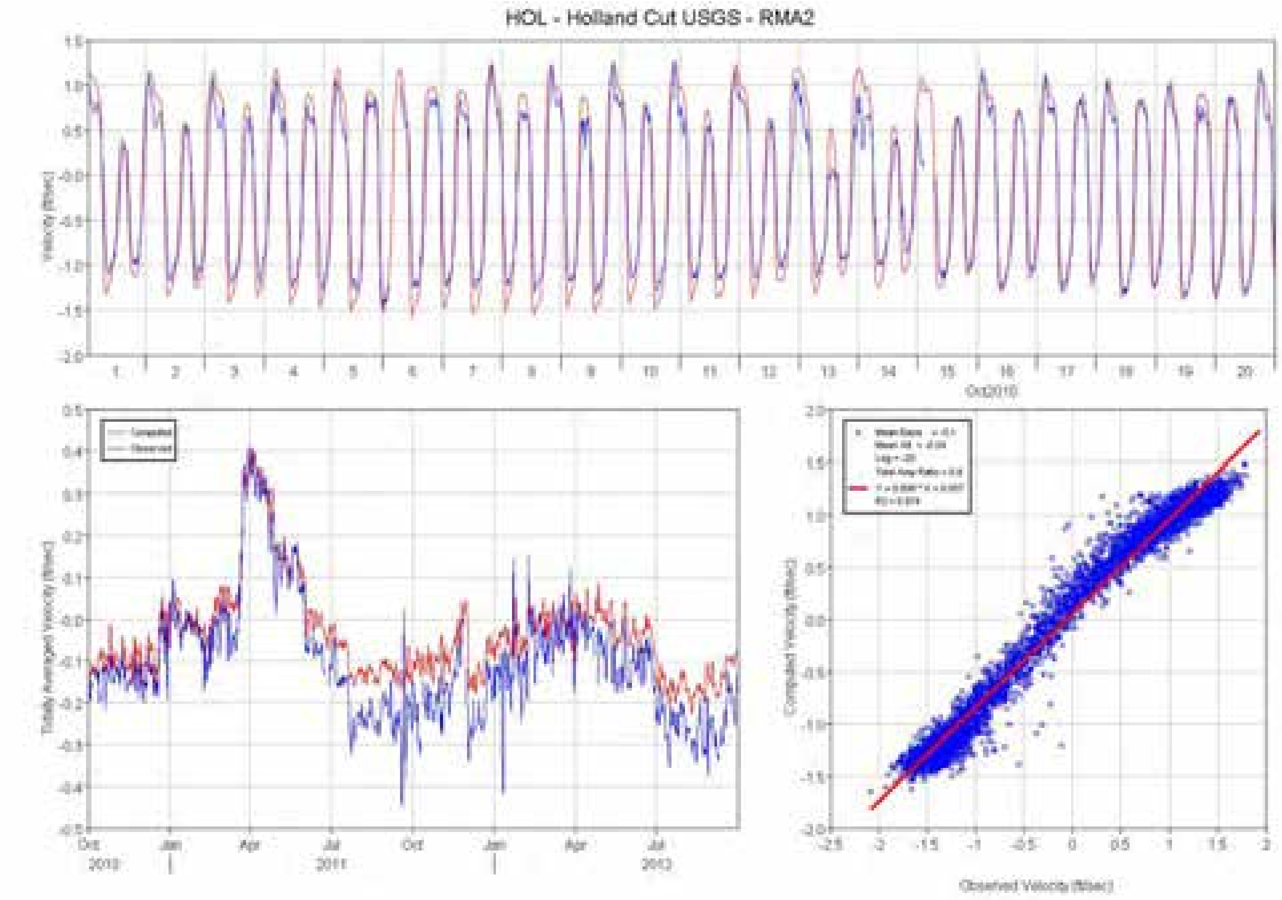


Figure 105 Computed (RMA2) and observed velocity comparison plots for Holland Tract.

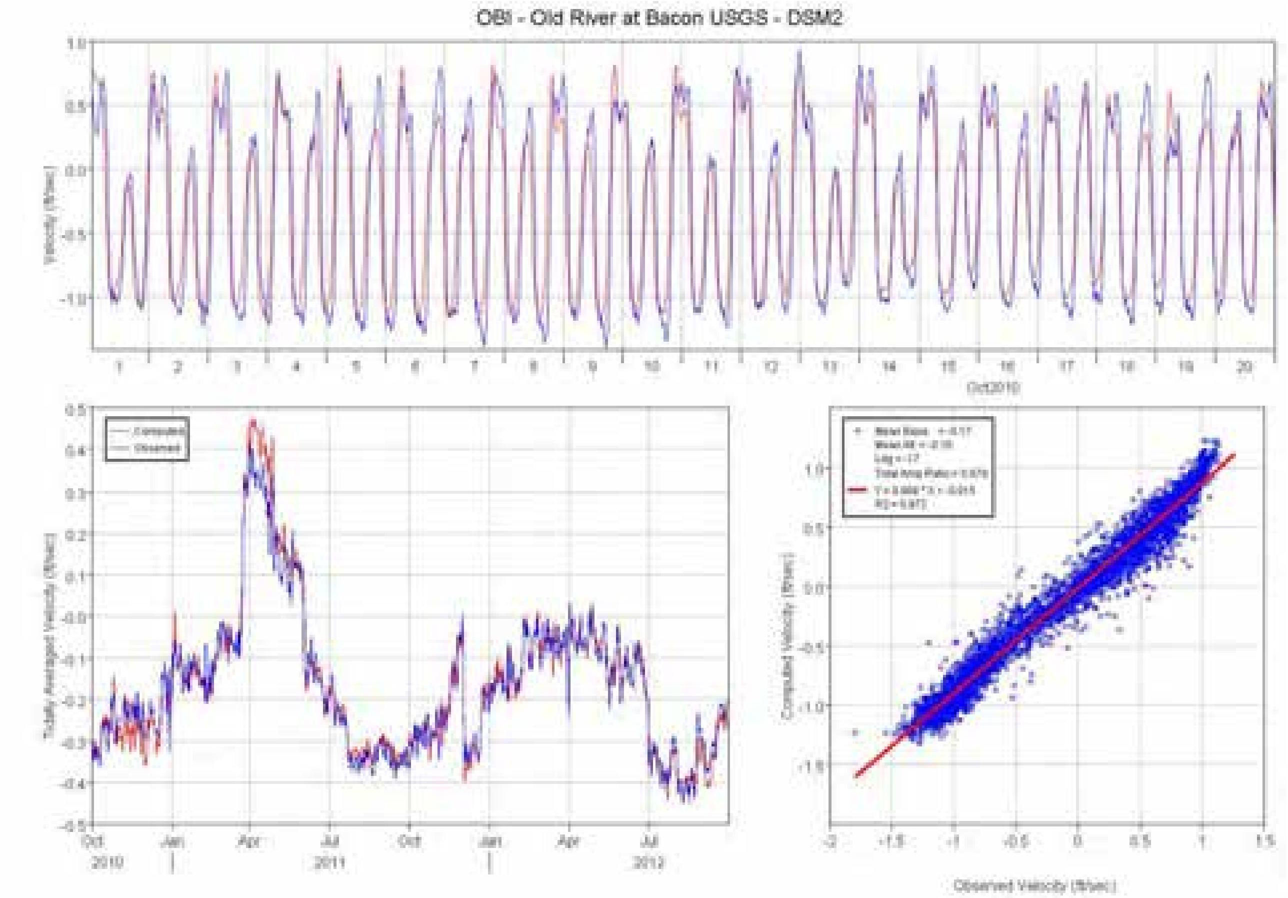


Figure 106 Computed (DSM2) and observed velocity comparison plots for Old River at Bacon Island.

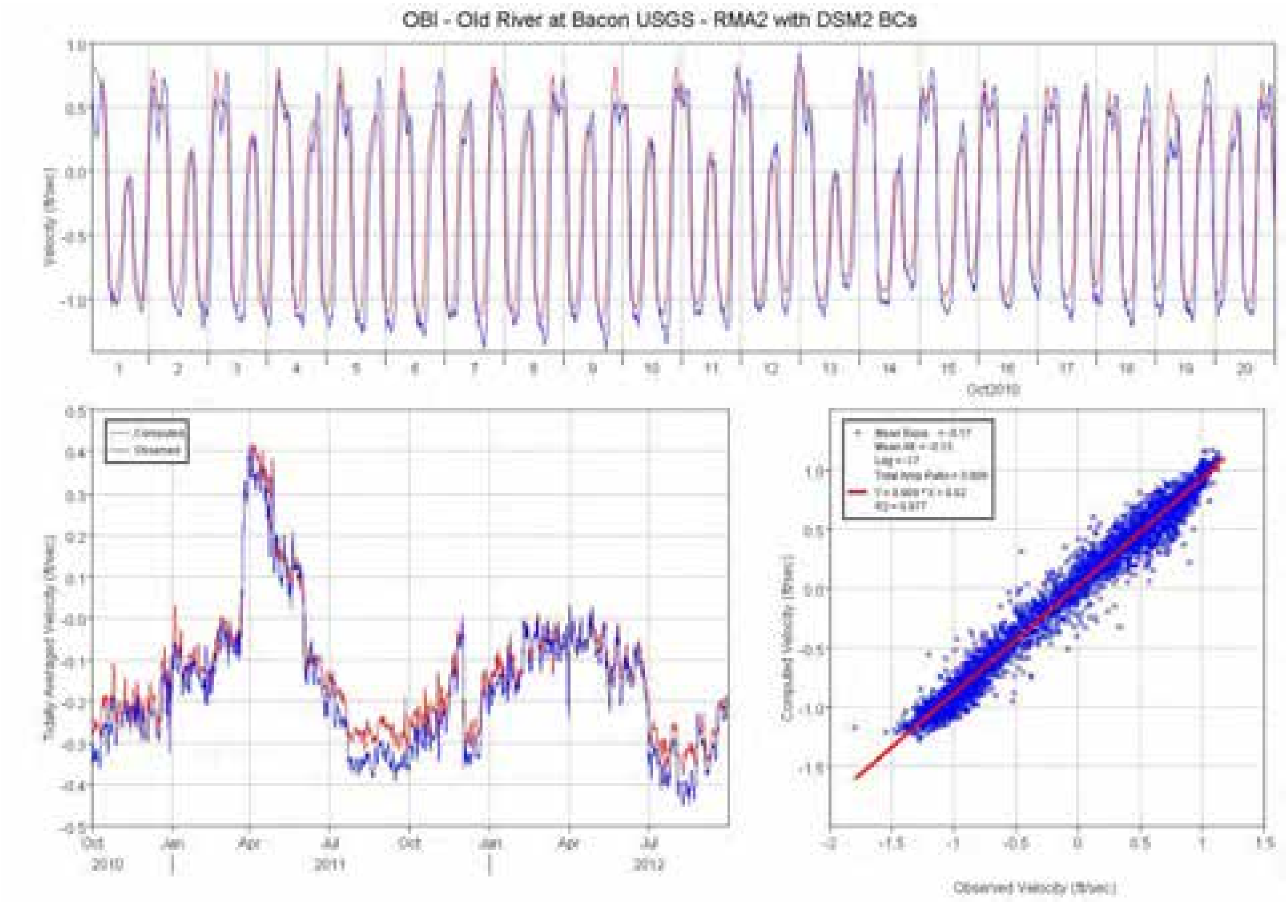


Figure 107 Computed (RMA2 with DSM2 BCs) and observed velocity comparison plots for Old River at Bacon Island.

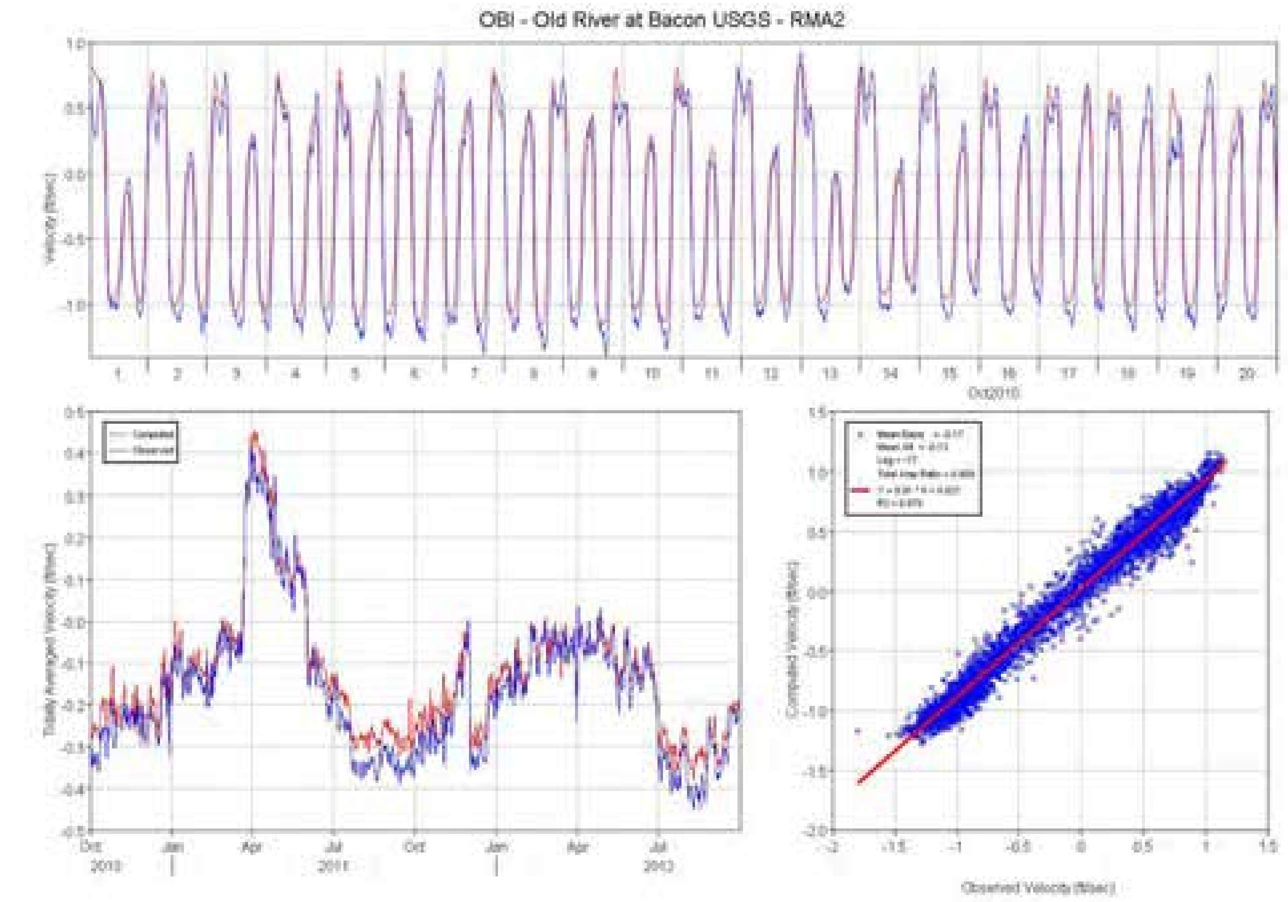


Figure 108 Computed (RMA2) and observed velocity comparison plots for Old River at Bacon Island.

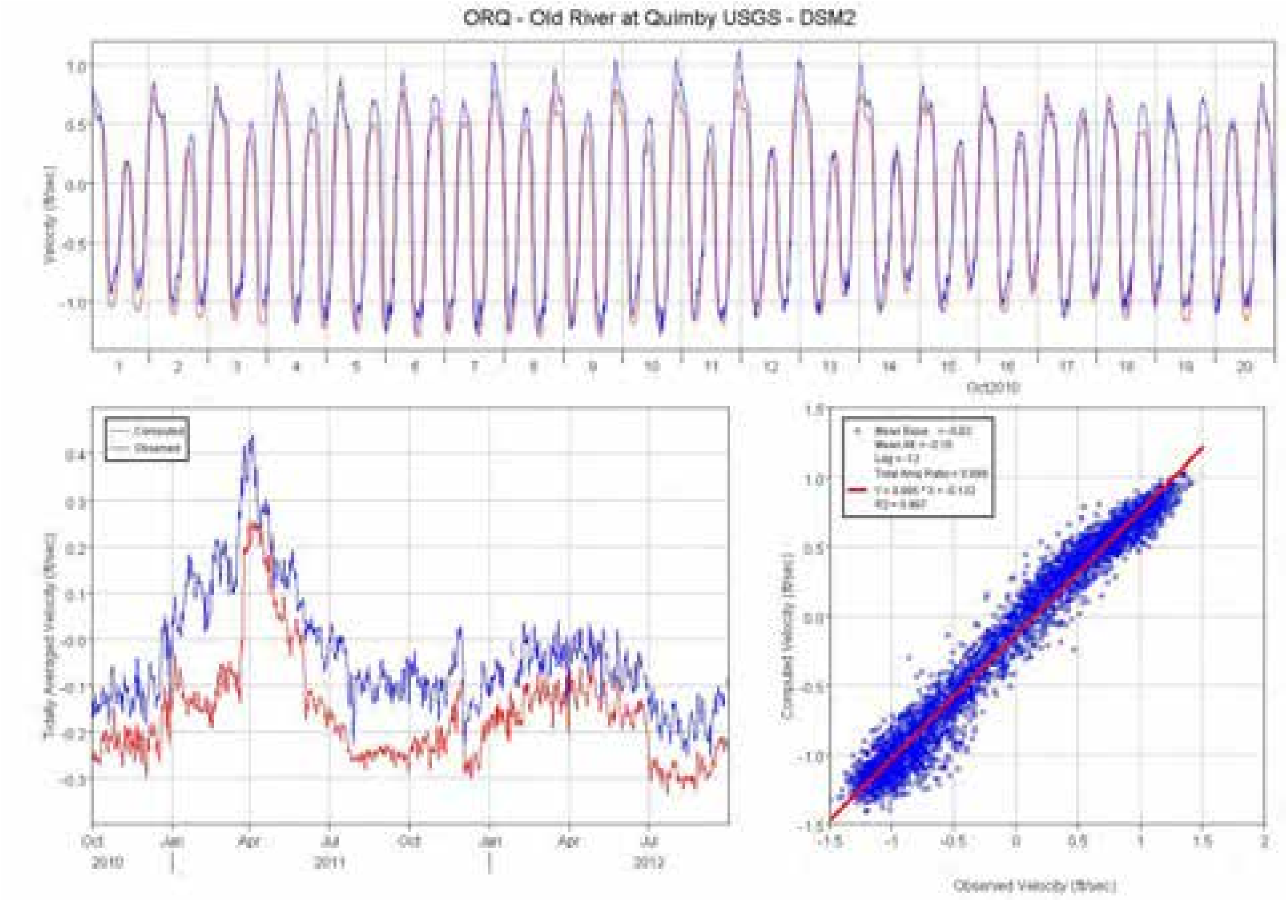


Figure 109 Computed (DSM2) and observed velocity comparison plots for Old River at Quimby.

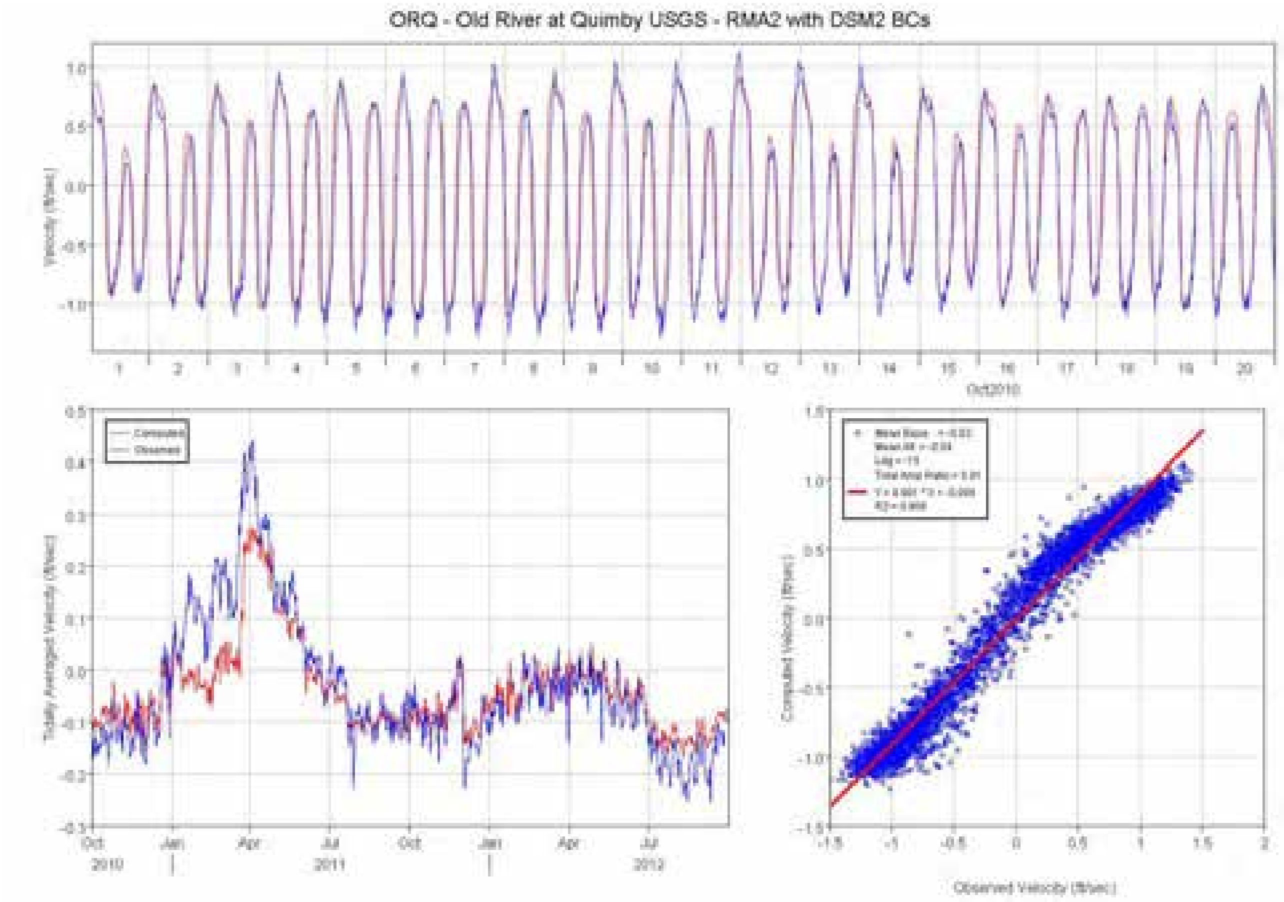


Figure 110 Computed (RMA2 with DSM2 BCs) and observed velocity comparison plots for Old River at Quimby.

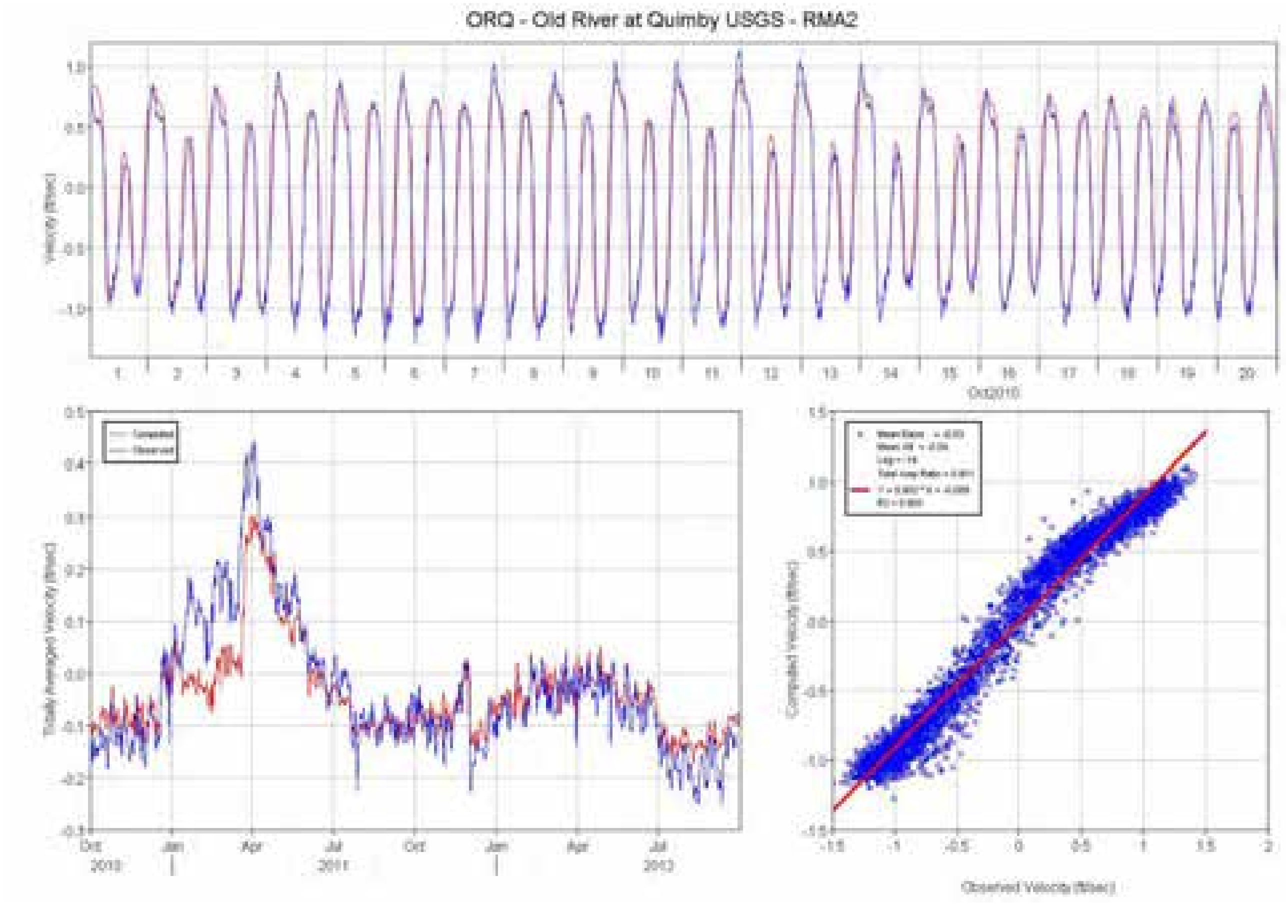


Figure 111 Computed (RMA2) and observed velocity comparison plots for Old River at Quimby.

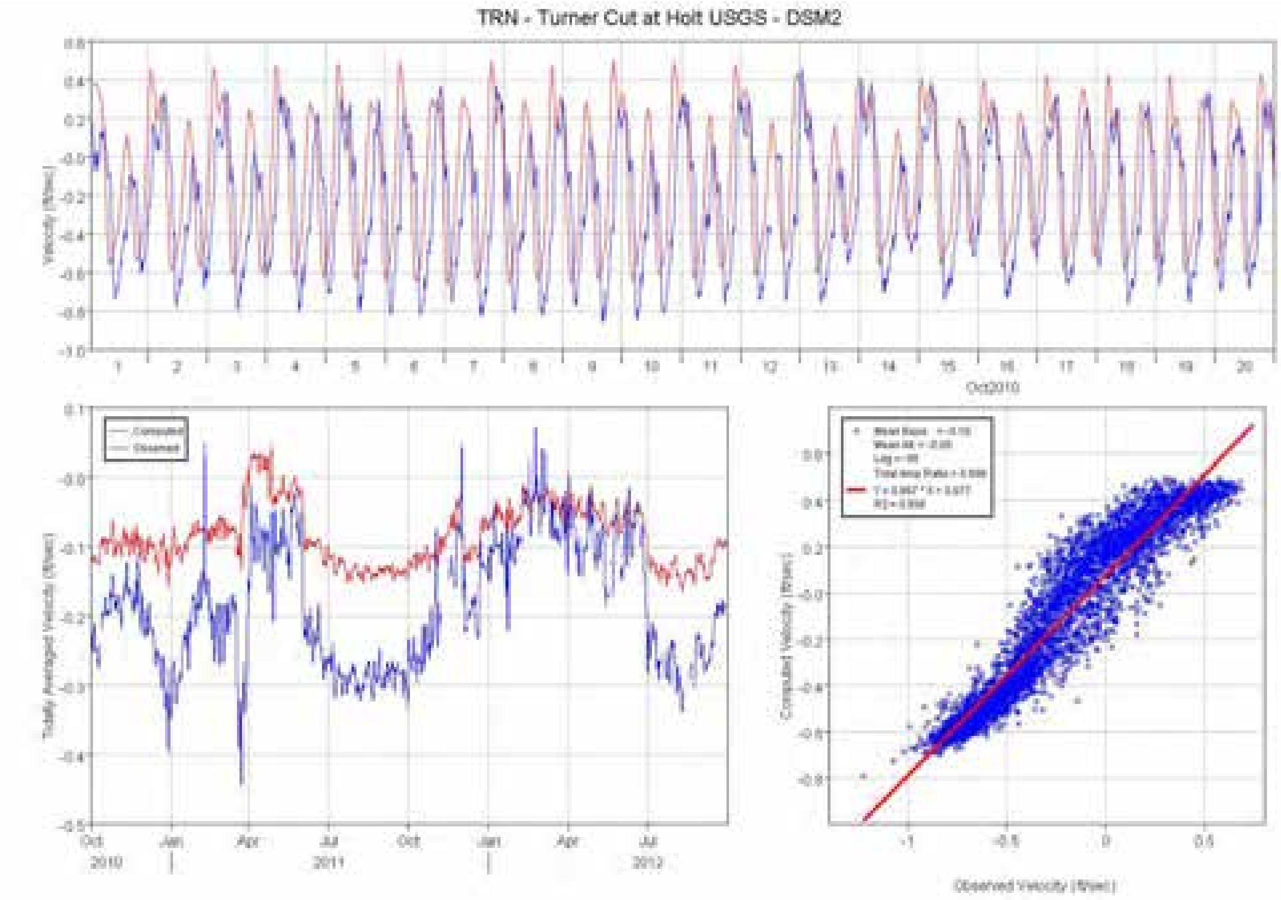


Figure 112 Computed (DSM2) and observed velocity comparison plots for Turner Cut at Holt.

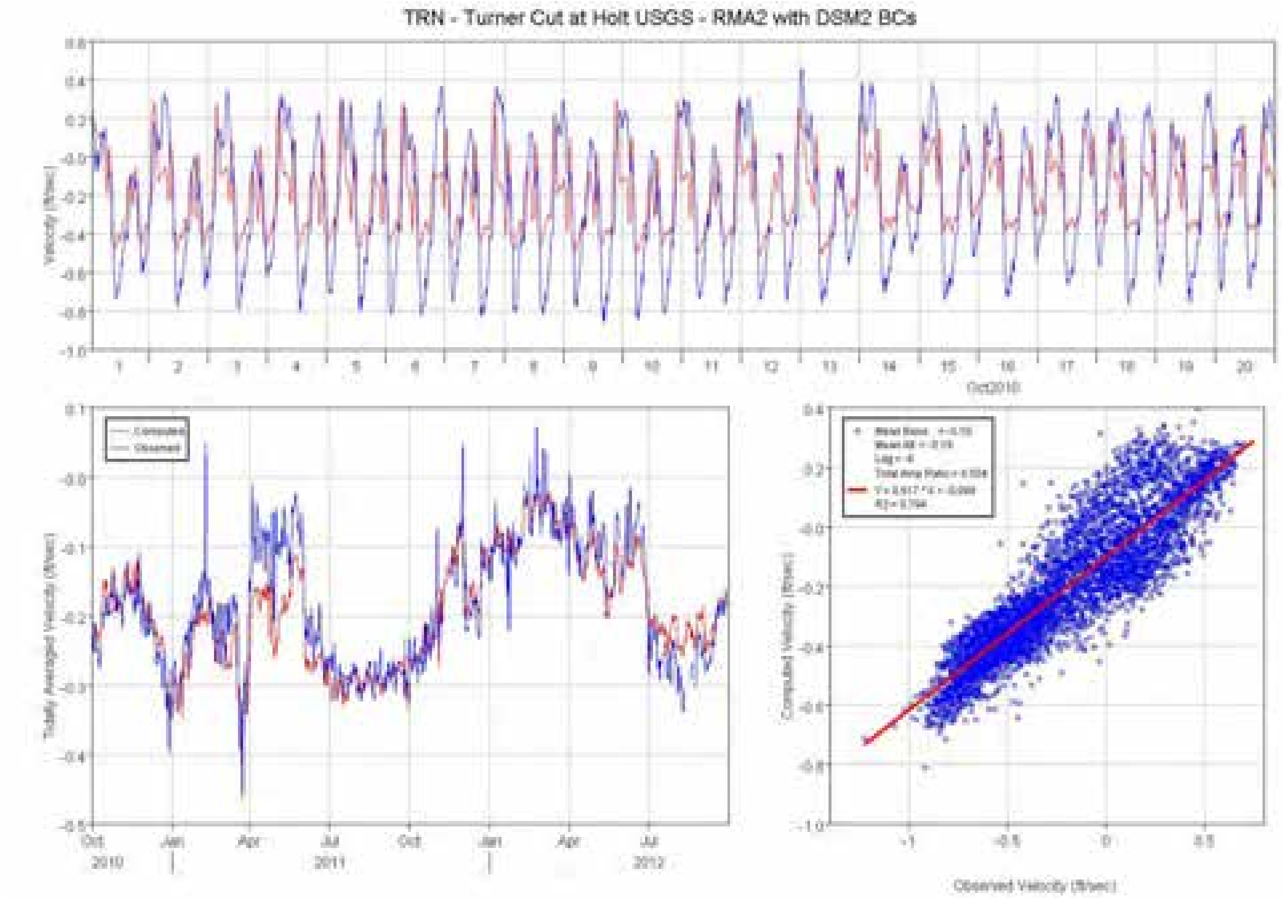


Figure 113 Computed (RMA2 with DSM2 BCs) and observed velocity comparison plots for Turner Cut at Holt.

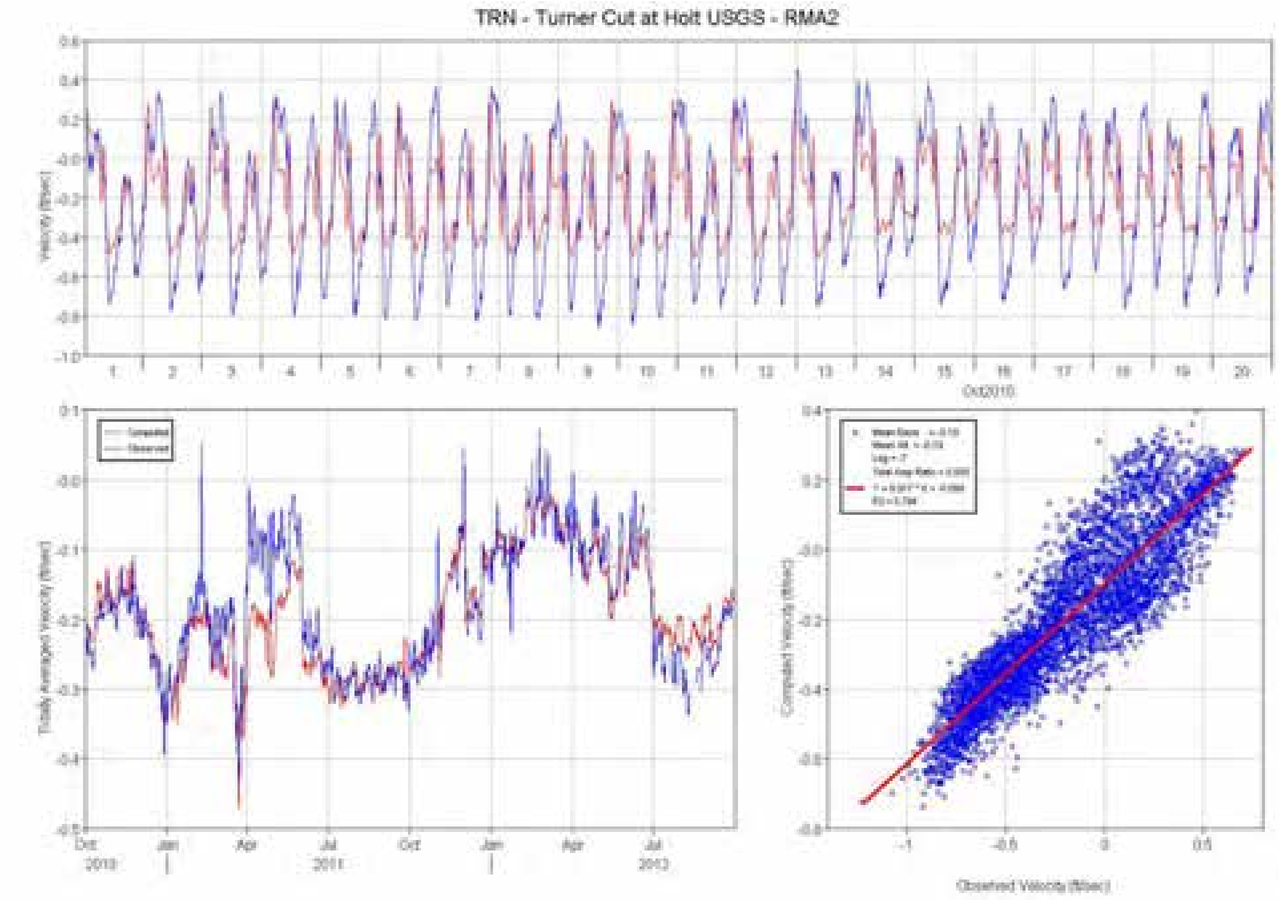


Figure 114 Computed (RMA2) and observed velocity comparison plots for Turner Cut at Holt.

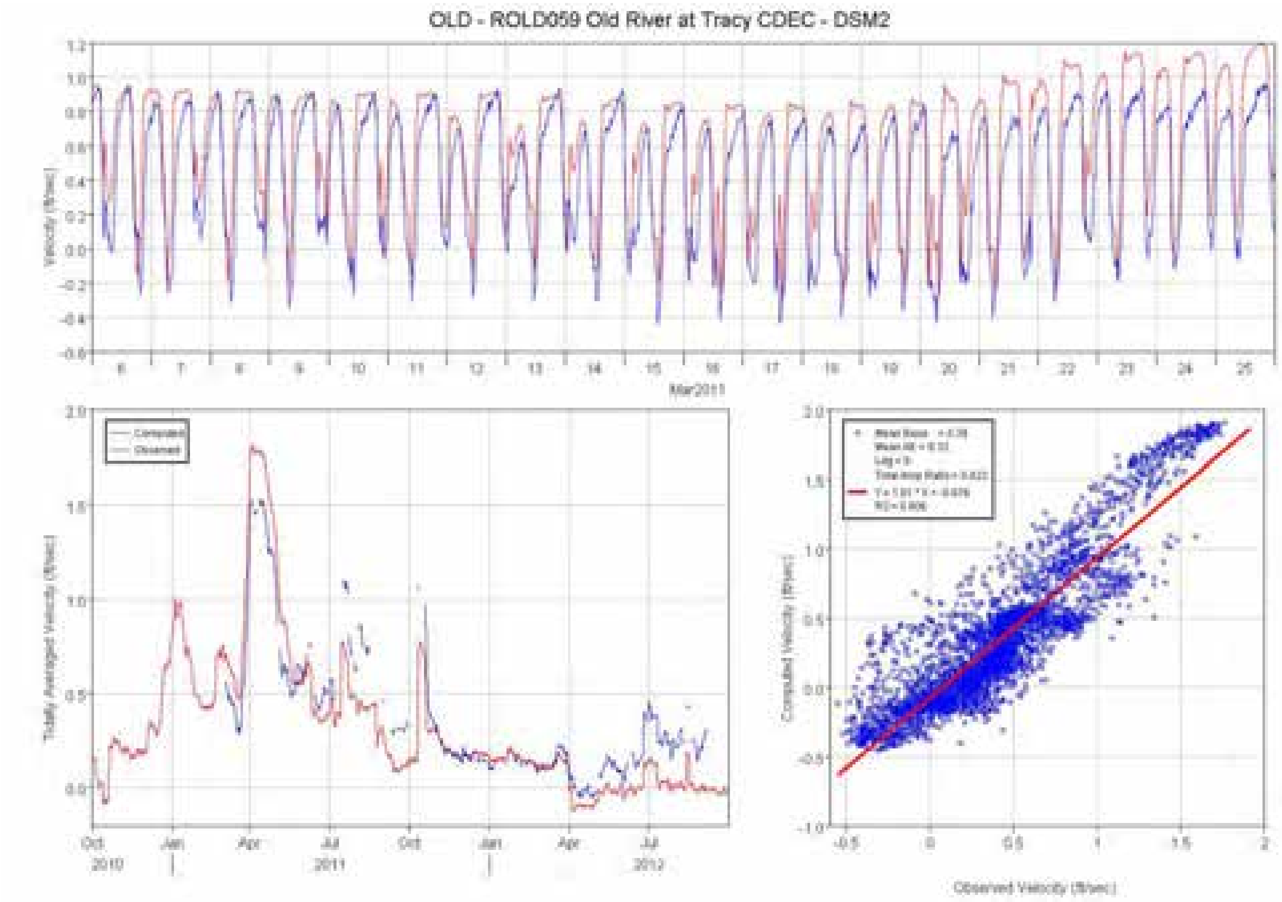


Figure 115 Computed (DSM2) and observed velocity comparison plots for Old River at Tracy.

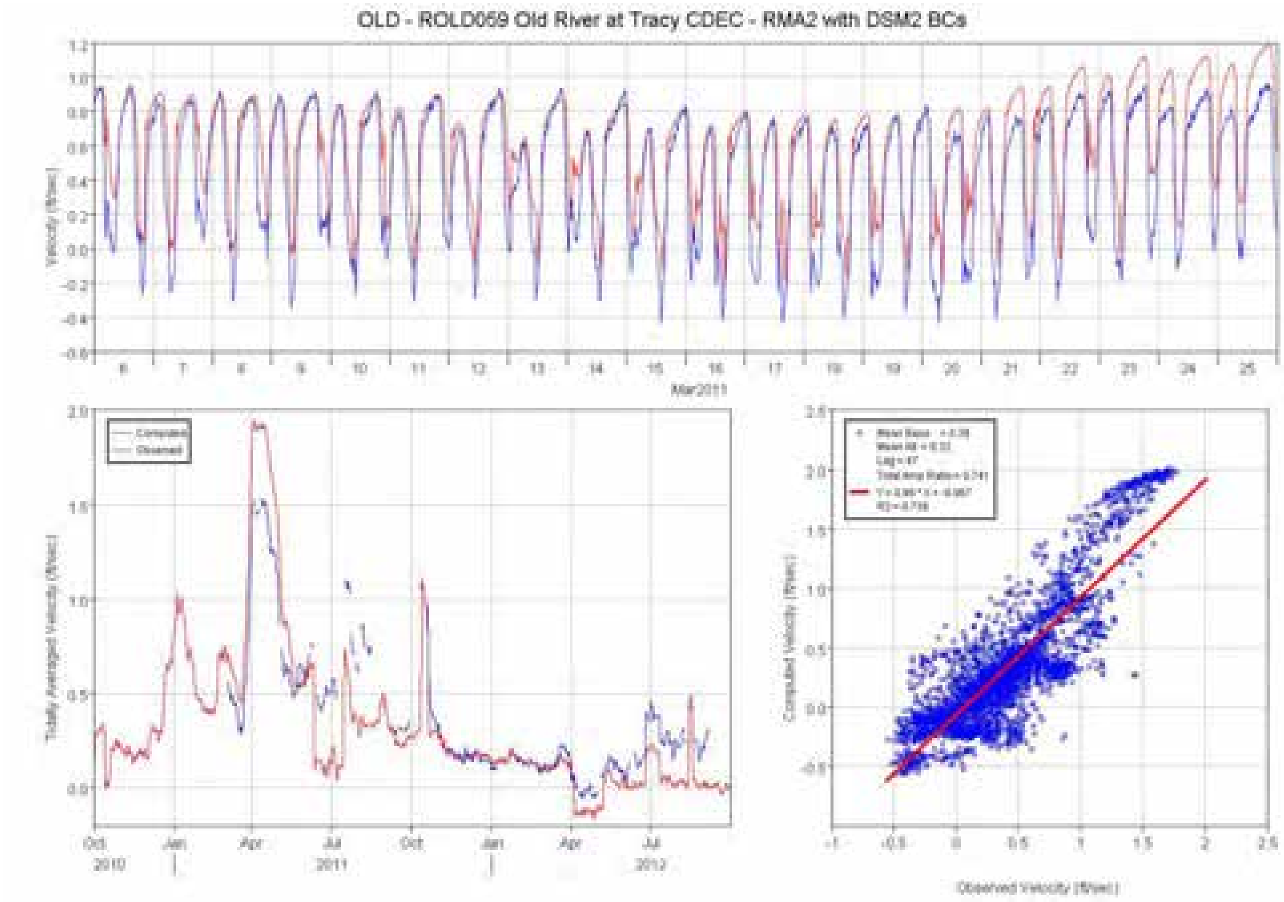


Figure 116 Computed (RMA2 with DSM2 BCs) and observed velocity comparison plots for Old River at Tracy.

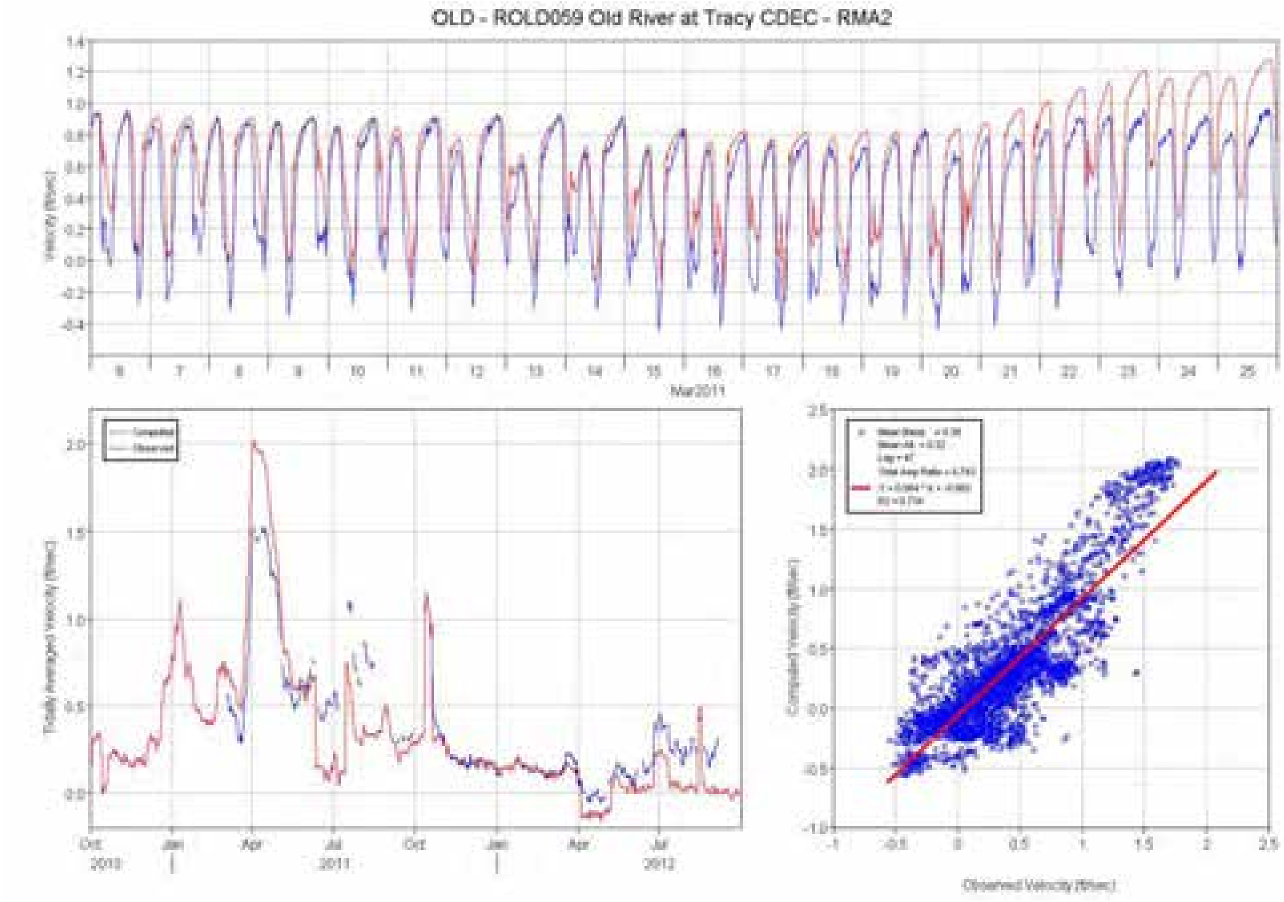


Figure 117 Computed (RMA2) and observed velocity comparison plots for Old River at Tracy.

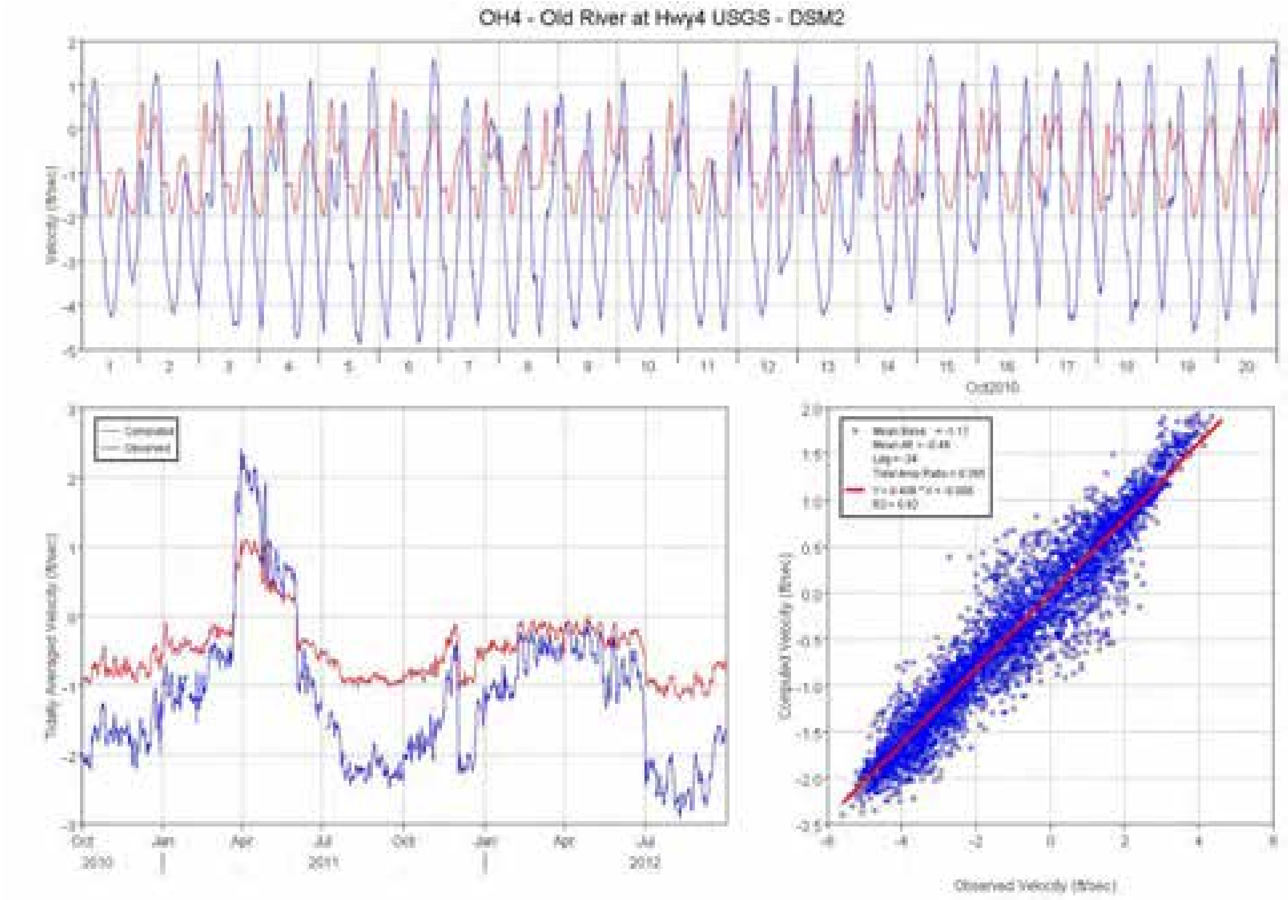


Figure 118 Computed (DSM2) and observed velocity comparison plots for Old River at Hwy 4.

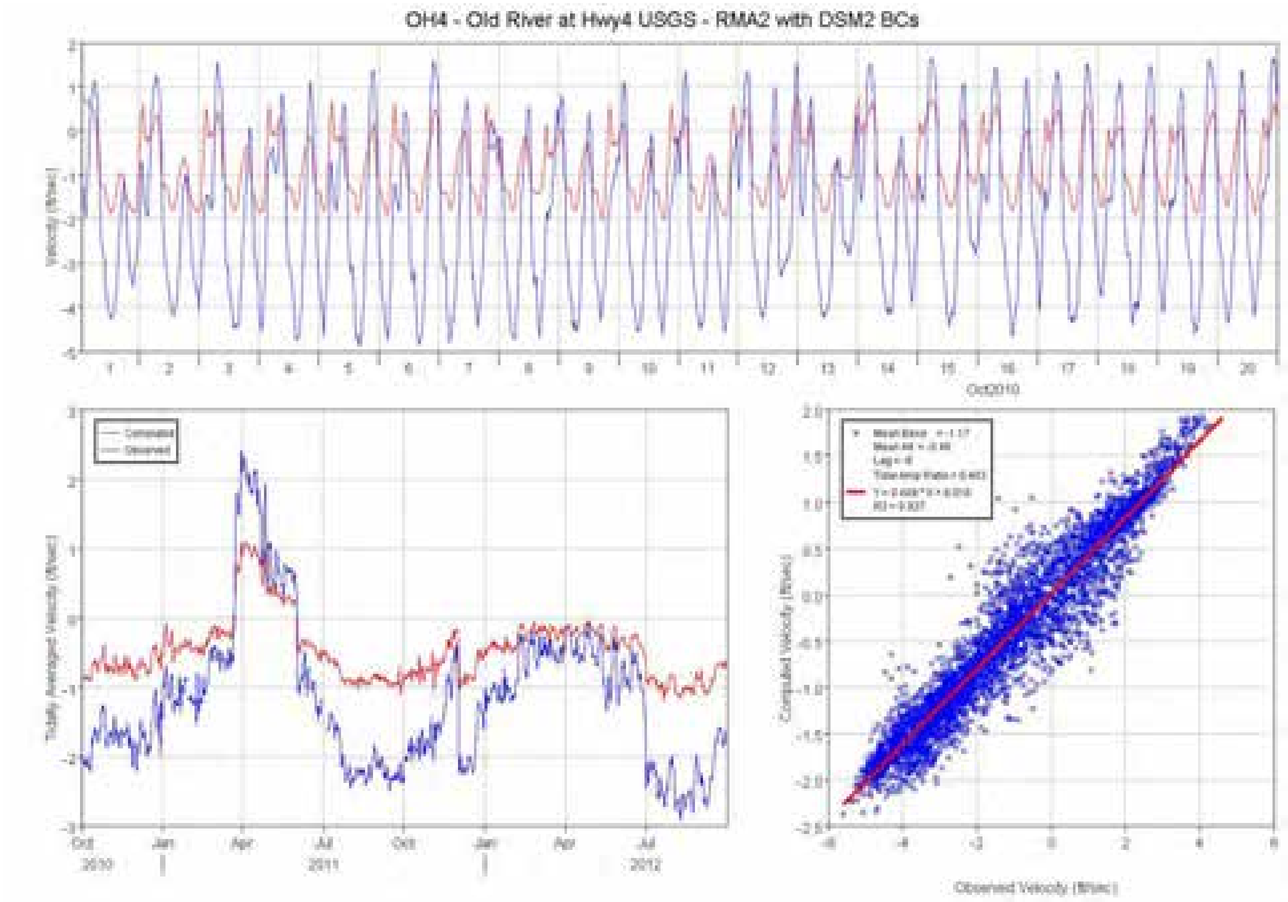


Figure 119 Computed (RMA2 with DSM2 BCs) and observed velocity comparison plots for Old River at Hwy 4.

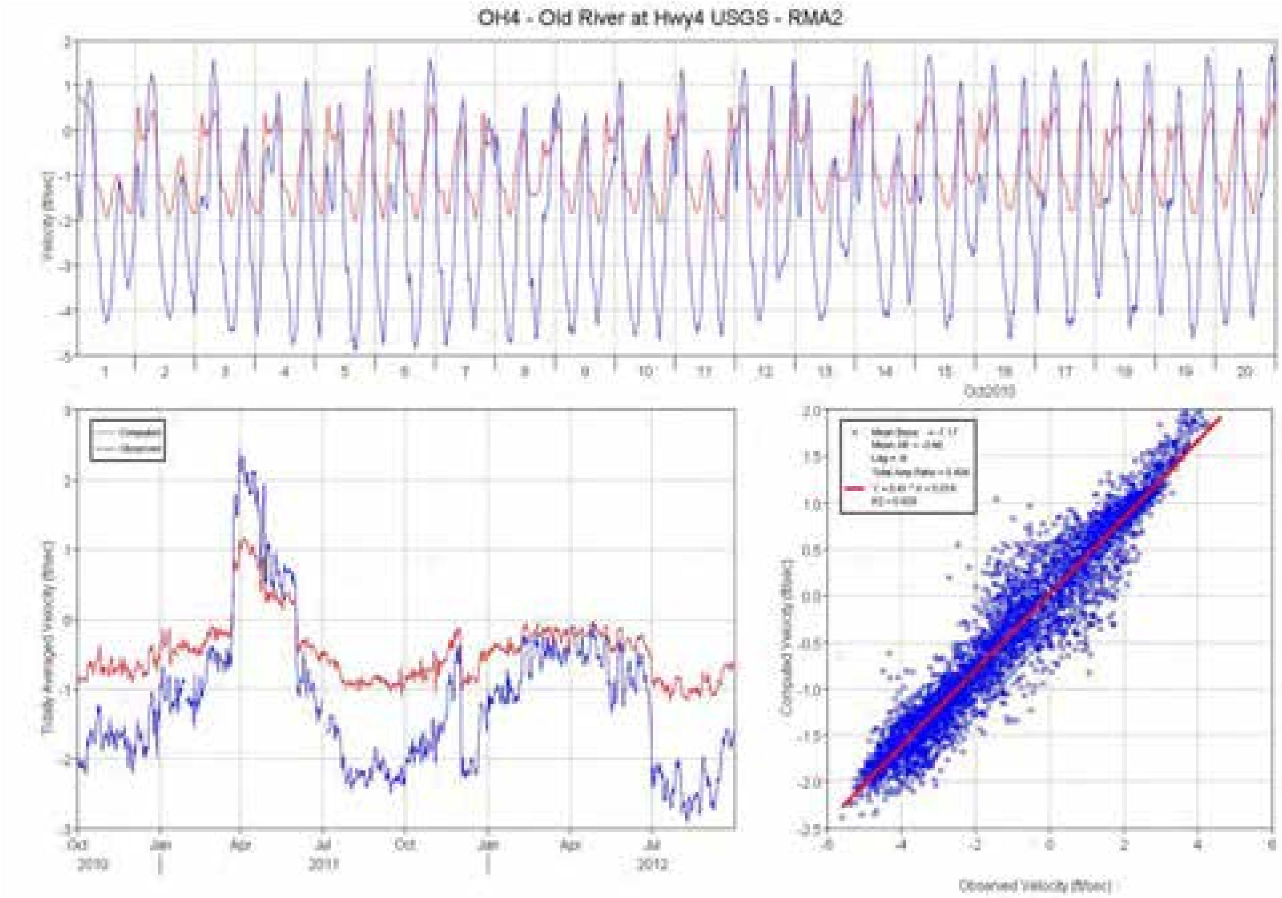


Figure 120 Computed (RMA2) and observed velocity comparison plots for Old River at Hwy 4.

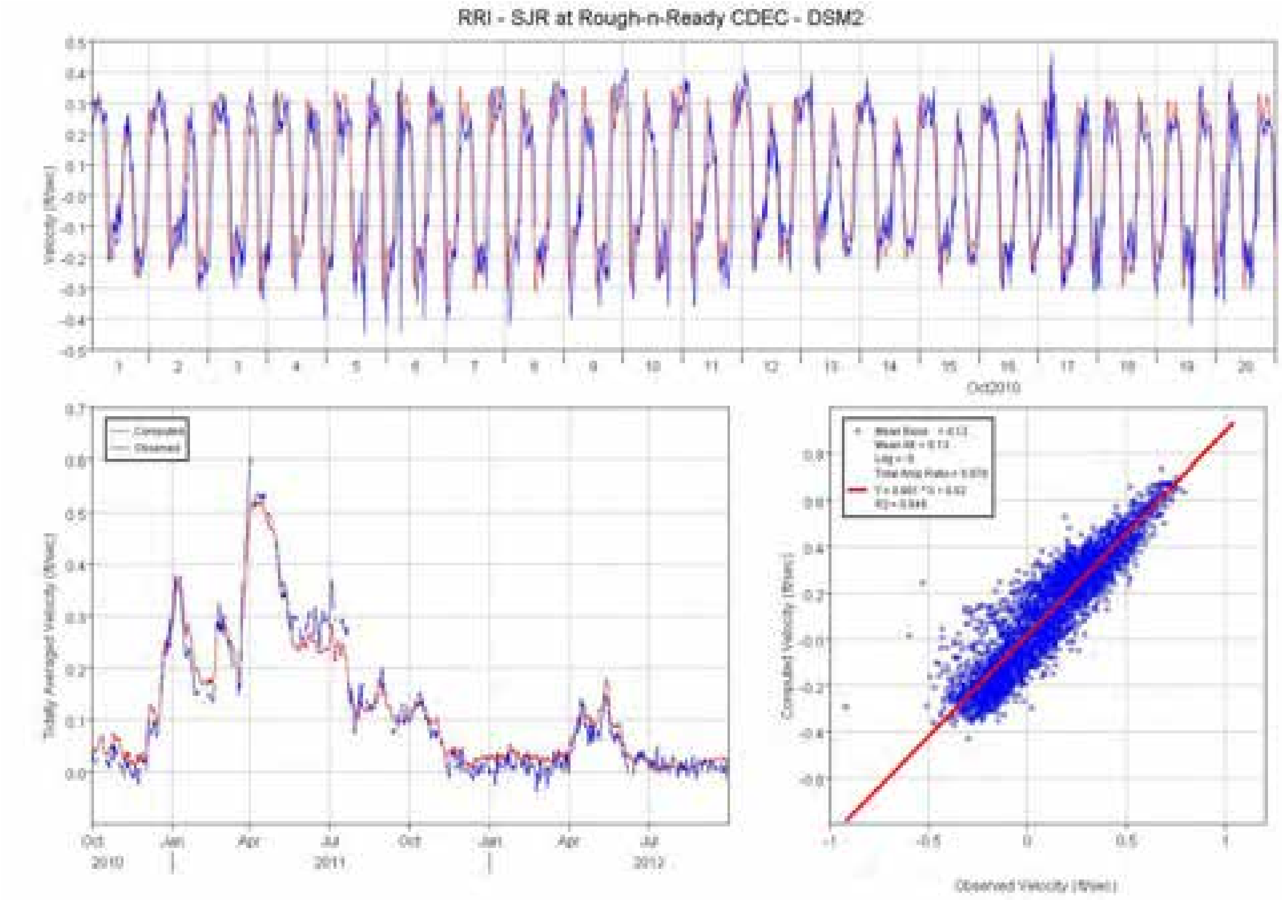


Figure 121 Computed (DSM2) and observed velocity comparison plots for SJR at Rough-n-Ready.

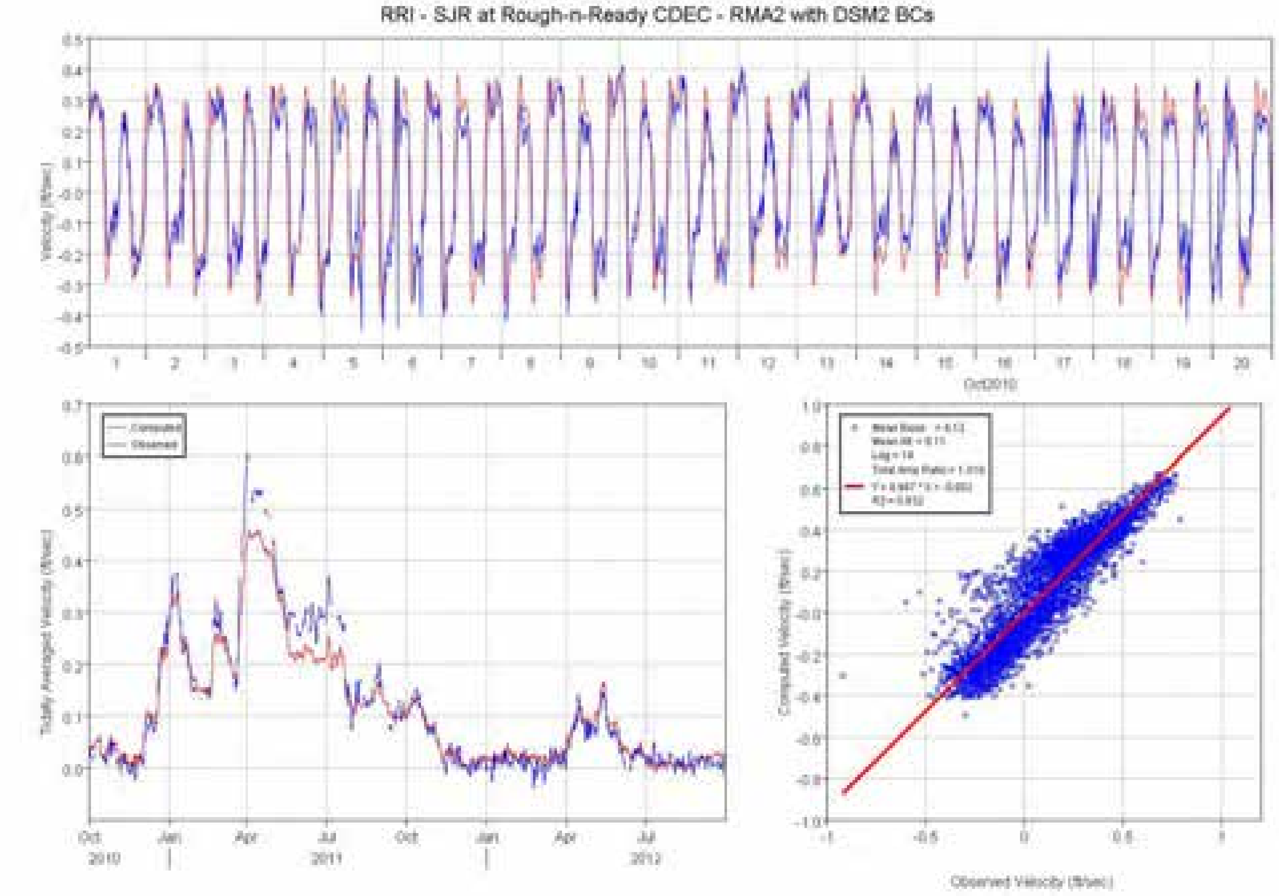


Figure 122 Computed (RMA2 with DSM2 BCs) and observed velocity comparison plots for SJR at Rough-n-Ready.

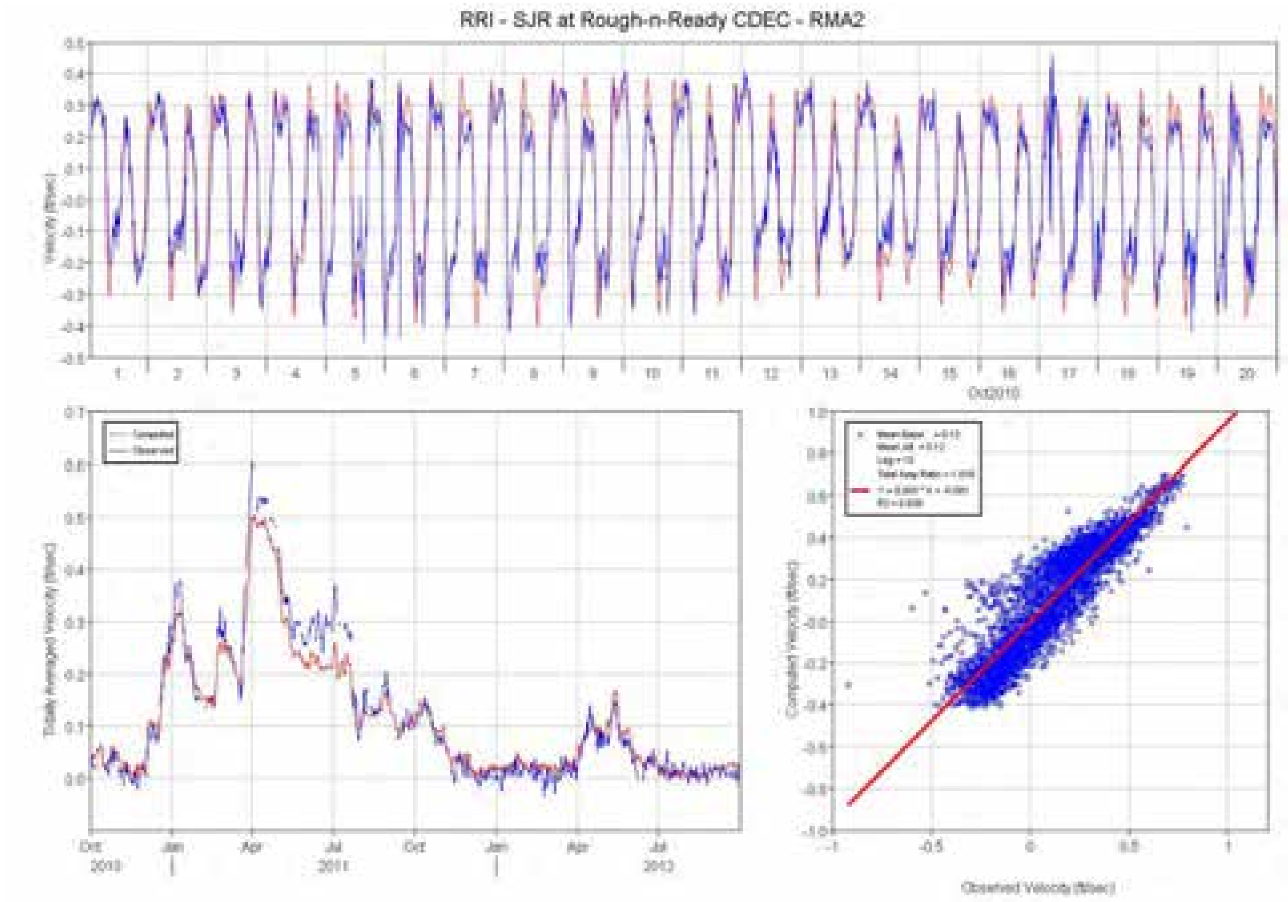


Figure 123 Computed (RMA2) and observed velocity comparison plots for SJR at Rough-n-Ready.

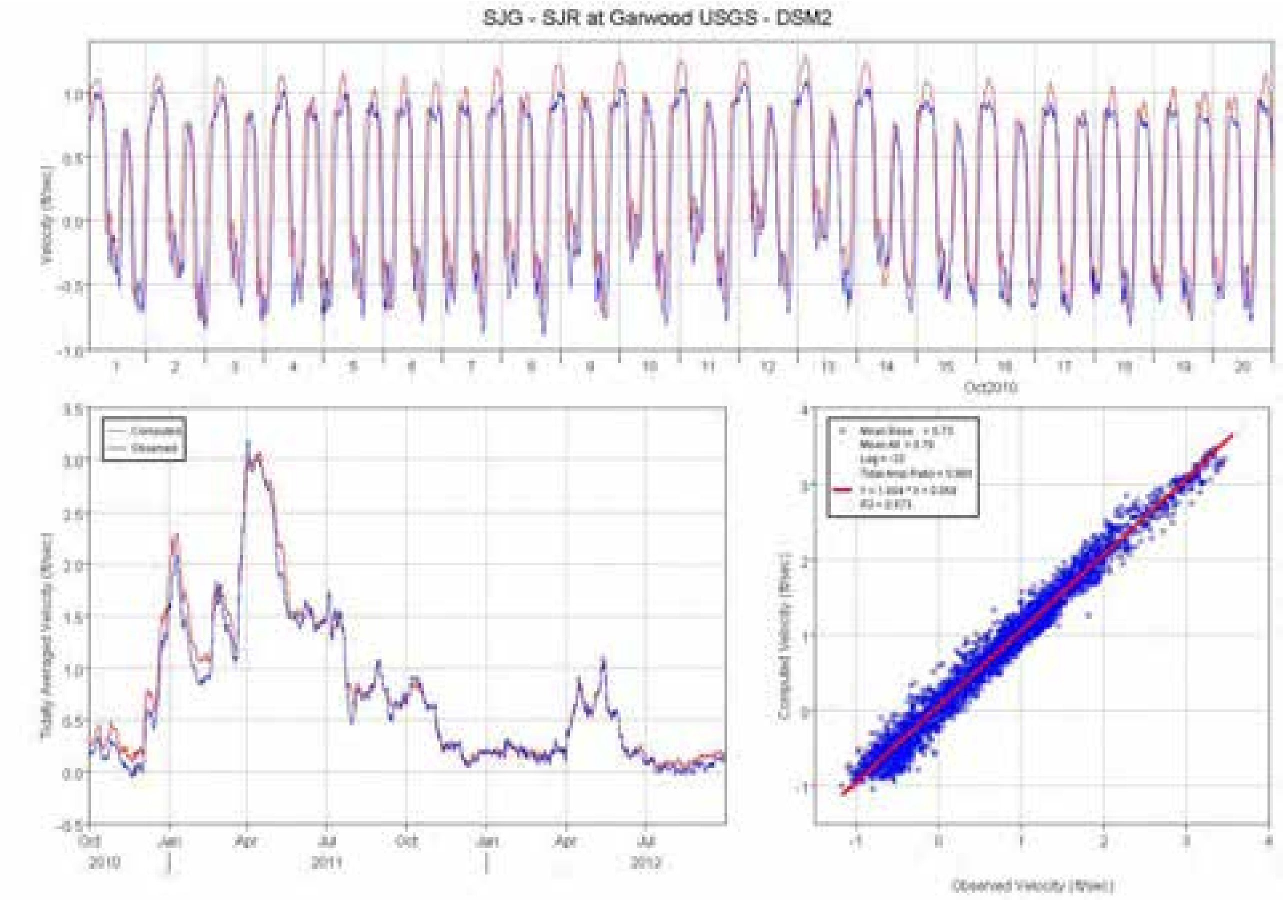


Figure 124 Computed (DSM2) and observed velocity comparison plots for SJR at Garwood.

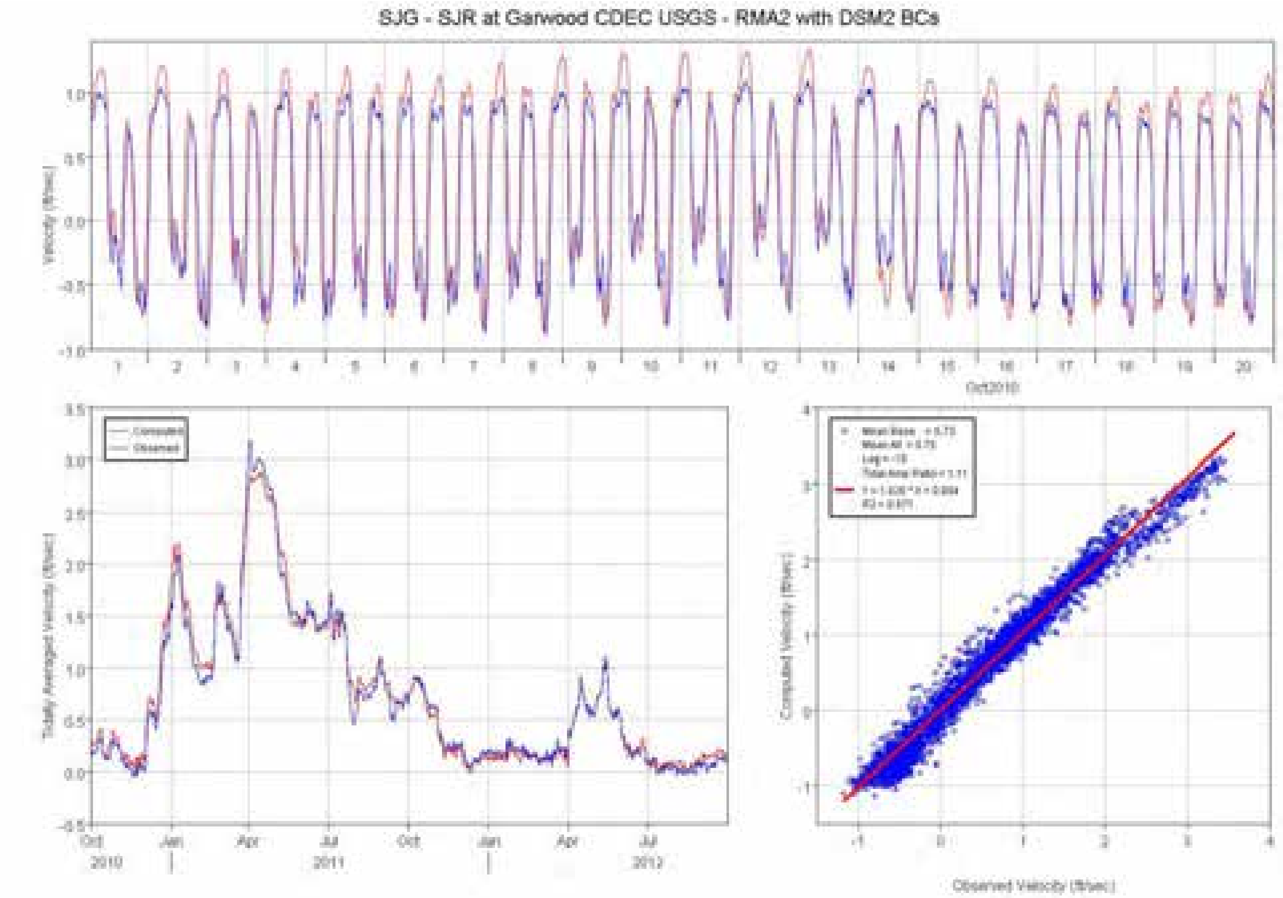


Figure 125 Computed (RMA2 with DSM2 BCs) and observed velocity comparison plots for SJR at Garwood.

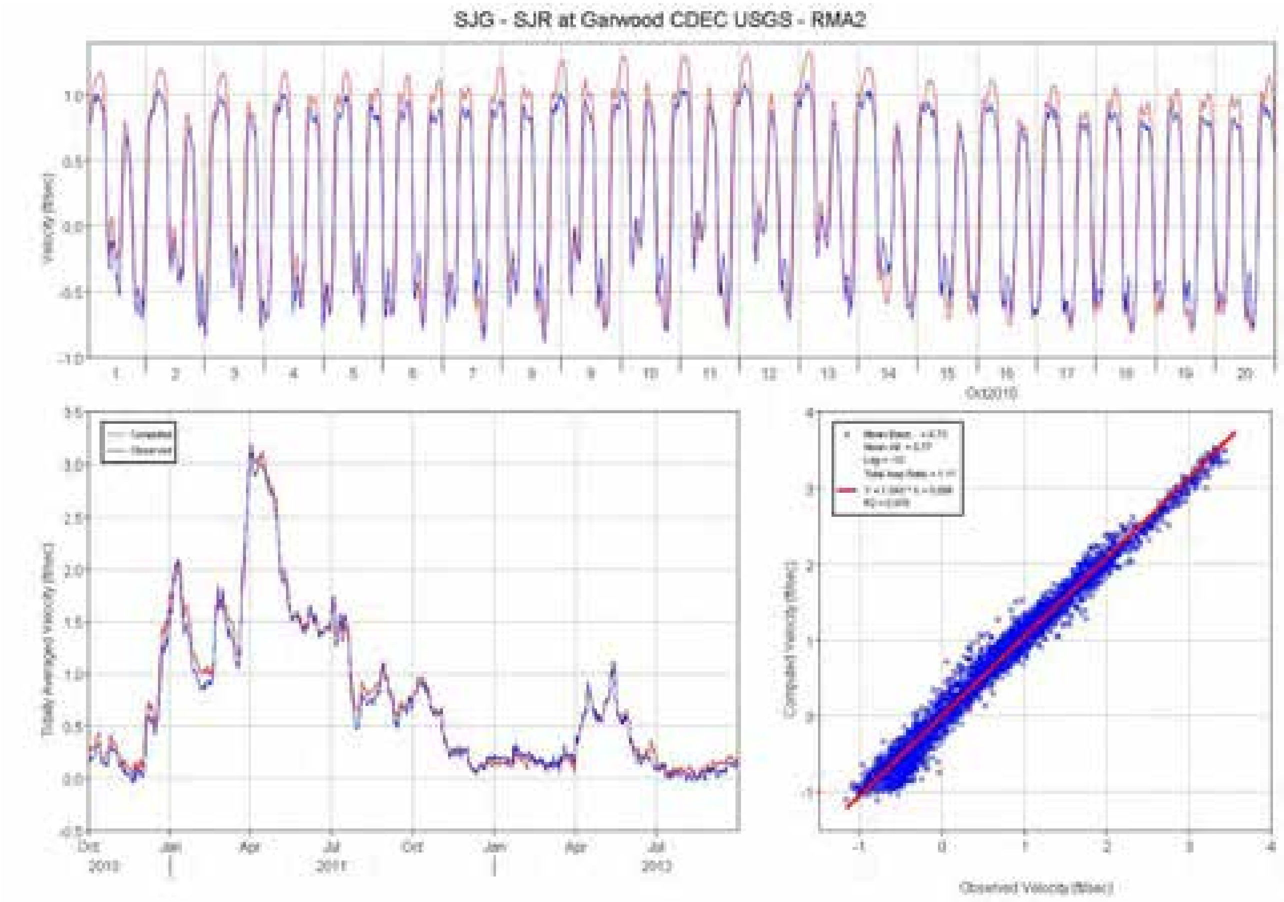


Figure 126 Computed (RMA2) and observed velocity comparison plots for SJR at Garwood.

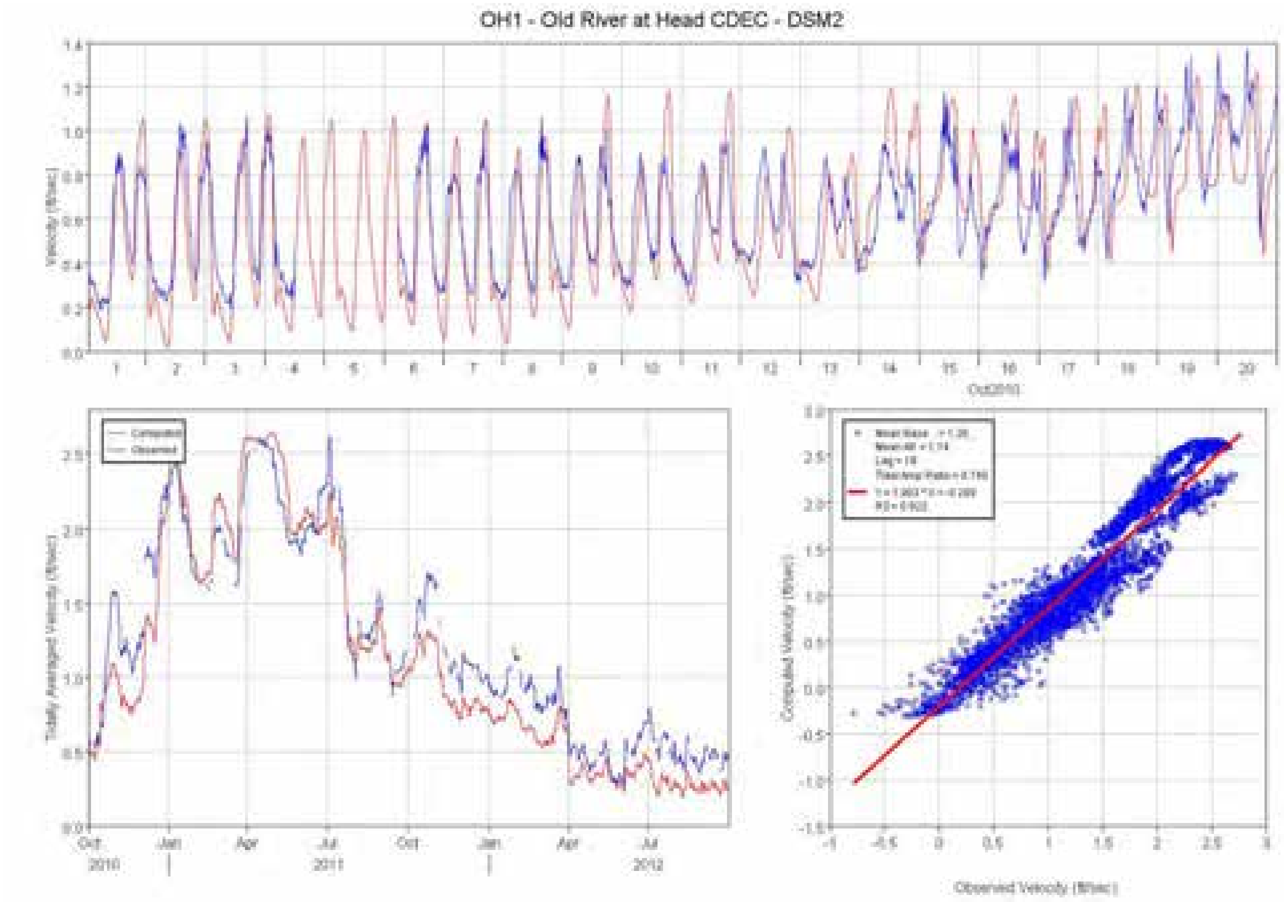


Figure 127 Computed (DSM2) and observed velocity comparison plots for Old River at Head.

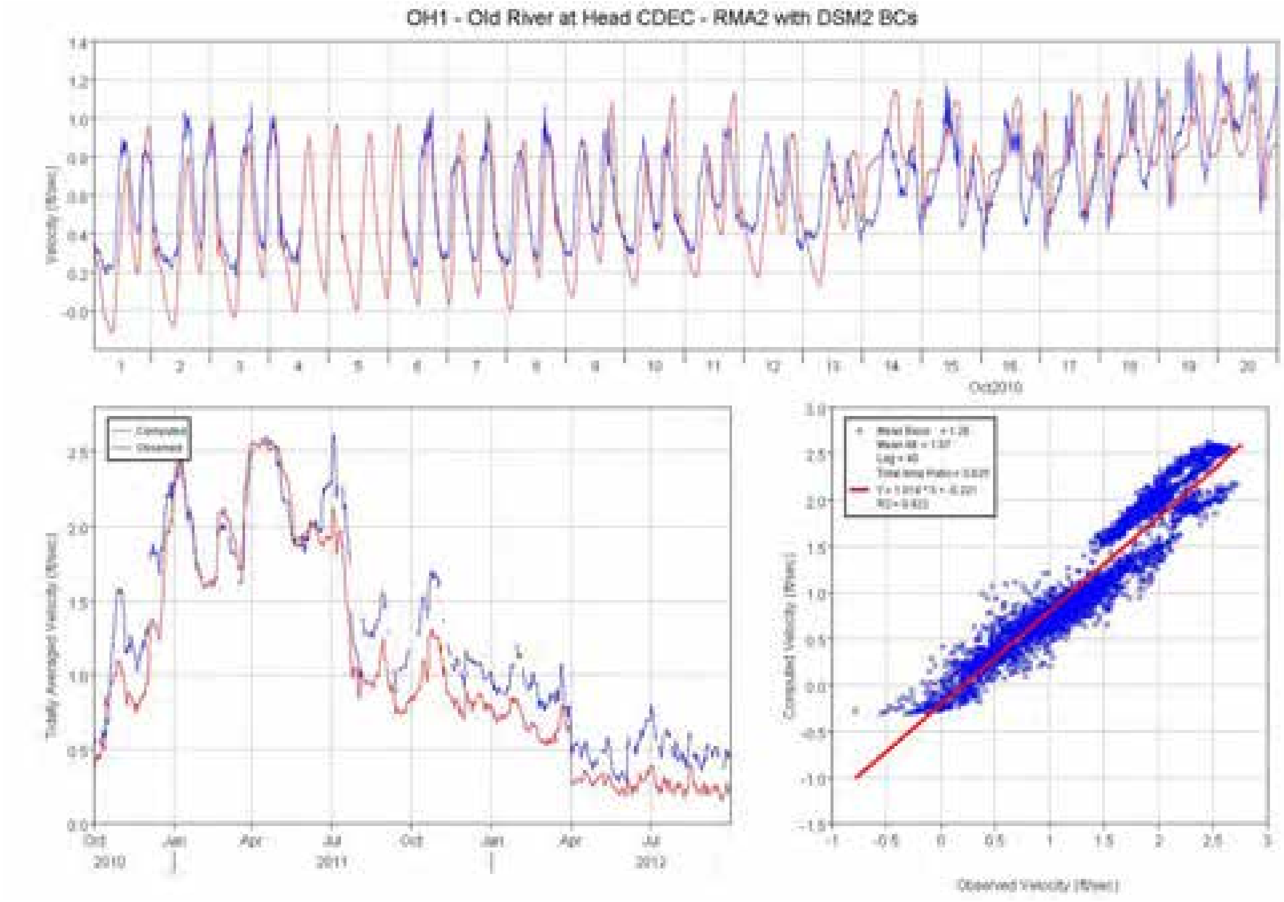


Figure 128 Computed (RMA2 with DSM2 BCs) and observed velocity comparison plots for Old River at Head.

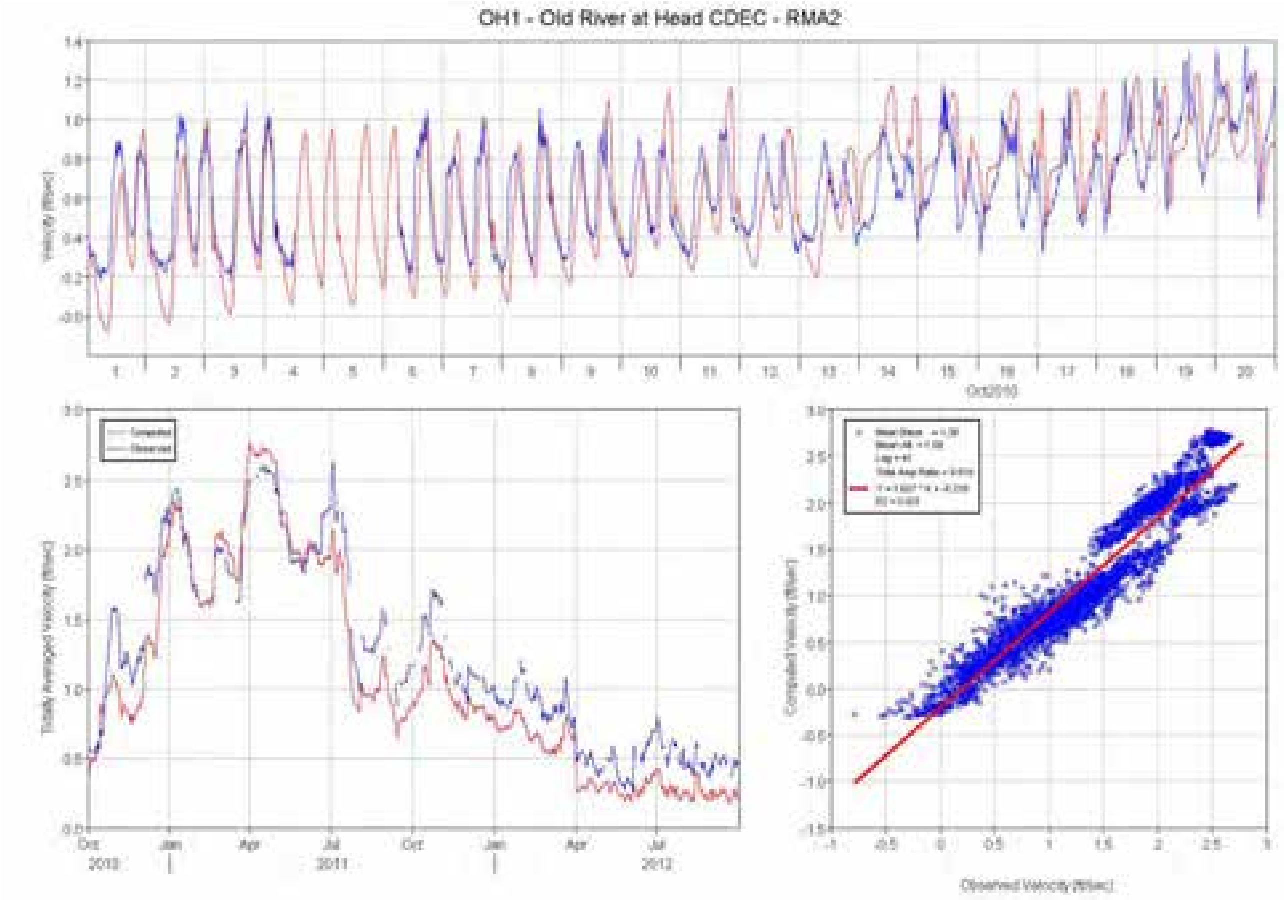


Figure 129 Computed (RMA2) and observed velocity comparison plots for Old River at Head.

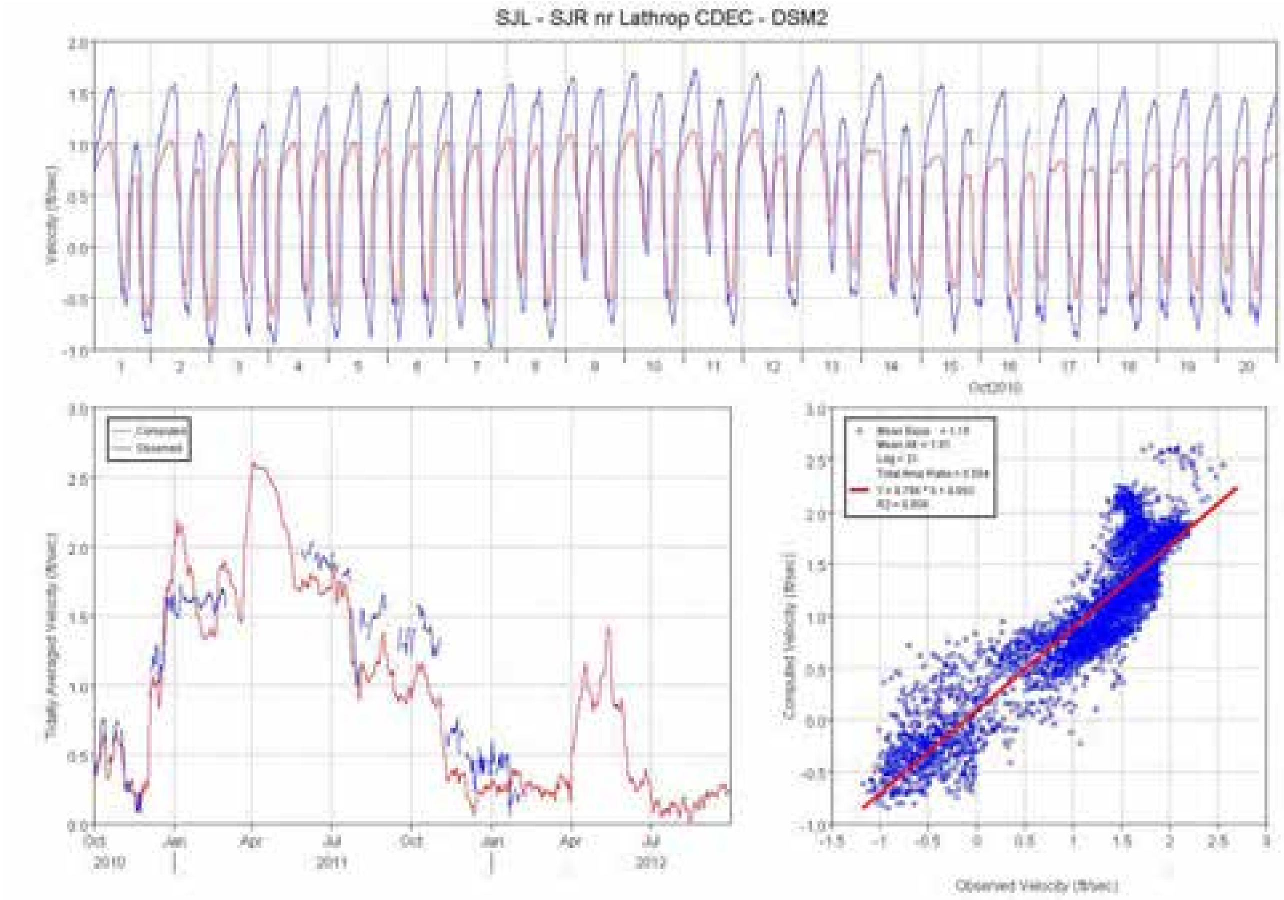


Figure 130 Computed (DSM2) and observed velocity comparison plots for SJR near Lathrop.

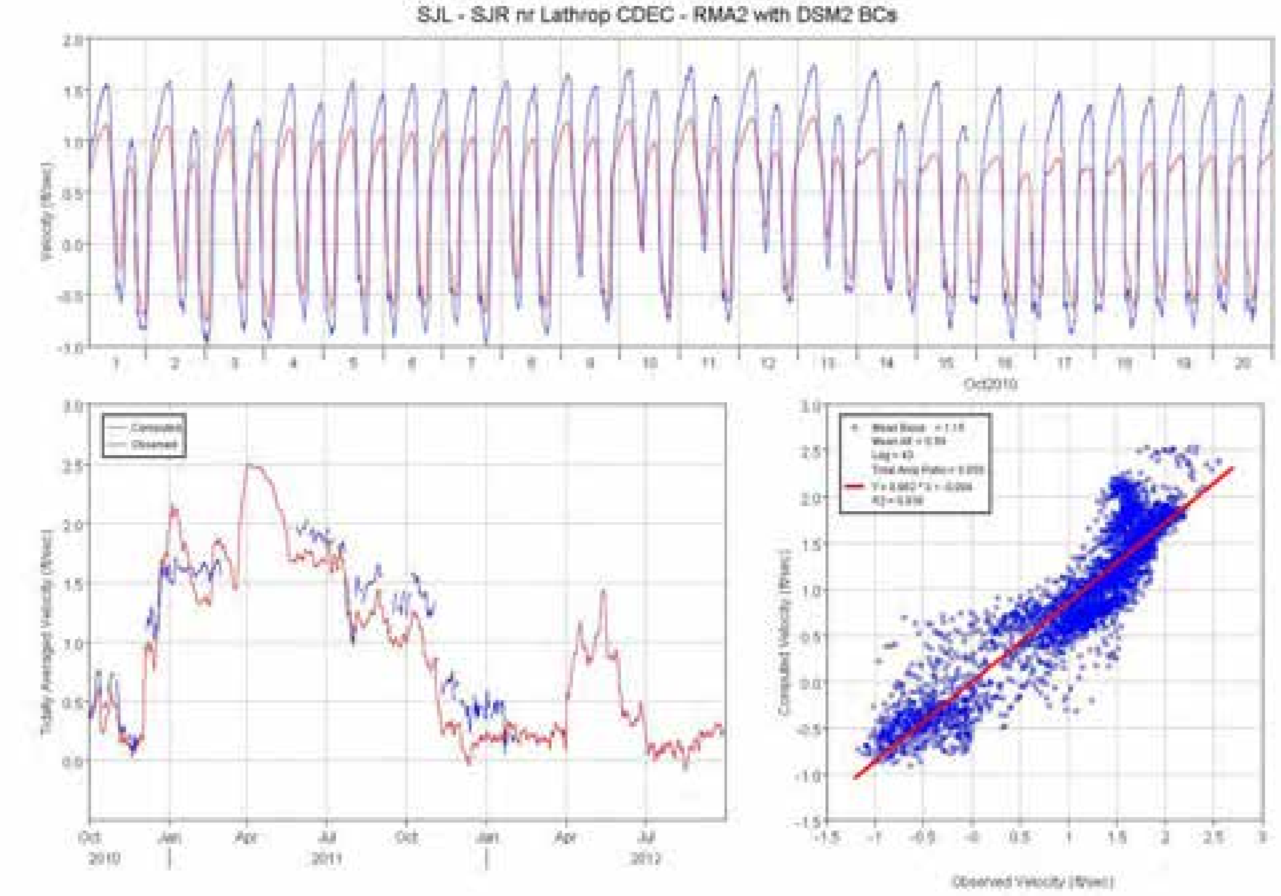


Figure 131 Computed (RMA2 with DSM2 BCs) and observed velocity comparison plots for SJR near Lathrop.

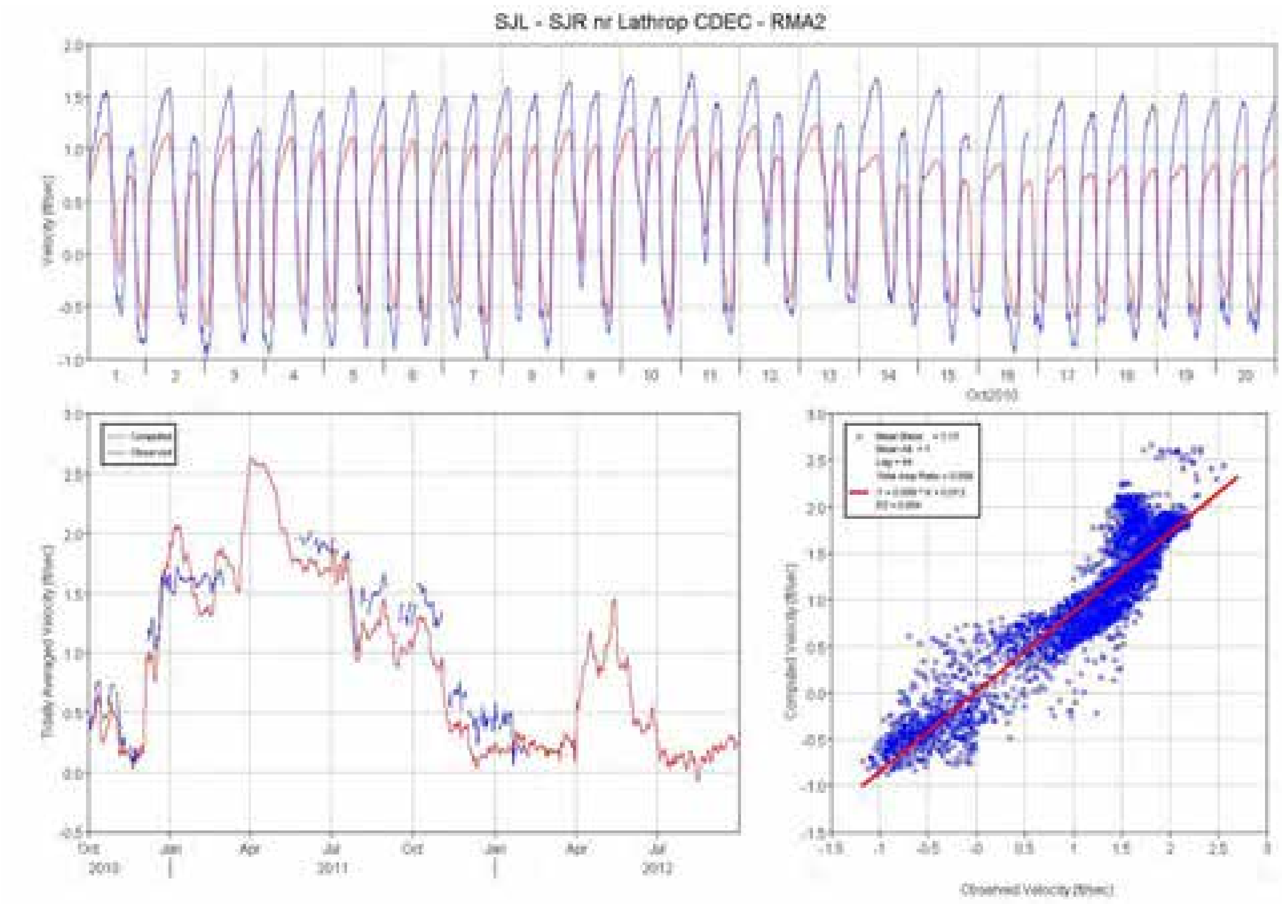


Figure 132 Computed (RMA2) and observed velocity comparison plots for SJR near Lathrop.

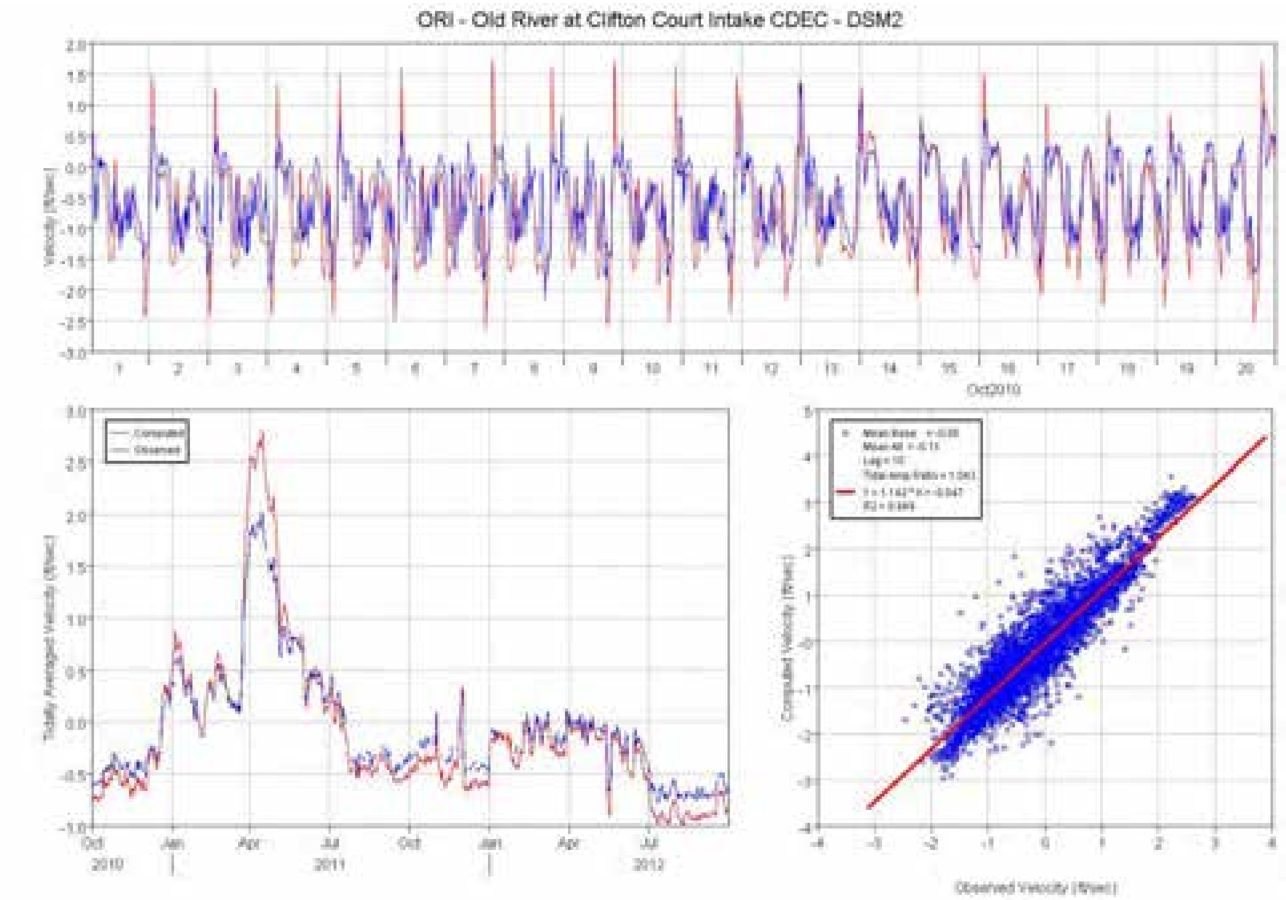


Figure 133 Computed (DSM2) and observed velocity comparison plots for Old River at Clifton Court Intake.

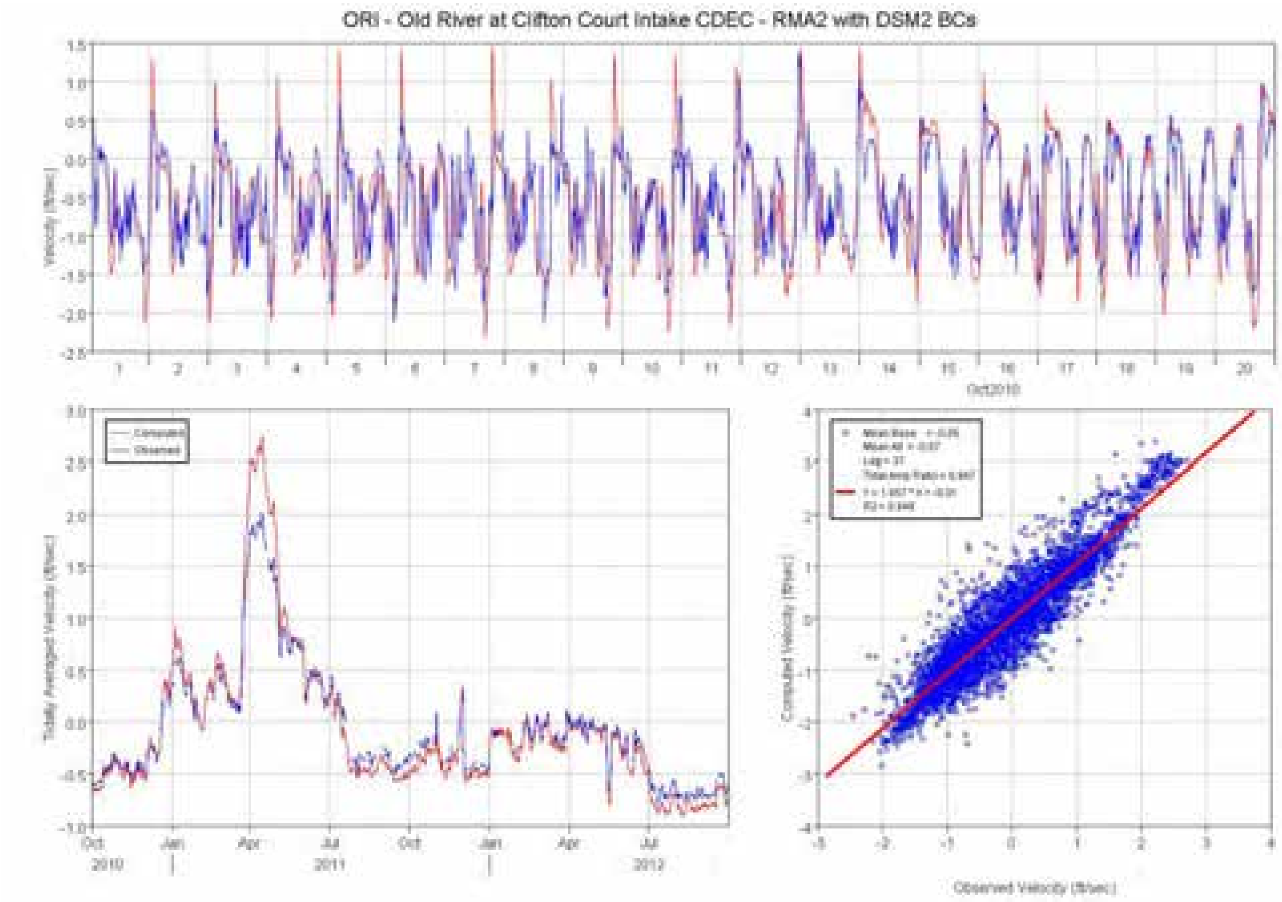


Figure 134 Computed (RMA2 with DSM2 BCs) and observed velocity comparison plots for Old River at Clifton Court Intake.

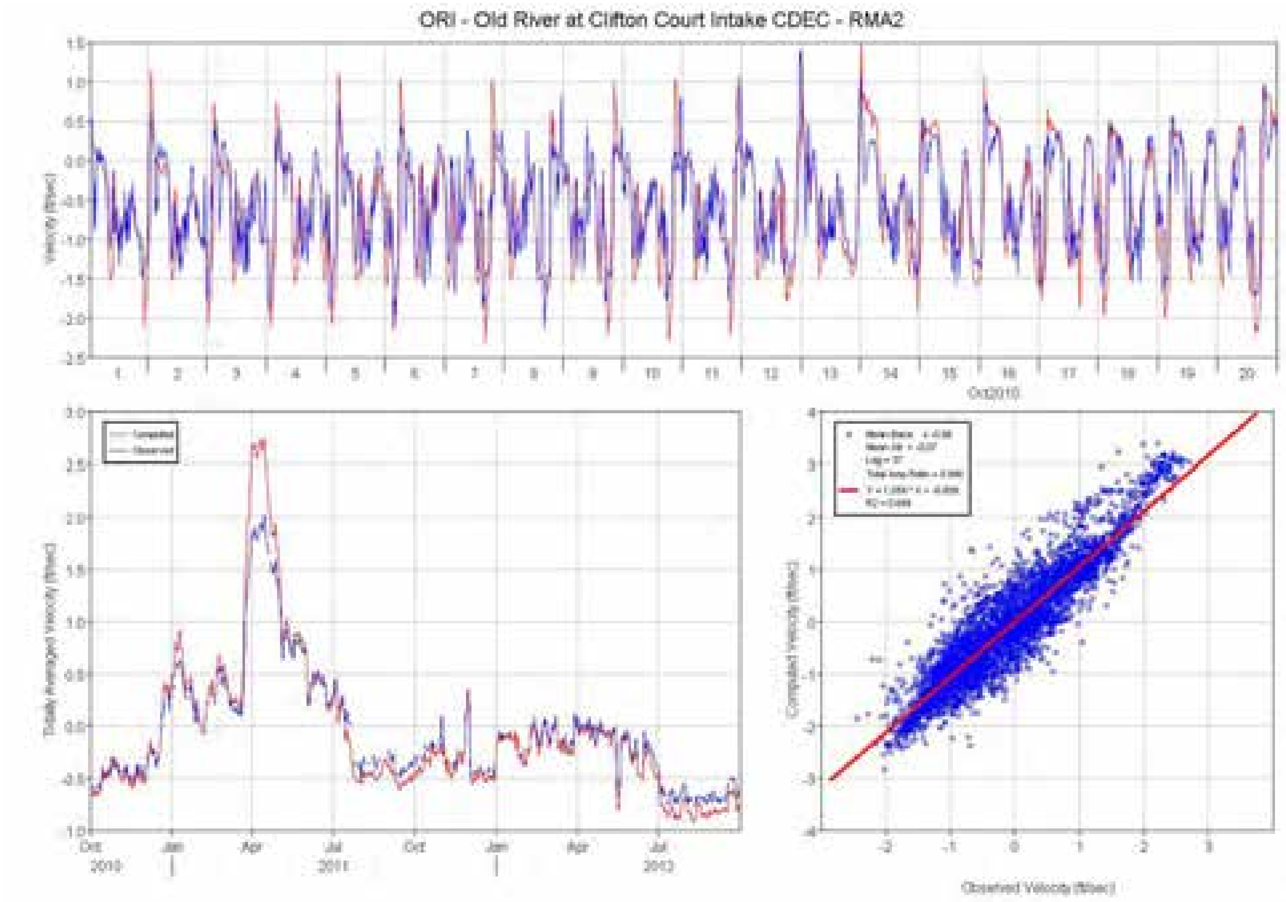


Figure 135 Computed (RMA2) and observed velocity comparison plots for Old River at Clifton Court Intake.

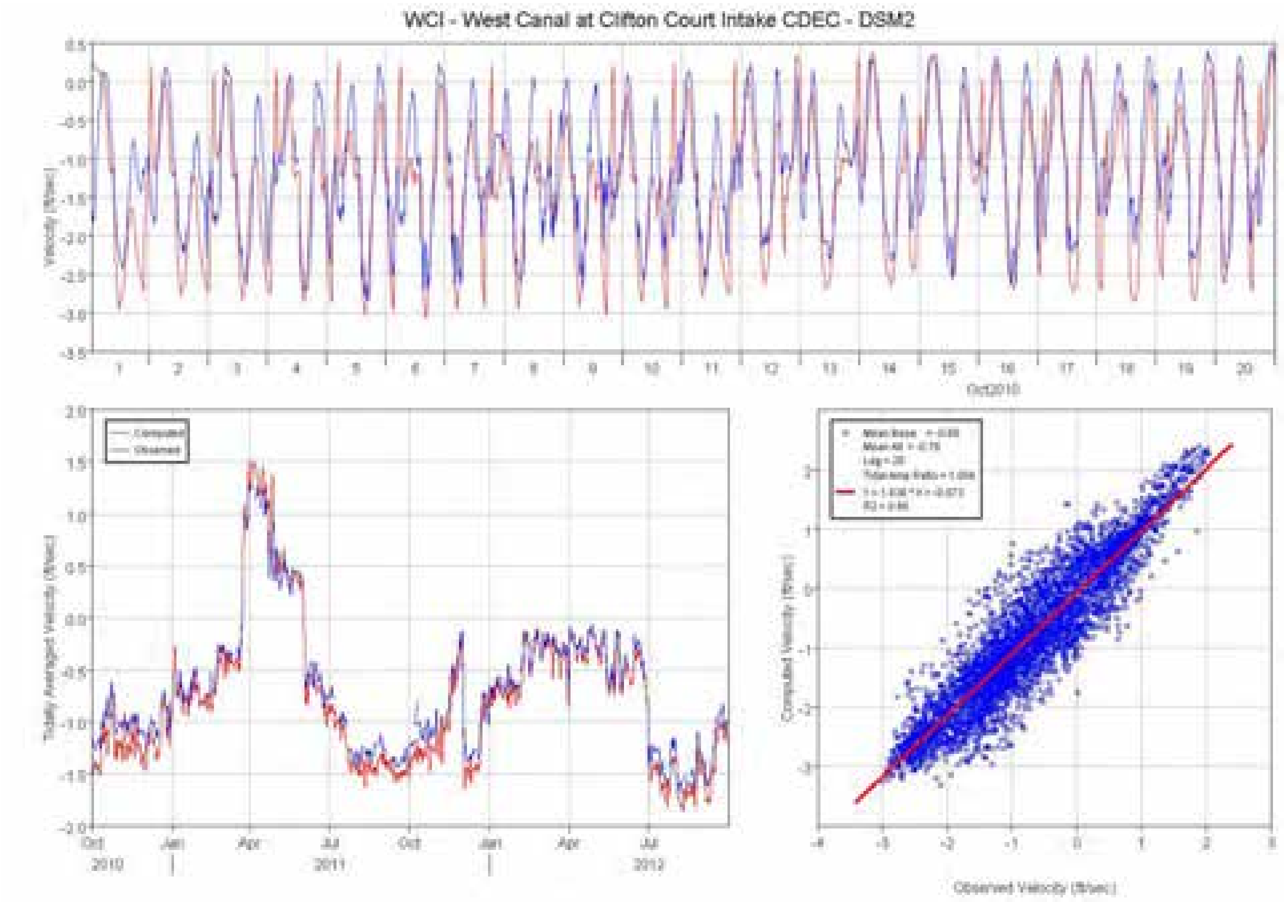


Figure 136 Computed (DSM2) and observed velocity comparison plots for West Canal at Clifton Court Intake.

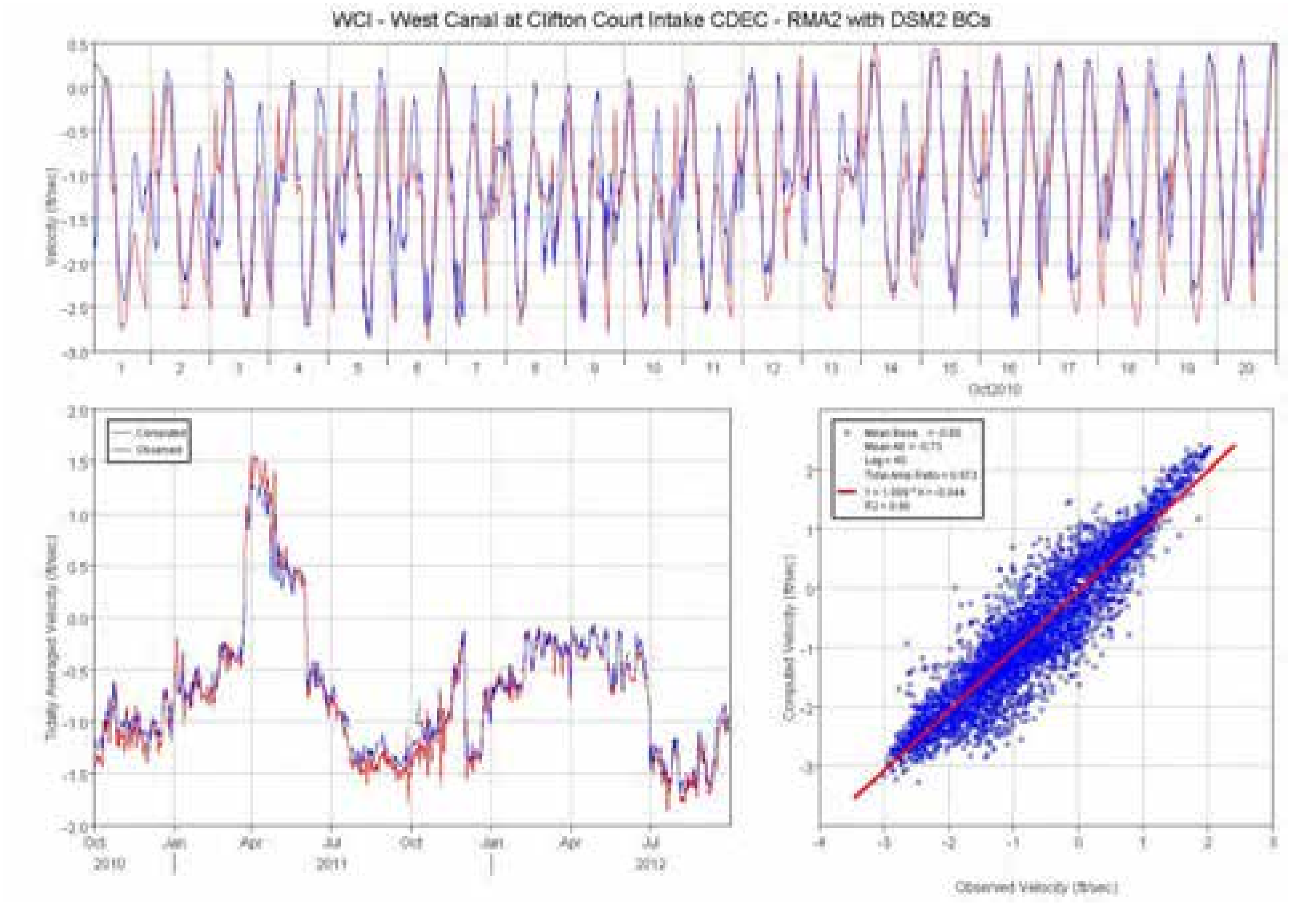


Figure 137 Computed (RMA2 with DSM2 BCs) and observed velocity comparison plots for West Canal at Clifton Court Intake.

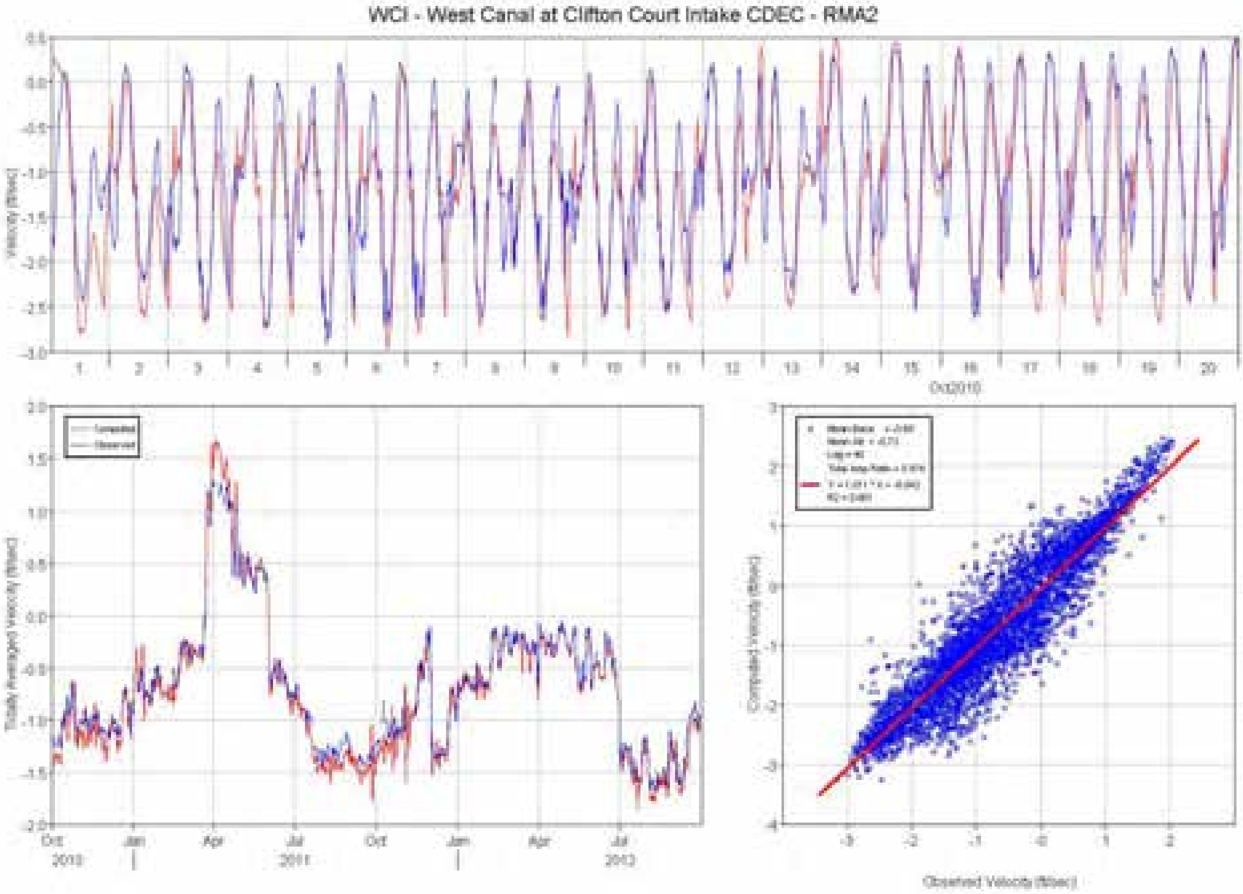


Figure 138 Computed (RMA2) and observed velocity comparison plots for West Canal at Clifton Court Intake.

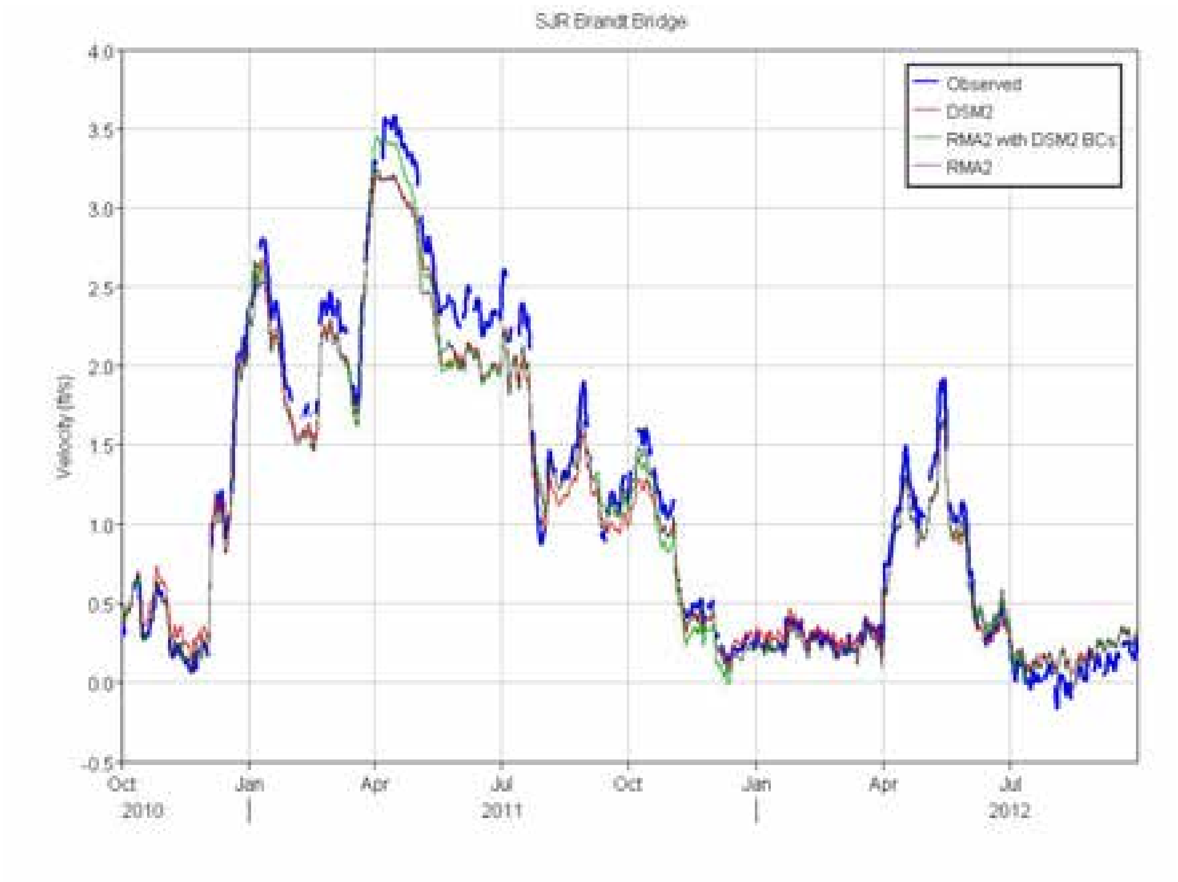


Figure 139 Tidally averaged observed and computed velocity for SJR at Brandt Bridge.

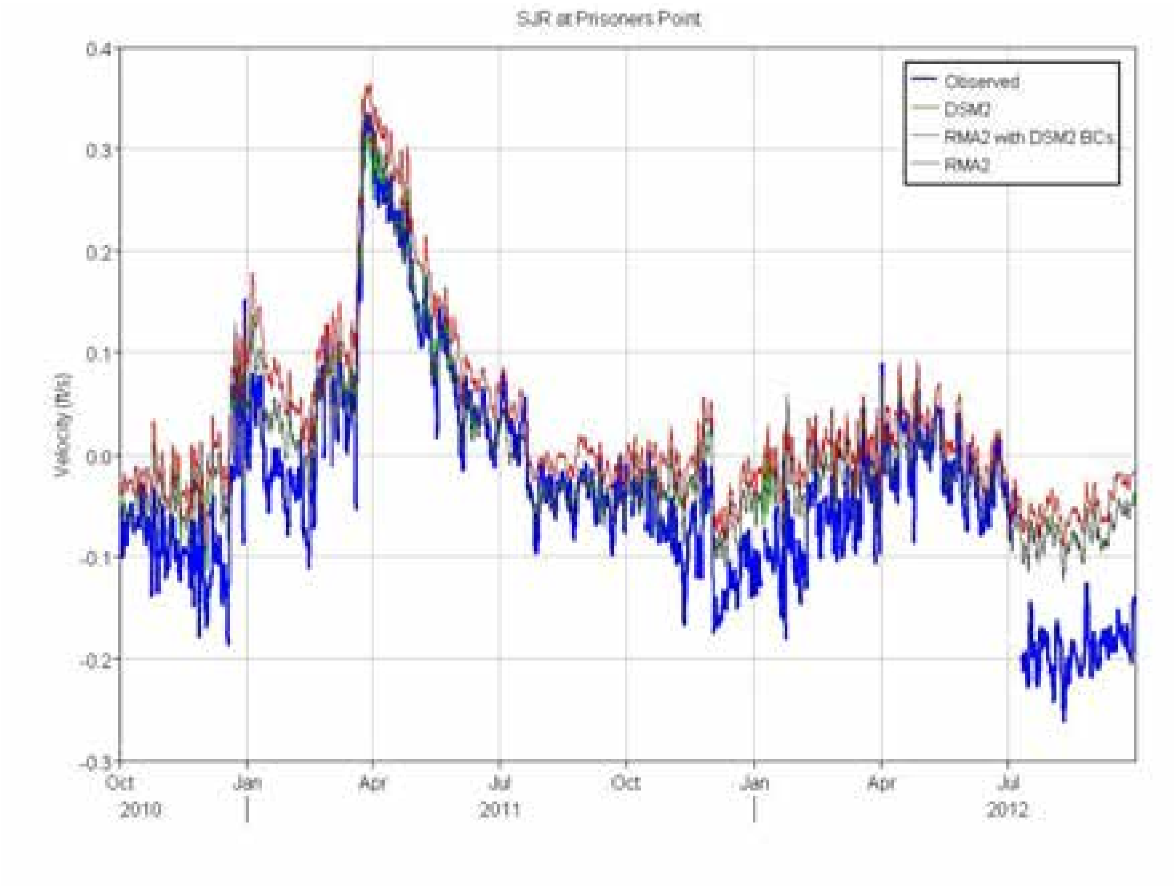


Figure 140 Tidally averaged observed and computed velocity for SJR at Prisoners Point.

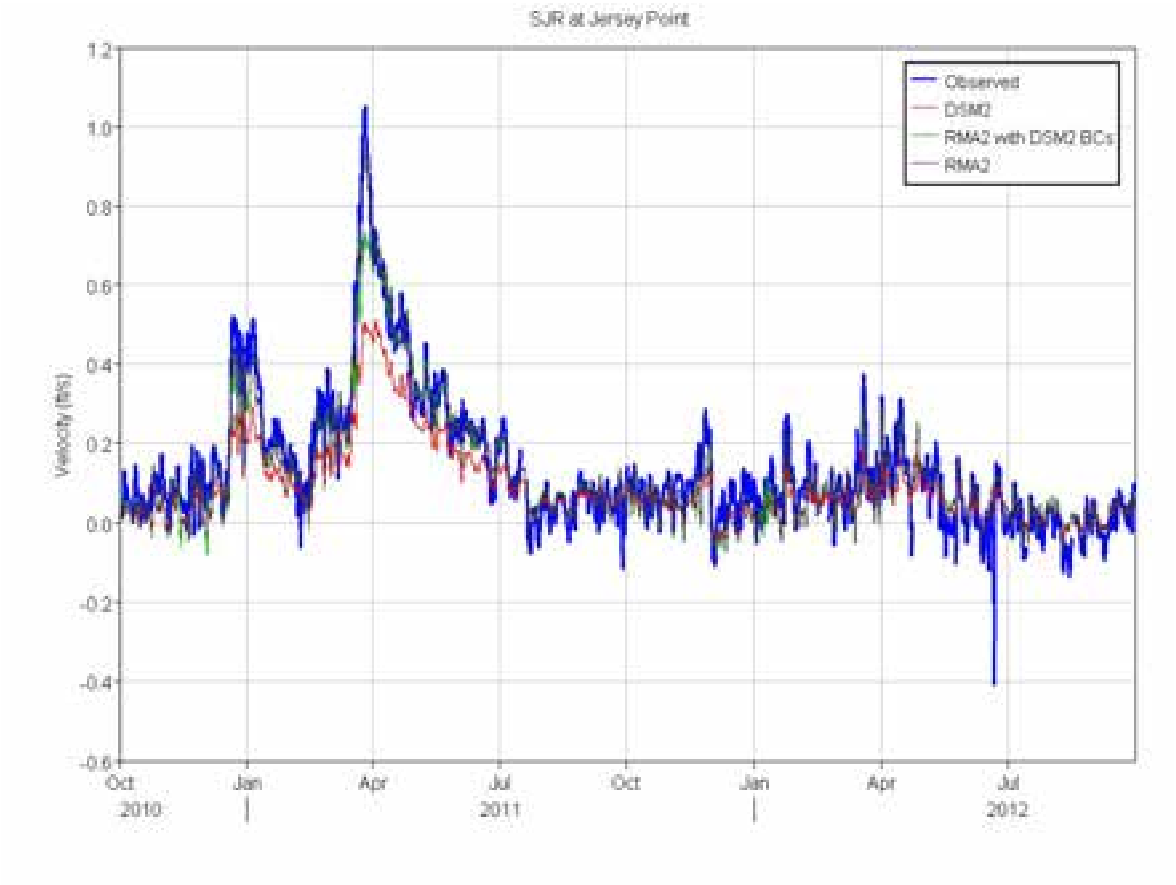


Figure 141 Tidally averaged observed and computed velocity for SJR at Jersey Point.

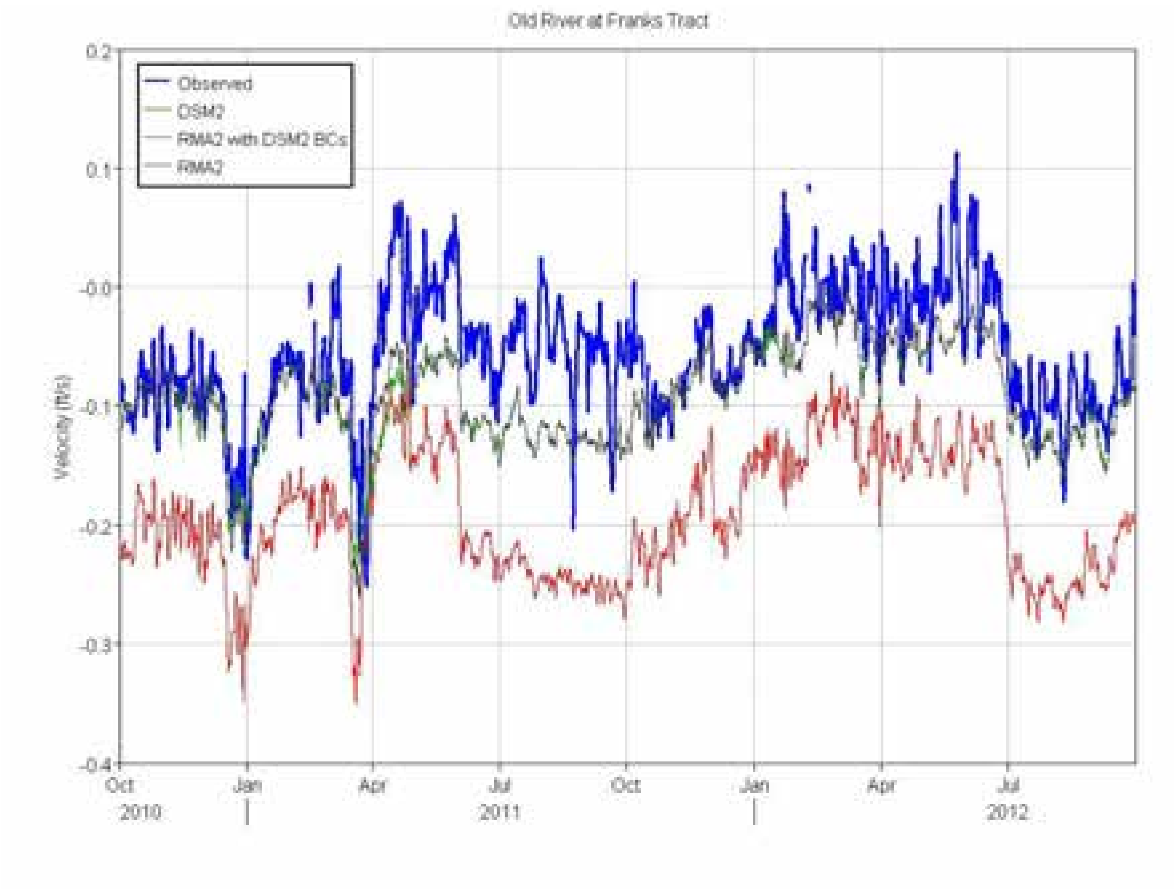


Figure 142 Tidally averaged observed and computed velocity for Old River at Franks Tract.

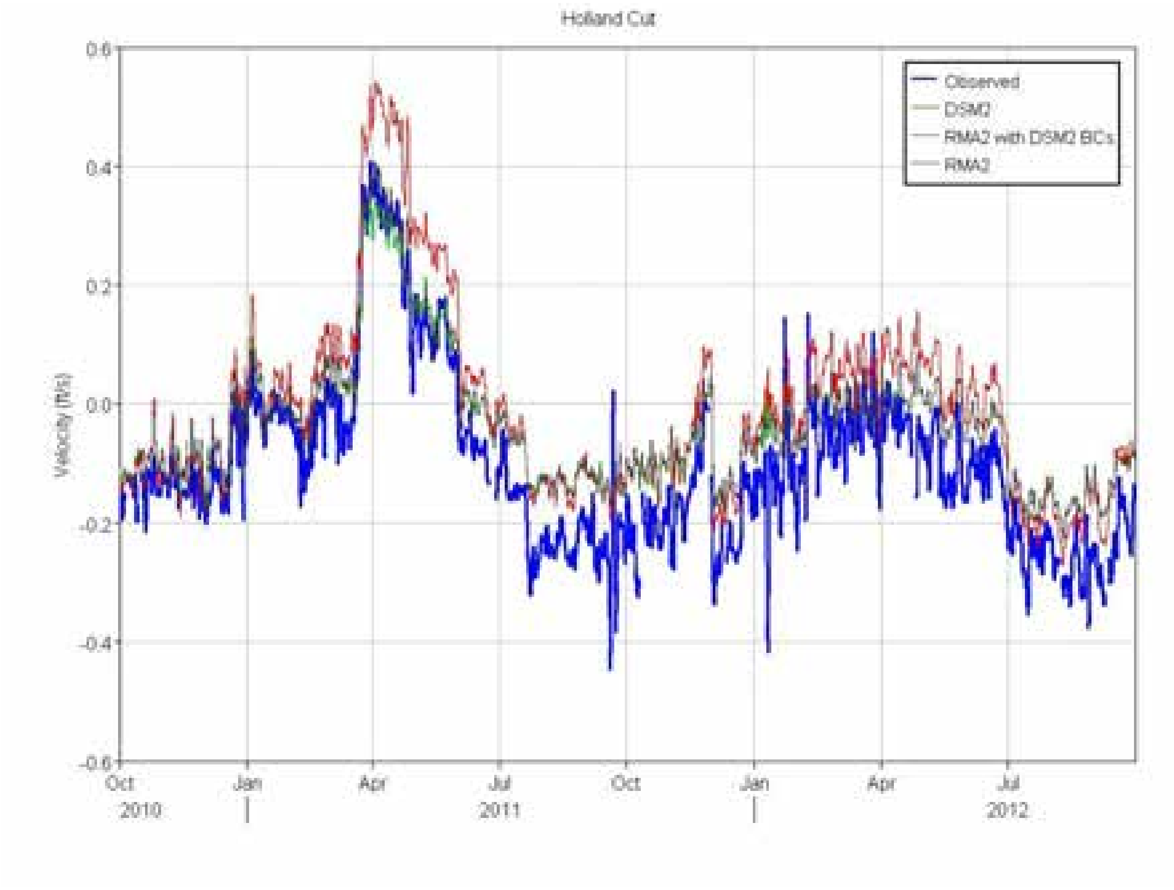


Figure 143 Tidally averaged observed and computed velocity for Holland Cut.

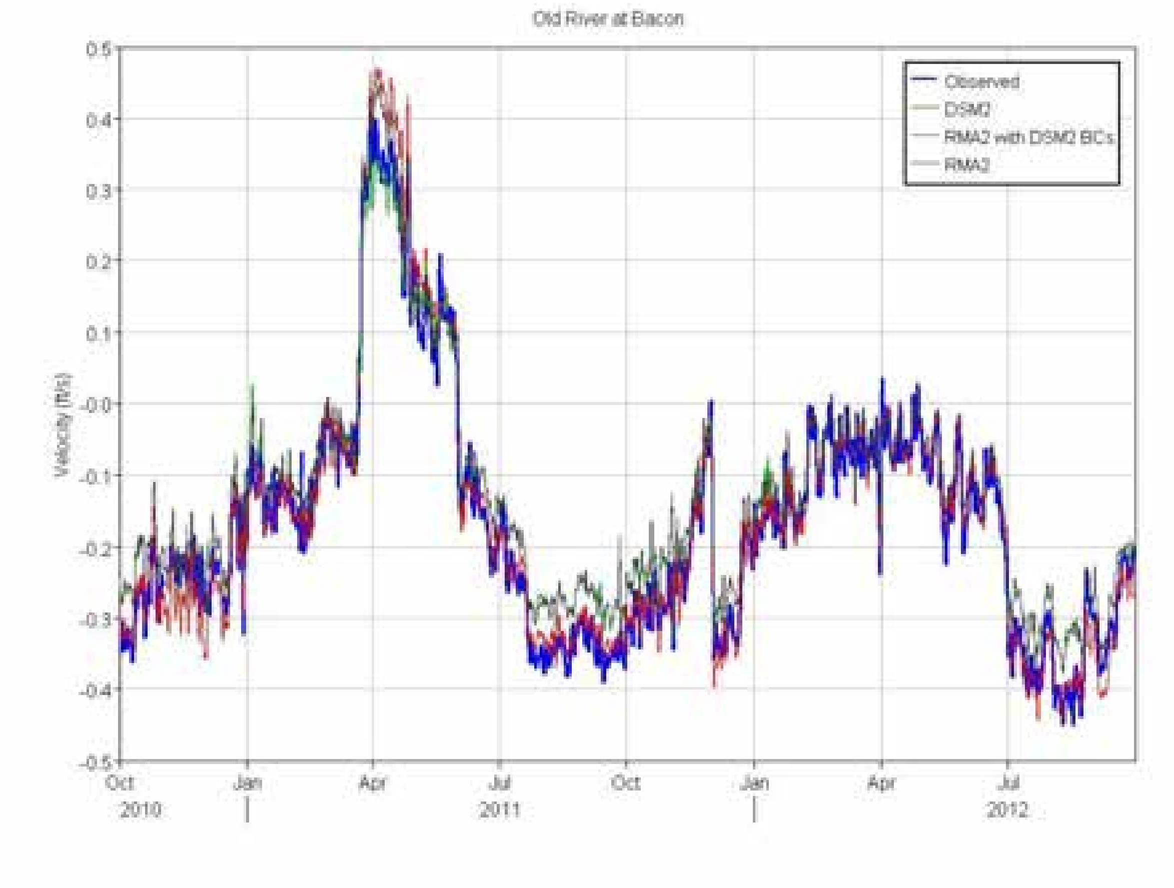


Figure 144 Tidally averaged observed and computed velocity for Old River at Bacon.

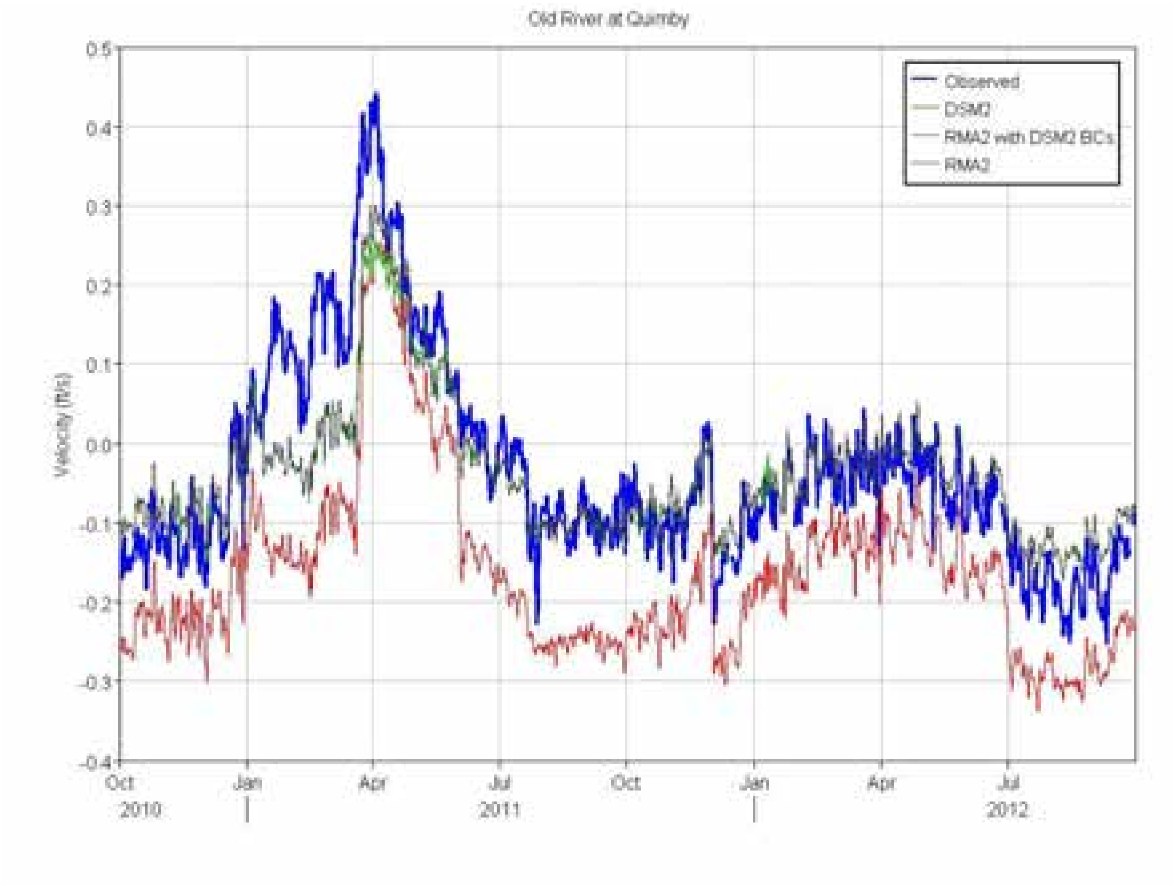


Figure 145 Tidally averaged observed and computed velocity for Old River at Quimby.

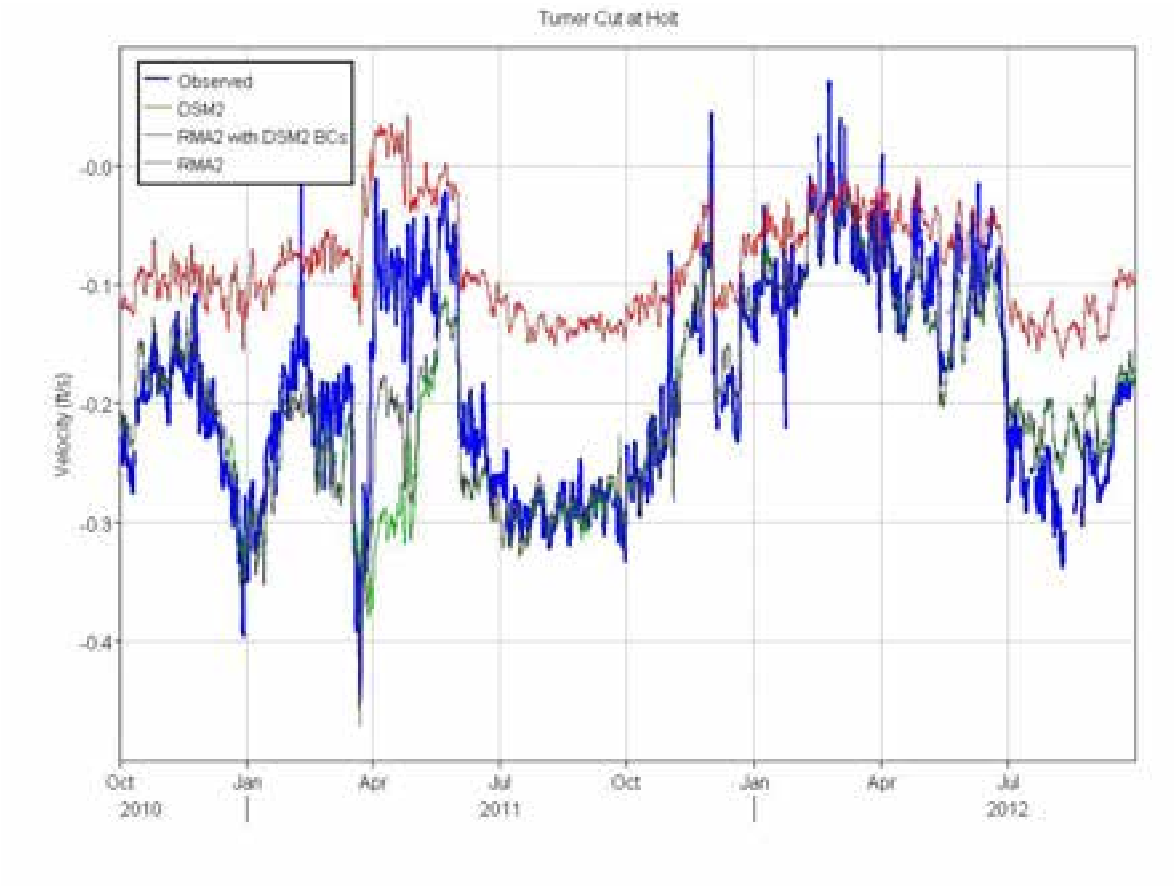


Figure 146 Tidally averaged observed and computed velocity for Turner Cut at Holt.

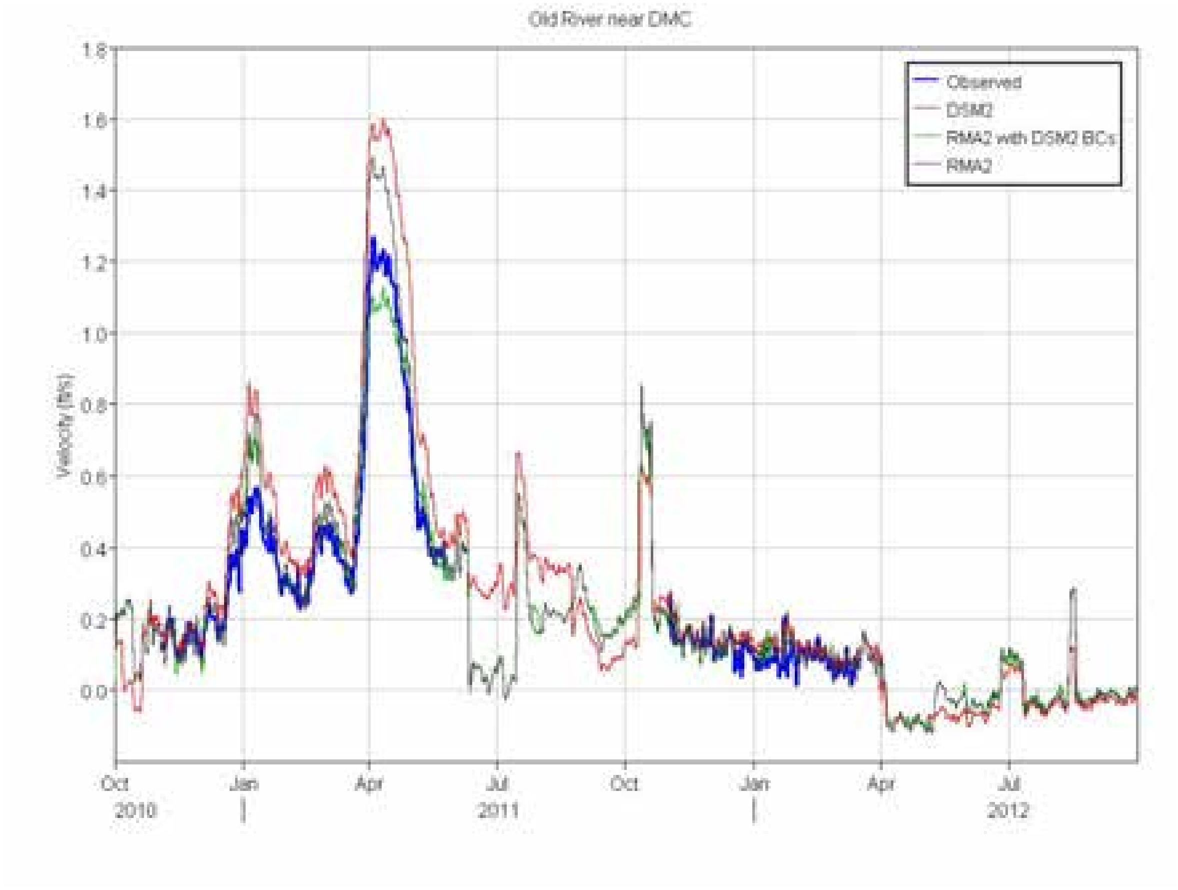


Figure 147 Tidally averaged observed and computed velocity for Old River near DMC.

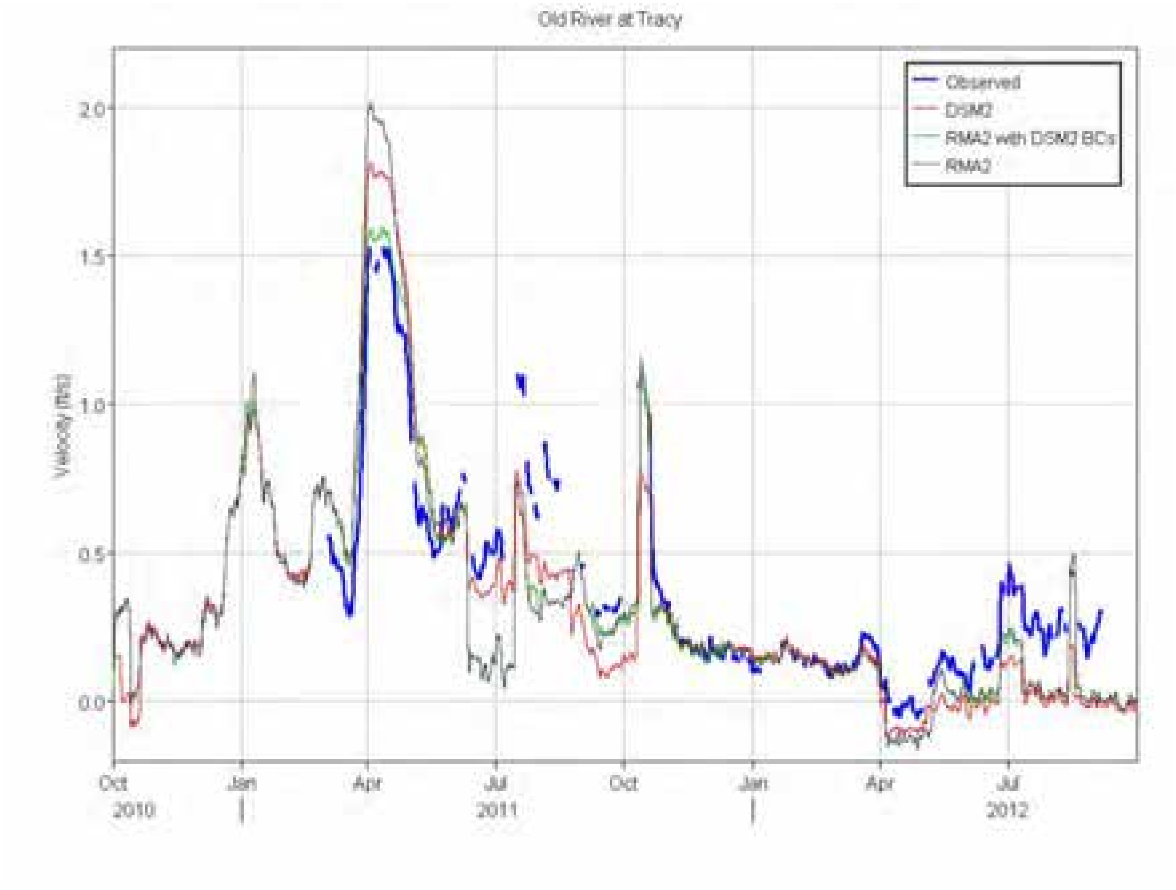


Figure 148 Tidally averaged observed and computed velocity for Old River at Tracy.

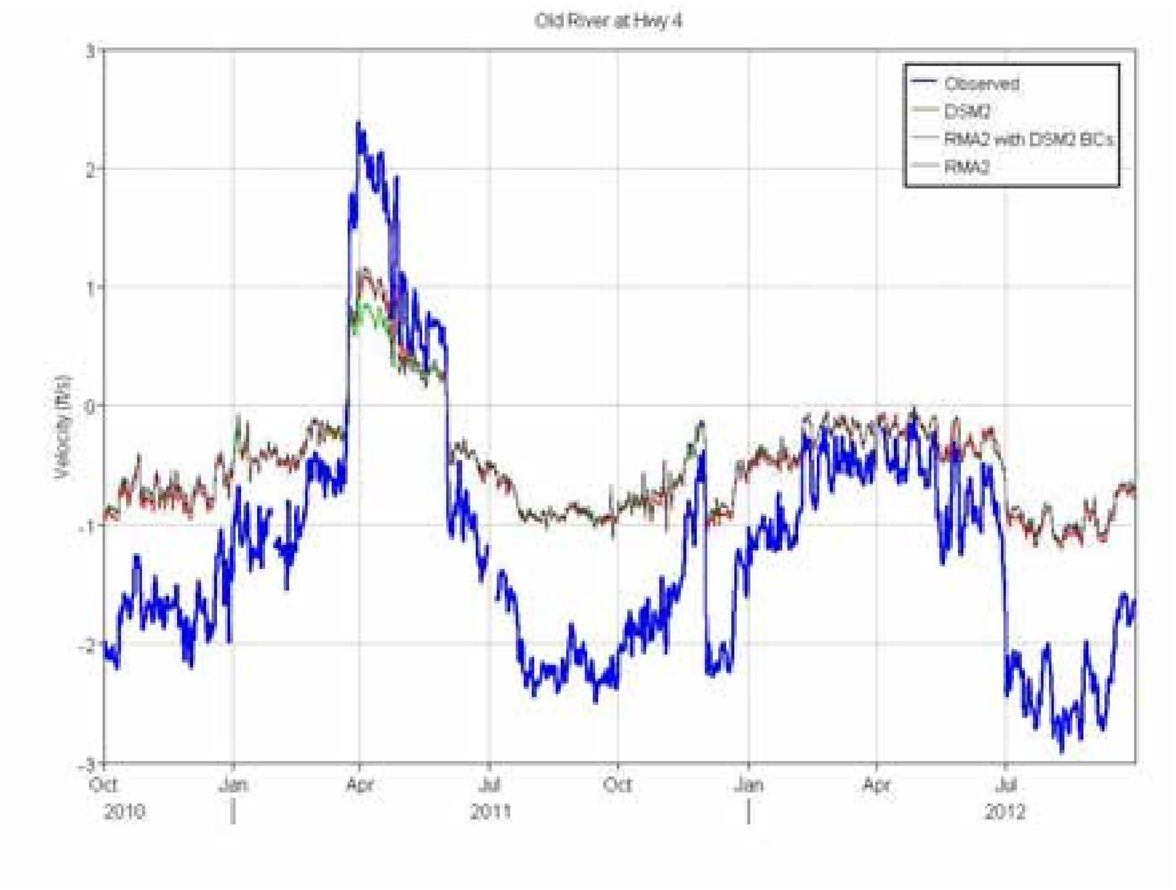


Figure 149 Tidally averaged observed and computed velocity for Old River at Hwy 4.

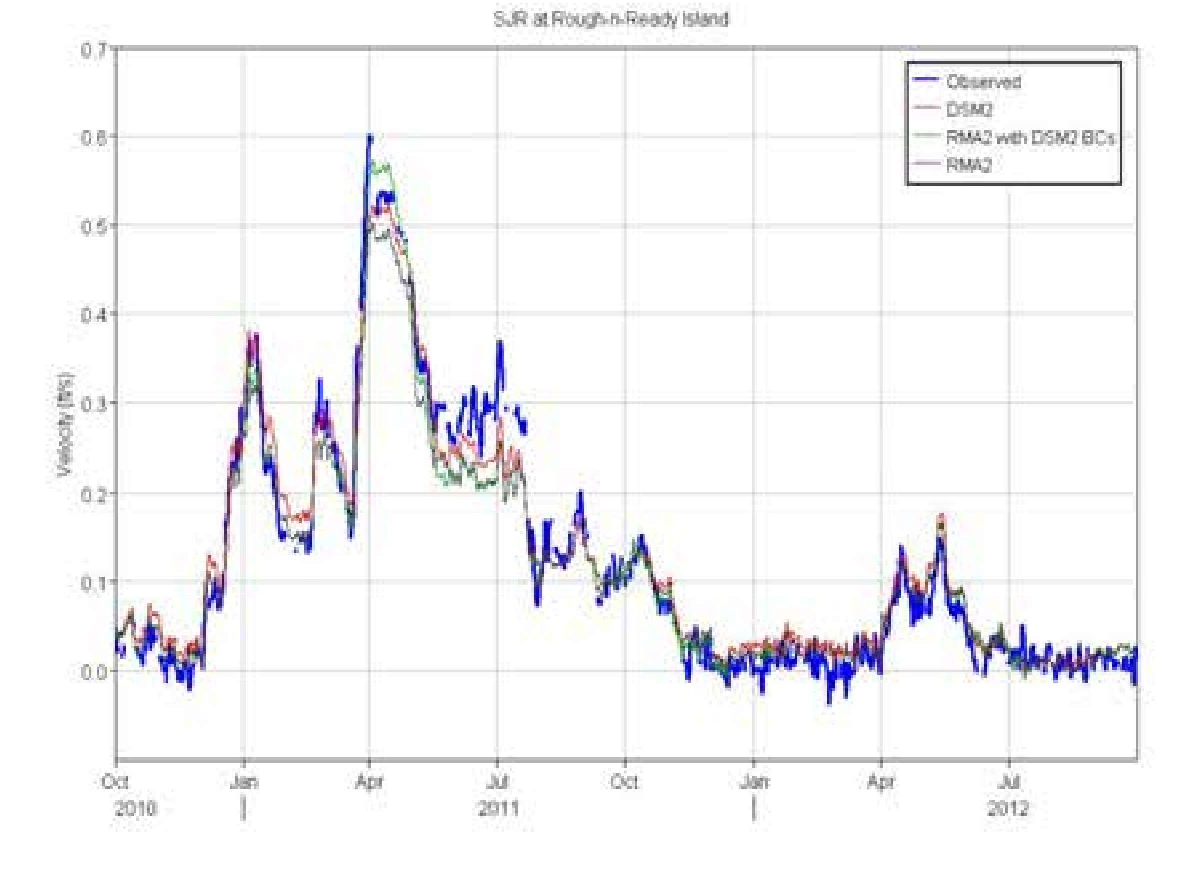


Figure 150 Tidally averaged observed and computed velocity for SJR at Rough-n-Ready Island.

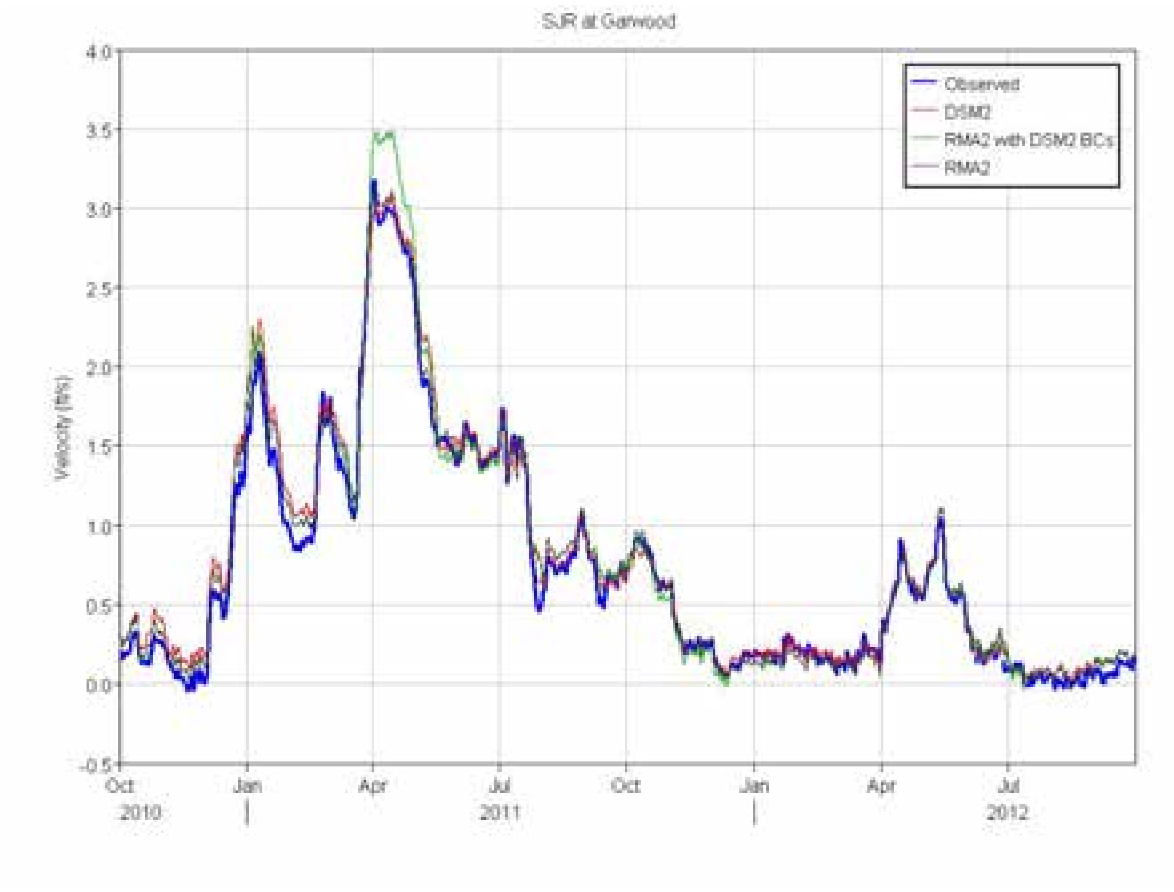


Figure 151 Tidally averaged observed and computed velocity for SJR at Garwood.

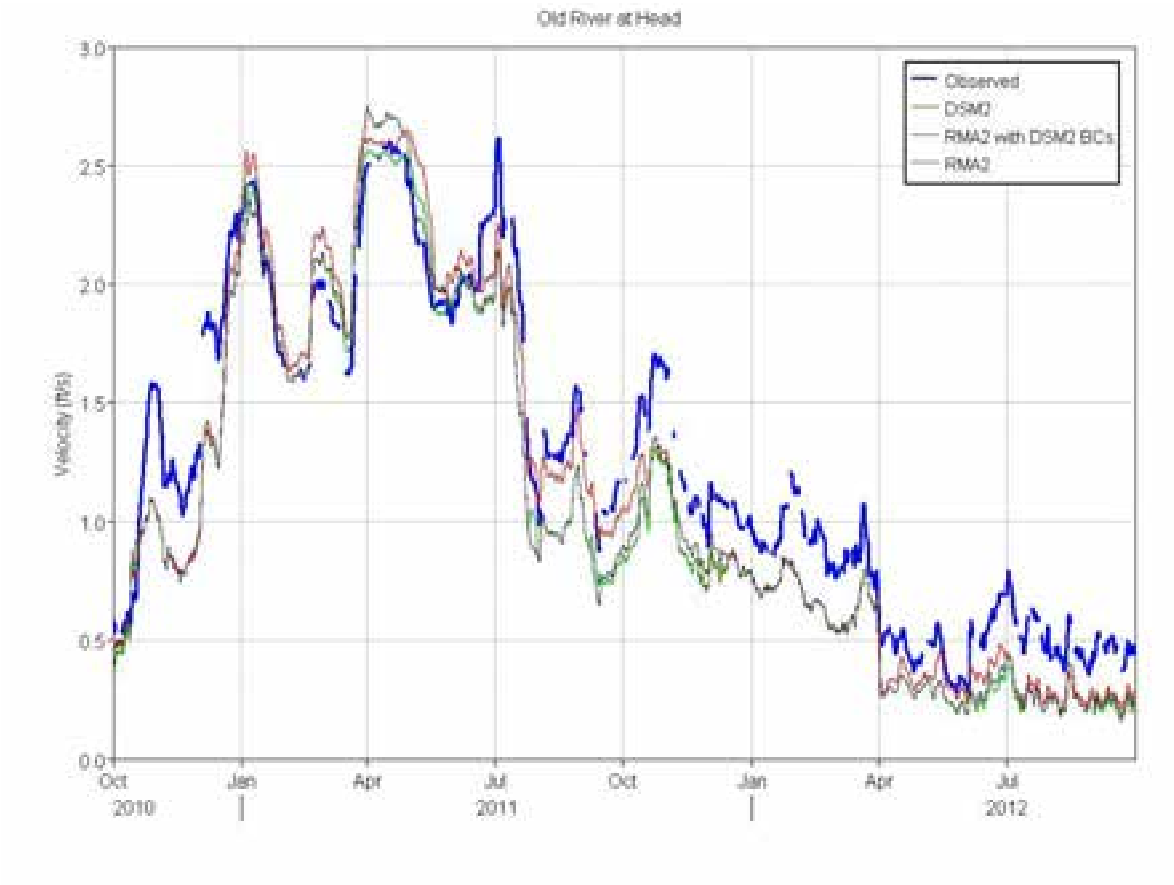


Figure 152 Tidally averaged observed and computed velocity for Old River at Head.

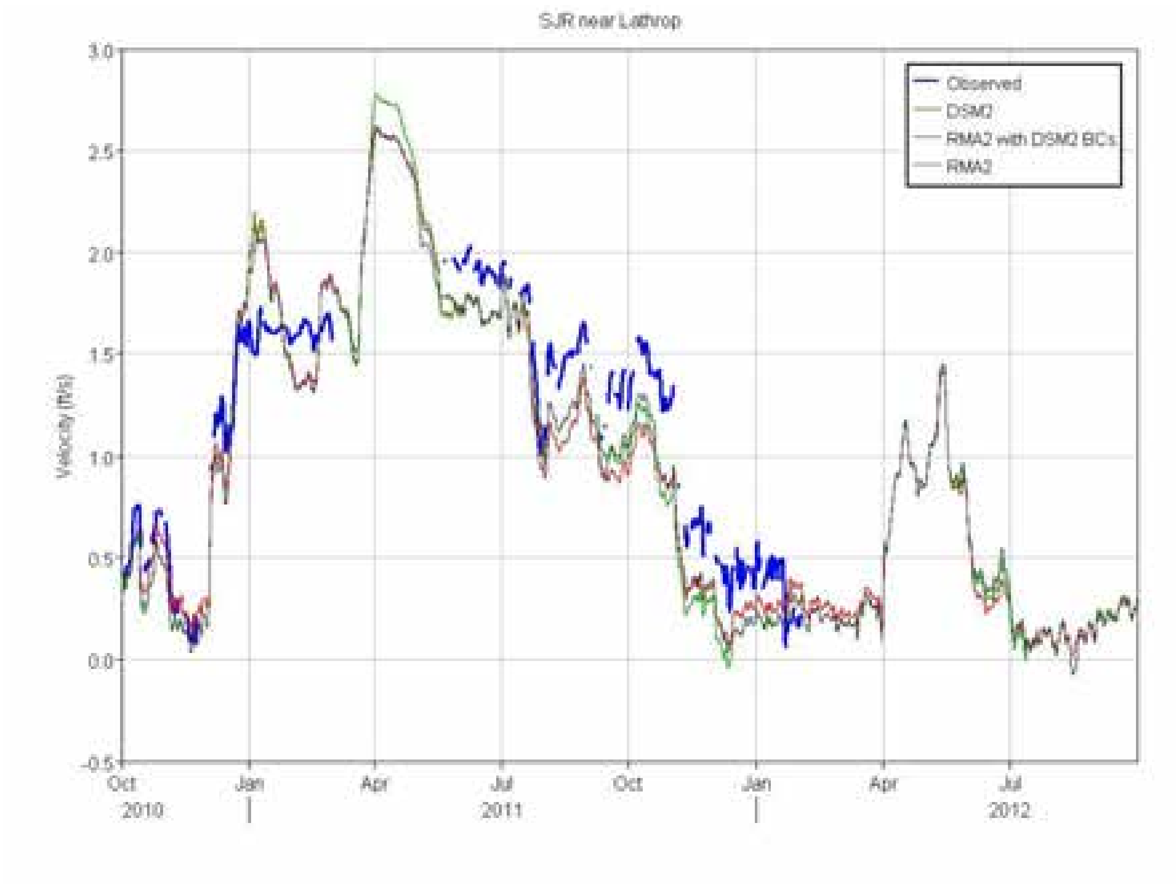


Figure 153 Tidally averaged observed and computed velocity for SJR near Lathrop.

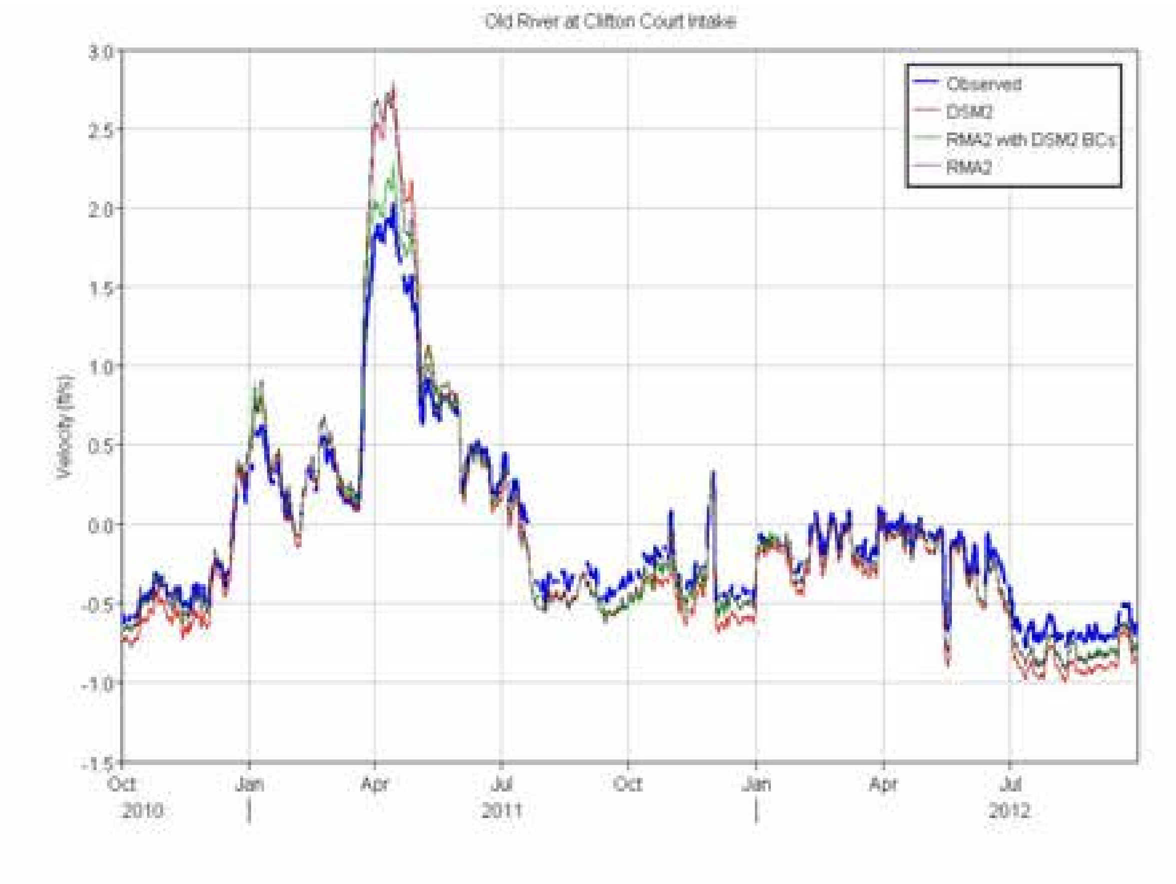


Figure 154 Tidally averaged observed and computed velocity for Old River at Clifton Court Intake.

Figure 155 Tidally averaged observed and computed velocity for West Canal at Clifton Court Intake.

Stage Results Comparison

In Figure 157 through Figure 220 computed stage results from the three model simulations are compared with observed data from CDEC and WDL (data sources are noted in plot titles). Error metrics from these plots are summarized by location in Table 6. Plot locations are shown in Figure 156. WDL data were used where available. CDEC data are likely to contain uncorrected time shifts which can result in apparent larger lag errors.

Table 7 summarizes stage results for each model by error metric (percent difference from observed, lag, amplitude ratio and R^2) and model skill. Table cells are color coded for a quick assessment of goodness of fit with observed data, ranging from green for better fit to red for worse fit. For stage, a skill accuracy greater than 0.975 is considered accurate, 0.95-0.975 is considered acceptable and a skill accuracy below 0.95 is considered poor agreement. The average model skill for stage is 0.973 for DSM2 and 0.979 for RMA2.

DSM2 stage results average about 0.24 feet lower than RMA2 stage. The salinity coupling in RMA2 raises stages in the Delta by about a 0.3 feet. At most locations, a closer match with observed stage is achieved with the RMA2 coupled model.

Table 6 Stage error metrics summary. Asterisks after station names indicate that observed data are from CDEC, which can contain time shift errors.

	DSM2	RMA2 w DSM2 BC	RMA2	DSM2	RMA2 w DSM2 BC	RMA2	DSM2	RMA2 w DSM2 BC	RMA2
	SJR at Brandt Bridge			SJR at Garwood*			Middle River at Tracy		
mean diff (ft)	-0.17	0.08	0.10	-0.30	-0.02	-0.02	-0.16	0.15	0.11
lag (minutes)	-22	7	7	-27	2	3	-32	-6	-7
ampRatio	0.980	0.909	0.908	1.095	1.041	1.040	1.061	0.889	0.915
slope	1.006	0.942	0.979	0.988	0.923	0.936	1.024	0.877	0.901
intercept	-0.2	0.4	0.2	-0.2	0.3	0.3	-0.3	0.7	0.5
R2	0.983	0.982	0.989	0.926	0.913	0.923	0.935	0.867	0.919
	SJR at Jersey Point*			Old River at Head			Old R at Clifton Court Ferry		
mean diff (ft)	-0.05	0.16	0.16	0.18	0.15	0.19	0.03	0.23	0.23
lag (minutes)	16	18	18	-19	-1	-1	-27	7	7
ampRatio	0.991	0.996	0.996	0.941	0.941	0.940	1.081	0.948	0.947
slope	0.971	0.952	0.956	1.000	0.901	0.928	1.046	0.932	0.939
intercept	0.1	0.4	0.3	0.2	0.8	0.6	-0.1	0.5	0.5
R2	0.941	0.923	0.927	0.984	0.984	0.992	0.934	0.928	0.929
	Middle River at Middle River			SJR nr Lathrop			Old River at DMC ds barr		
mean diff (ft)	-0.37	-0.11	-0.11	0.12	0.19	0.23	0.01	0.18	0.18
lag (minutes)	-17	-6	-5	-10	5	5	-25	7	8
ampRatio	1.126	1.042	1.042	0.952	0.940	0.937	1.032	0.904	0.904
slope	1.088	0.994	0.999	0.989	0.919	0.947	1.046	0.922	0.930
intercept	-0.8	-0.1	-0.1	0.2	0.7	0.6	-0.2	0.5	0.4
R2	0.980	0.967	0.971	0.985	0.985	0.993	0.936	0.927	0.928
	Old River at Hwy 4*			Old River at Tracy			SJR at Venice Island		
mean diff (ft)	-0.20	0.02	0.02	0.00	0.44	0.44	-0.52	-0.28	-0.28
lag (minutes)	-12	14	14	-17	38	39	-15	-1	-1
ampRatio	1.133	0.993	0.992	0.968	0.727	0.726	1.098	1.033	1.033
slope	1.063	0.933	0.939	0.924	0.982	0.979	1.058	0.981	0.986
intercept	-0.5	0.3	0.3	0.3	0.5	0.5	-0.8	-0.2	-0.2
R2	0.921	0.914	0.918	0.921	0.840	0.844	0.978	0.963	0.967
	Old River at Bacon			Antioch			SJR at Rindge Pump		
mean diff (ft)	-0.27	-0.02	-0.02	-0.25	0.01	0.01	-0.39	-0.14	-0.14
lag (minutes)	-21	-11	-10	-10	1	2	-22	0	0
ampRatio	1.130	1.049	1.049	1.092	1.007	1.007	1.087	1.030	1.030
slope	1.086	0.992	0.997	1.071	0.986	0.988	1.056	0.991	0.995
intercept	-0.6	0.0	0.0	-0.5	0.1	0.1	-0.6	-0.1	-0.1
R2	0.972	0.953	0.958	0.988	0.978	0.982	0.982	0.971	0.975
	SJR at Rough-n-Ready								
mean diff (ft)	-0.33	-0.06	-0.06						
lag (minutes)	-23	4	4						
ampRatio	1.073	1.033	1.034						
slope	1.045	0.994	0.999						
intercept	-0.5	0.0	-0.1						
R2	0.980	0.971	0.975						

Table 7 Summary of stage error metrics and model skill, with shading ranging from green for better fit to red for worse fit. Asterisks after station names indicate that observed data are from CDEC, which can contain time shift errors.

	% diff from observed			lag (minutes)			ampRatio			R2			Model Skill		
Station	**DSM2**	**RMA2 w DSM2 BC**	**RMA2**	**DSM2**	**RMA2 w DSM2 BC**	**RMA2**	**DSM2**	**RMA2 w DSM2 BC**	**RMA2**	**DSM2**	**RMA2 w DSM2 BC**	**RMA2**	**DSM2**	**RMA2 w DSM2 BC**	**RMA2**
SJR at Brandt Bridge	-3.1%	1.4%	1.9%	-22	7	7	0.980	0.909	0.908	0.983	0.982	0.989	0.992	0.994	0.996
SJR at Jersey Point*	-1.2%	3.9%	3.8%	16	18	18	0.991	0.996	0.996	0.941	0.923	0.927	0.981	0.971	0.972
Middle River at Middle River	-8.5%	-2.5%	-2.5%	-17	-6	-5	1.126	1.042	1.042	0.980	0.967	0.971	0.962	0.989	0.990
Old River at Hwy 4*	-4.8%	0.5%	0.4%	-12	14	14	1.133	0.993	0.992	0.921	0.914	0.918	0.967	0.975	0.976
Old River at Bacon Island	-6.3%	-0.4%	-0.4%	-21	-11	-10	1.130	1.049	1.049	0.972	0.953	0.958	0.970	0.987	0.988
SJR at Rough-n-Ready Island	-7.5%	-1.3%	-1.3%	-23	4	4	1.073	1.033	1.034	0.980	0.971	0.975	0.968	0.992	0.993
SJR at Garwood*	-6.6%	-0.5%	-0.3%	-27	2	3	1.095	1.041	1.040	0.926	0.913	0.923	0.957	0.977	0.980
Old River at Head	2.9%	2.4%	3.0%	-19	-1	-1	0.941	0.941	0.940	0.984	0.984	0.992	0.995	0.993	0.995
SJR near Lathrop	1.9%	2.9%	3.6%	-10	5	5	0.952	0.940	0.937	0.985	0.985	0.993	0.996	0.993	0.996
Old River at Tracy	0.0%	10.2%	10.1%	-17	38	39	0.968	0.727	0.726	0.921	0.840	0.844	0.978	0.897	0.898
Antioch	-5.9%	0.3%	0.2%	-10	1	2	1.092	1.007	1.007	0.988	0.978	0.982	0.985	0.995	0.995
Middle River at Tracy	-3.7%	3.6%	2.6%	-32	-6	-7	1.061	0.889	0.915	0.935	0.867	0.919	0.966	0.957	0.974
Old River at Clifton Court Ferry	0.7%	6.1%	6.1%	-27	7	7	1.081	0.948	0.947	0.934	0.928	0.929	0.972	0.969	0.970
Old River at DMC d/s of barrier	0.2%	4.8%	4.8%	-25	7	8	1.032	0.904	0.904	0.936	0.927	0.928	0.976	0.973	0.973
SJR at Venice Island	-11.4%	-6.0%	-6.0%	-15	-1	-1	1.098	1.033	1.033	0.978	0.963	0.967	0.938	0.974	0.975
SJR at Rindge Pump	-8.7%	-3.1%	-3.1%	-22	0	0	1.087	1.030	1.030	0.982	0.971	0.975	0.961	0.989	0.990
Average of absolute values	4.6%	3.1%	3.2%	20	8	8	1.053	0.968	0.969	0.959	0.942	0.949	0.973	0.977	0.979

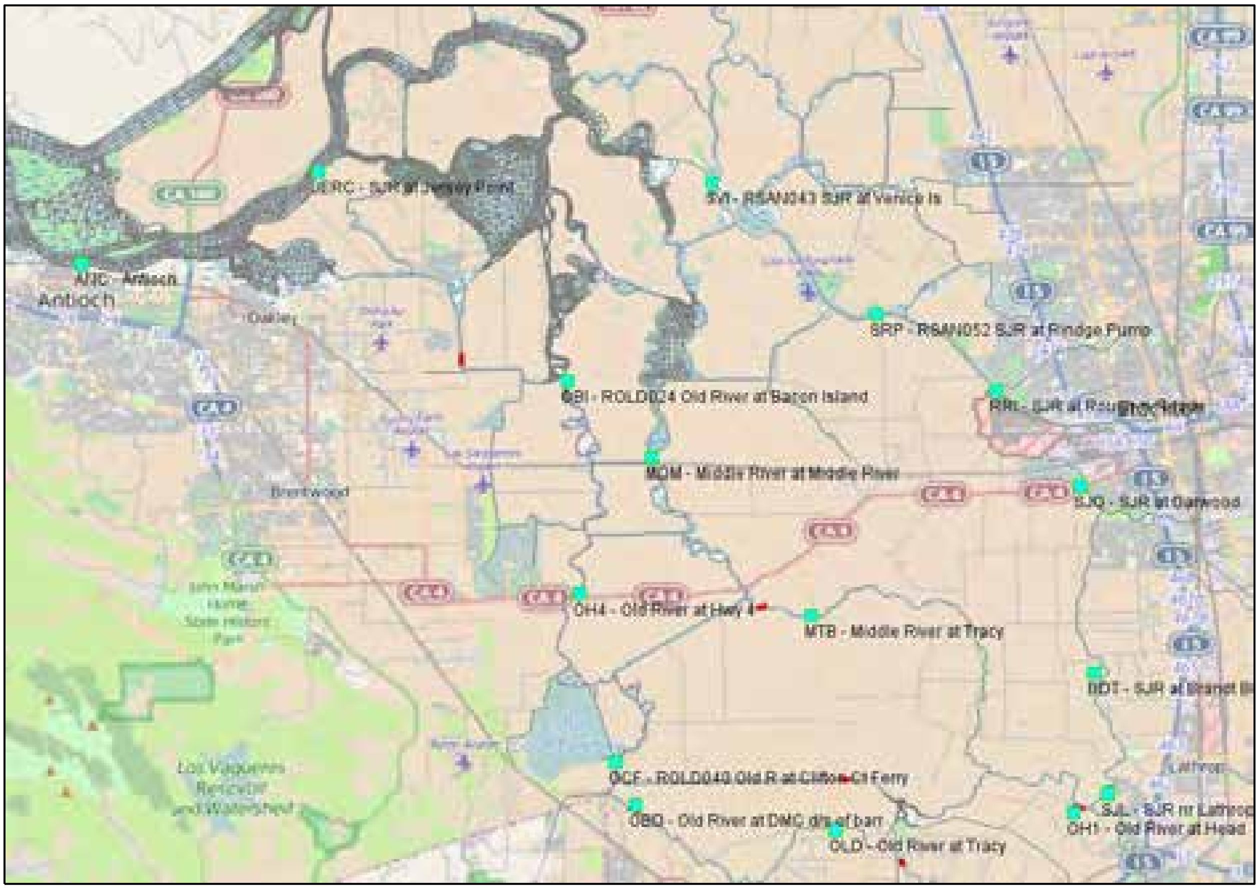


Figure 156 Stage comparison plot locations.

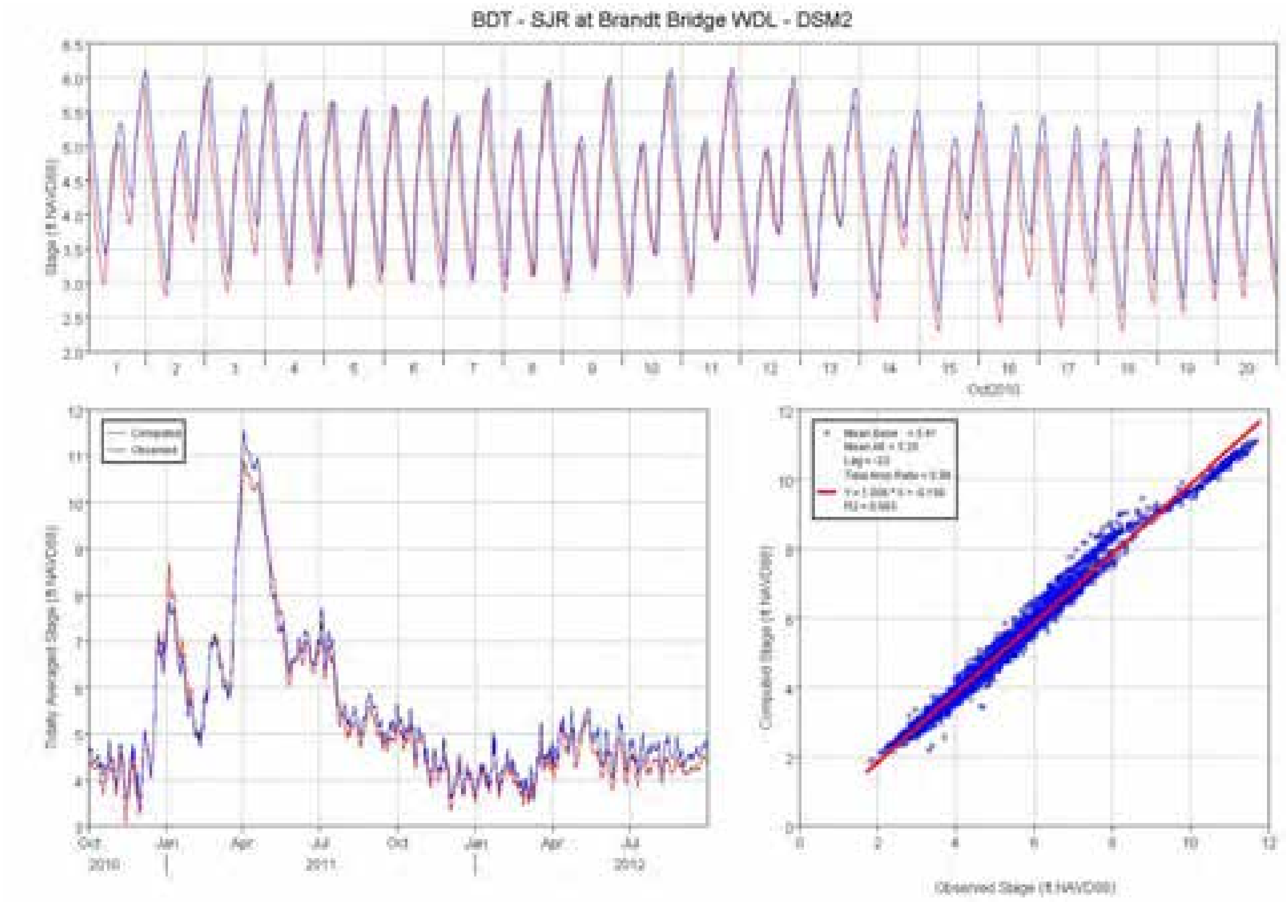


Figure 157 Computed (DSM2) and observed stage comparison plots for San Joaquin River at Brandt Bridge.

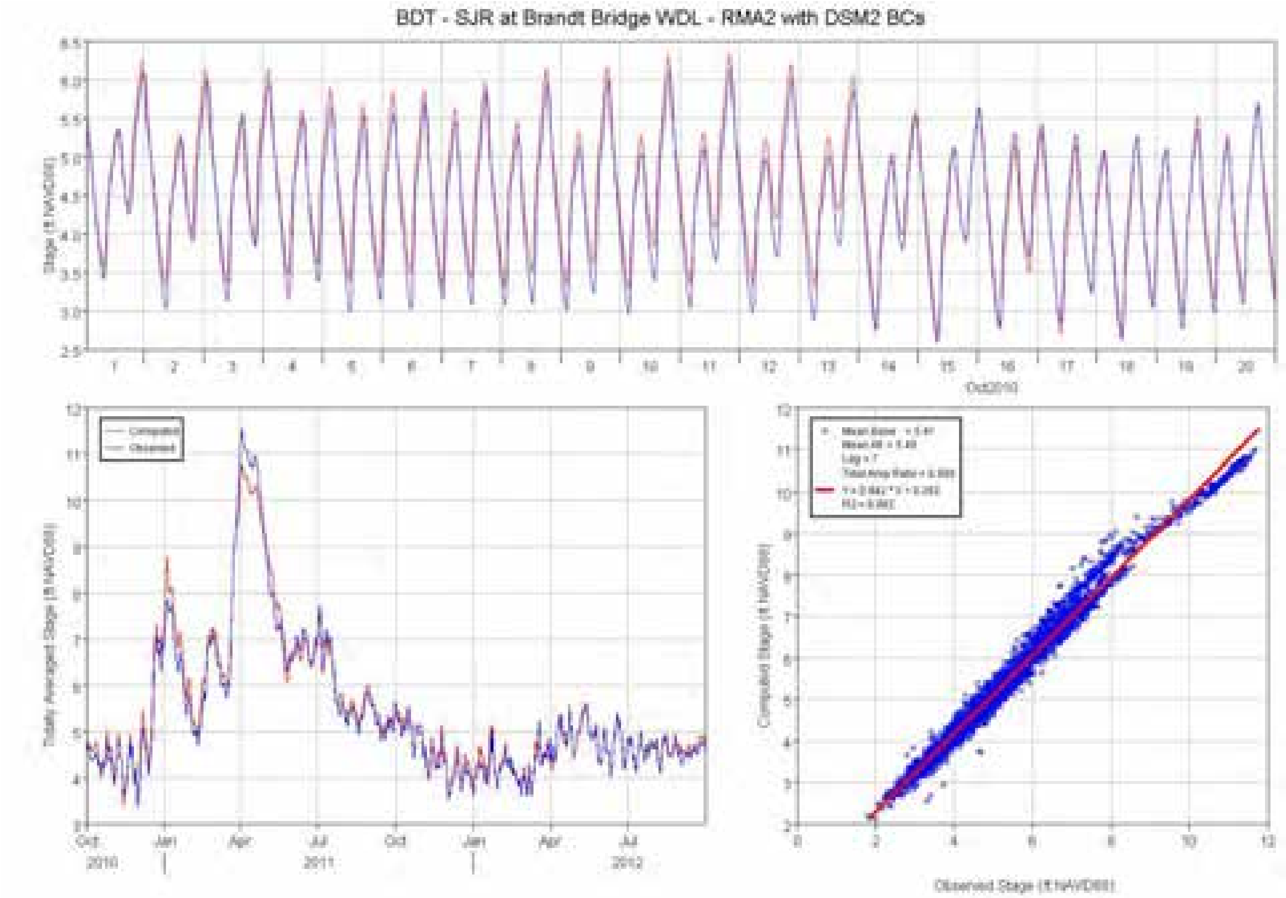


Figure 158 Computed (RMA2 with DSM2 BCs) and observed stage comparison plots for San Joaquin River at Brandt Bridge.

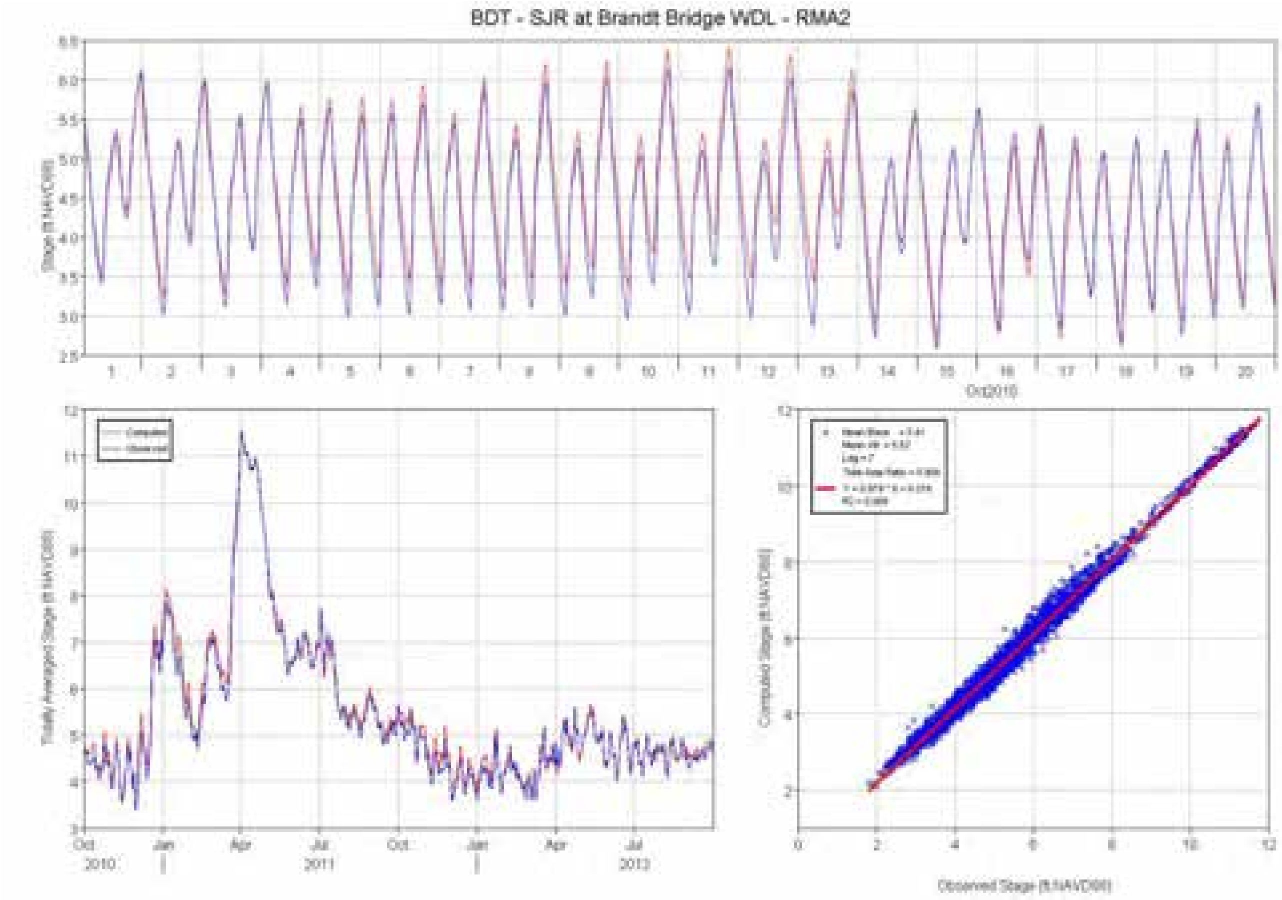


Figure 159 Computed (RMA2) and observed stage comparison plots for San Joaquin River at Brandt Bridge.

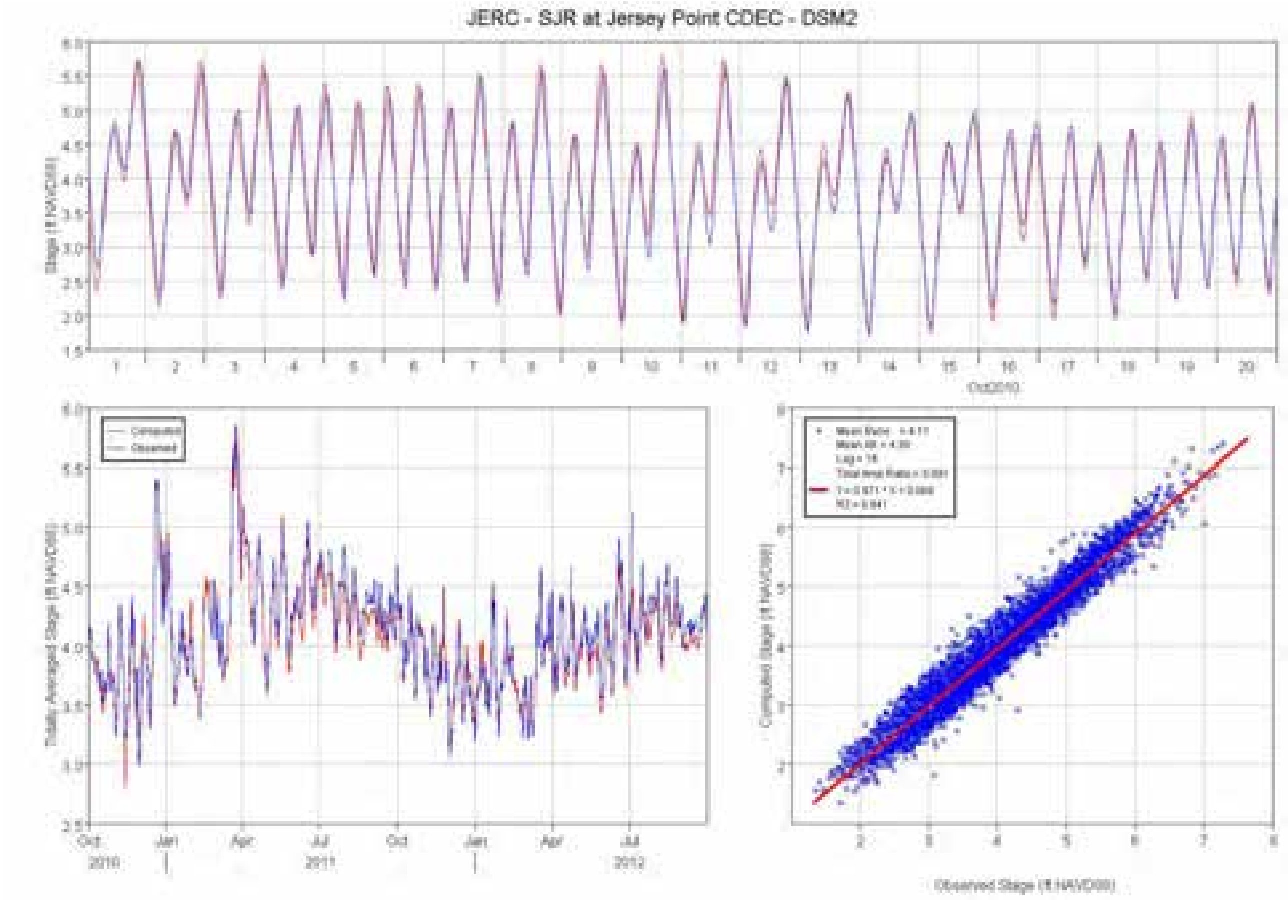


Figure 160 Computed (DSM2) and observed stage comparison plots for San Joaquin River at Jersey Point.

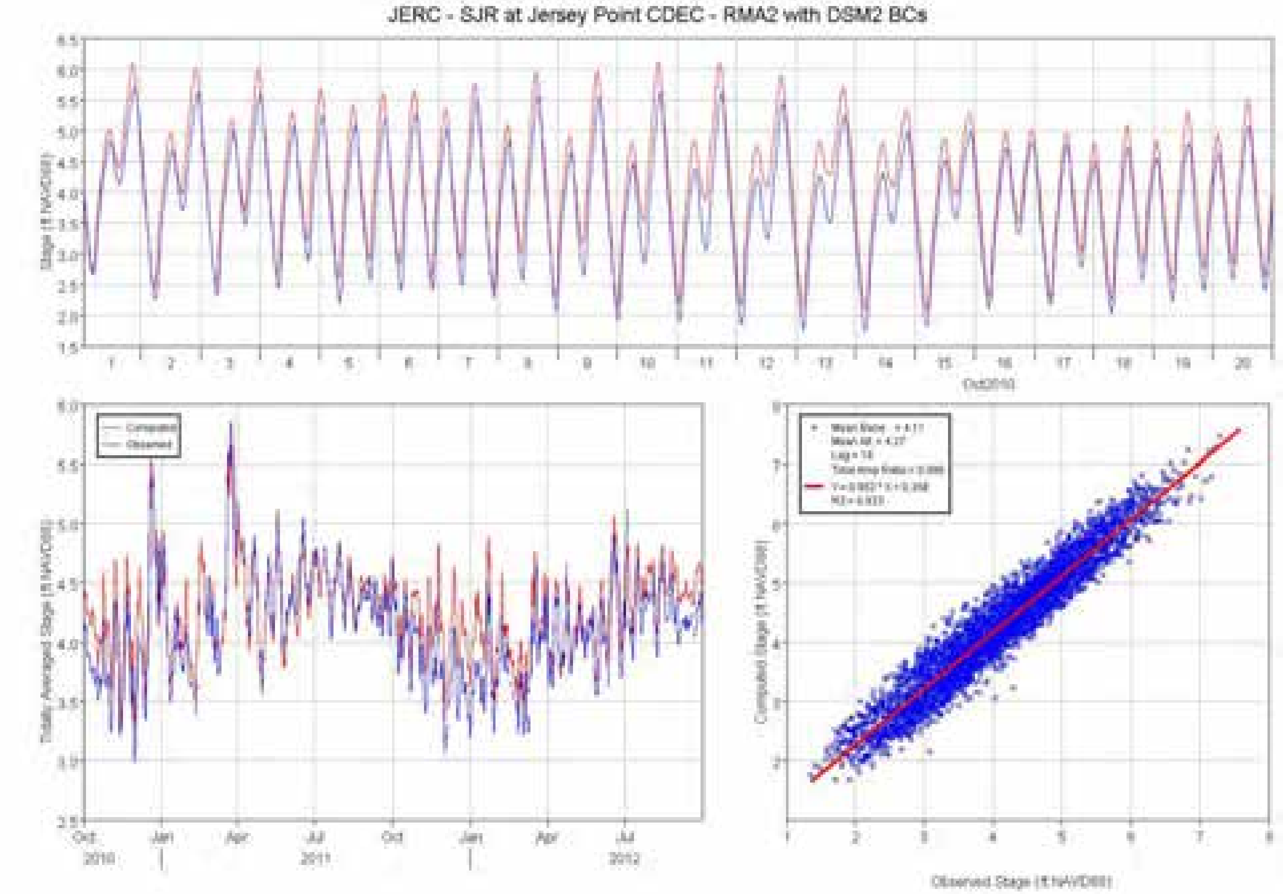
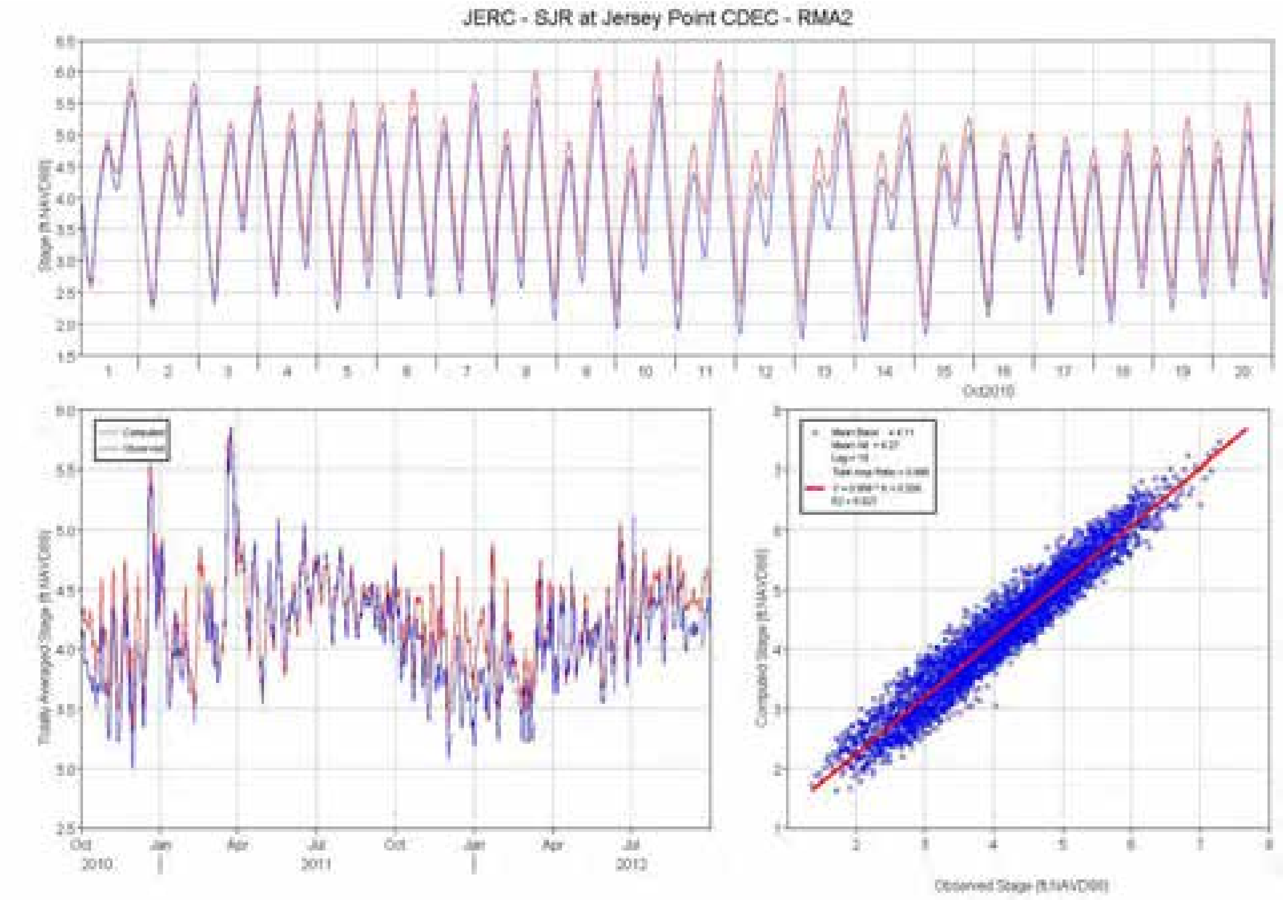


Figure 161 Computed (RMA2 with DSM2 BCs) and observed stage comparison plots for San Joaquin River at Jersey Point.



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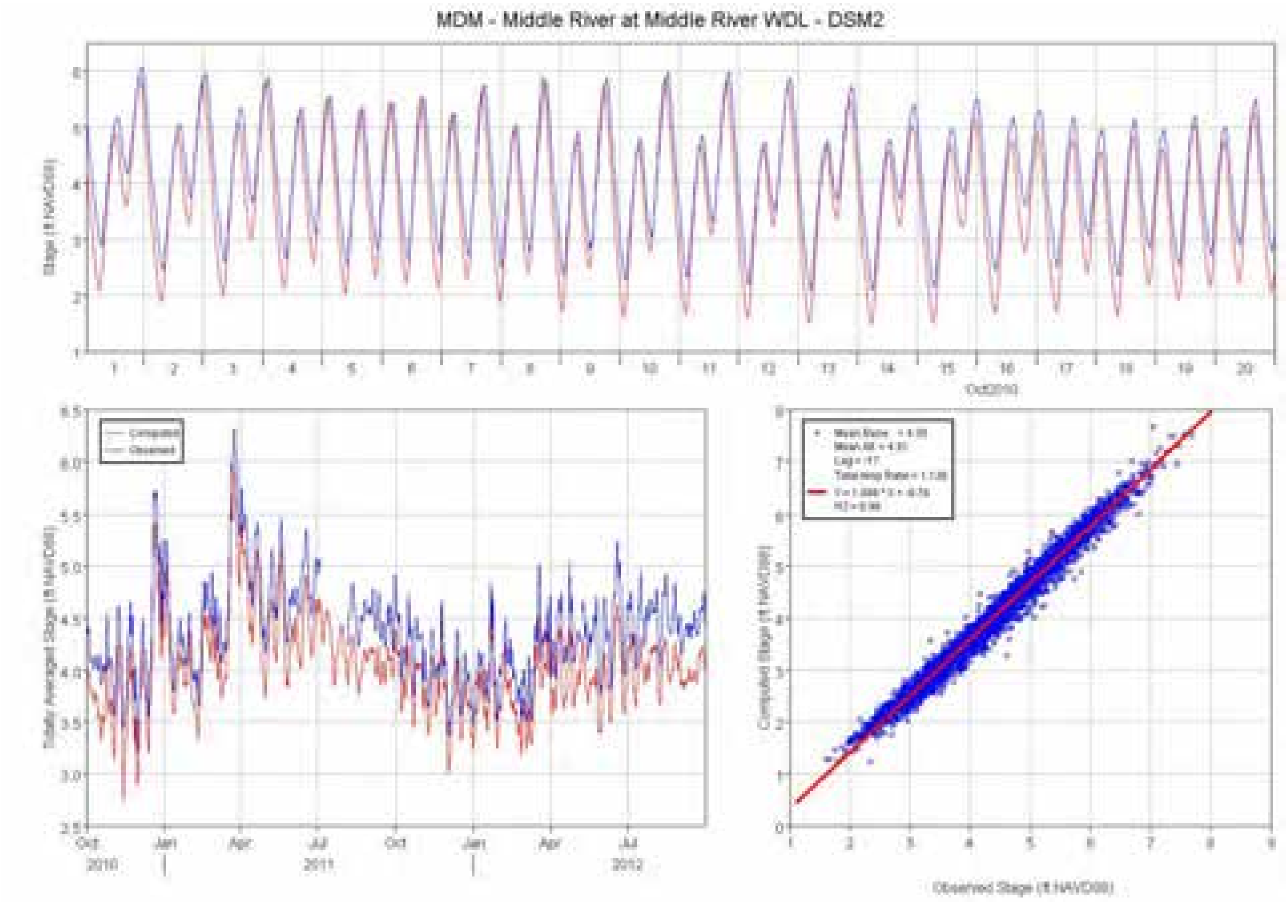
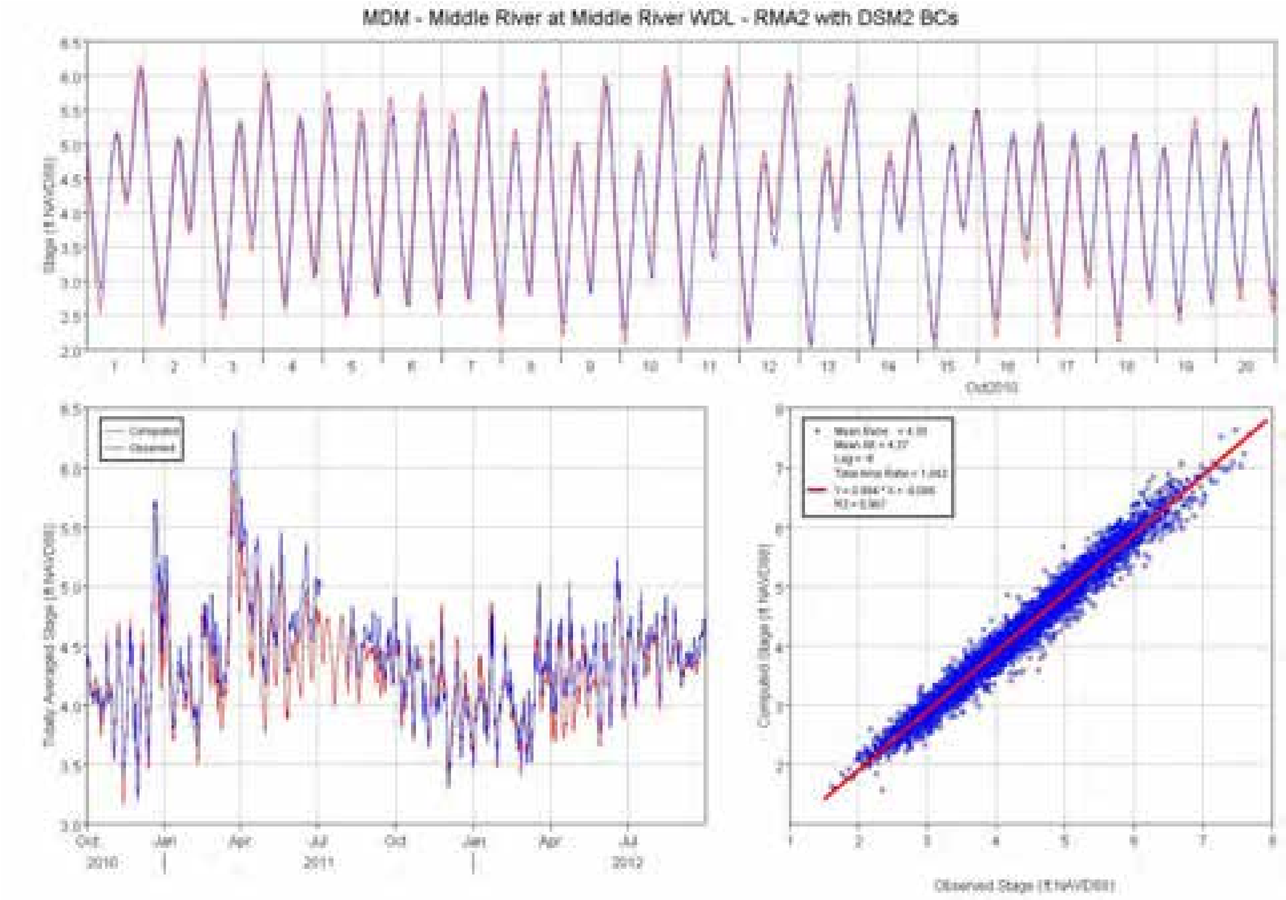


Figure 163 Computed (DSM2) and observed stage comparison plots for Middle River at Middle River.



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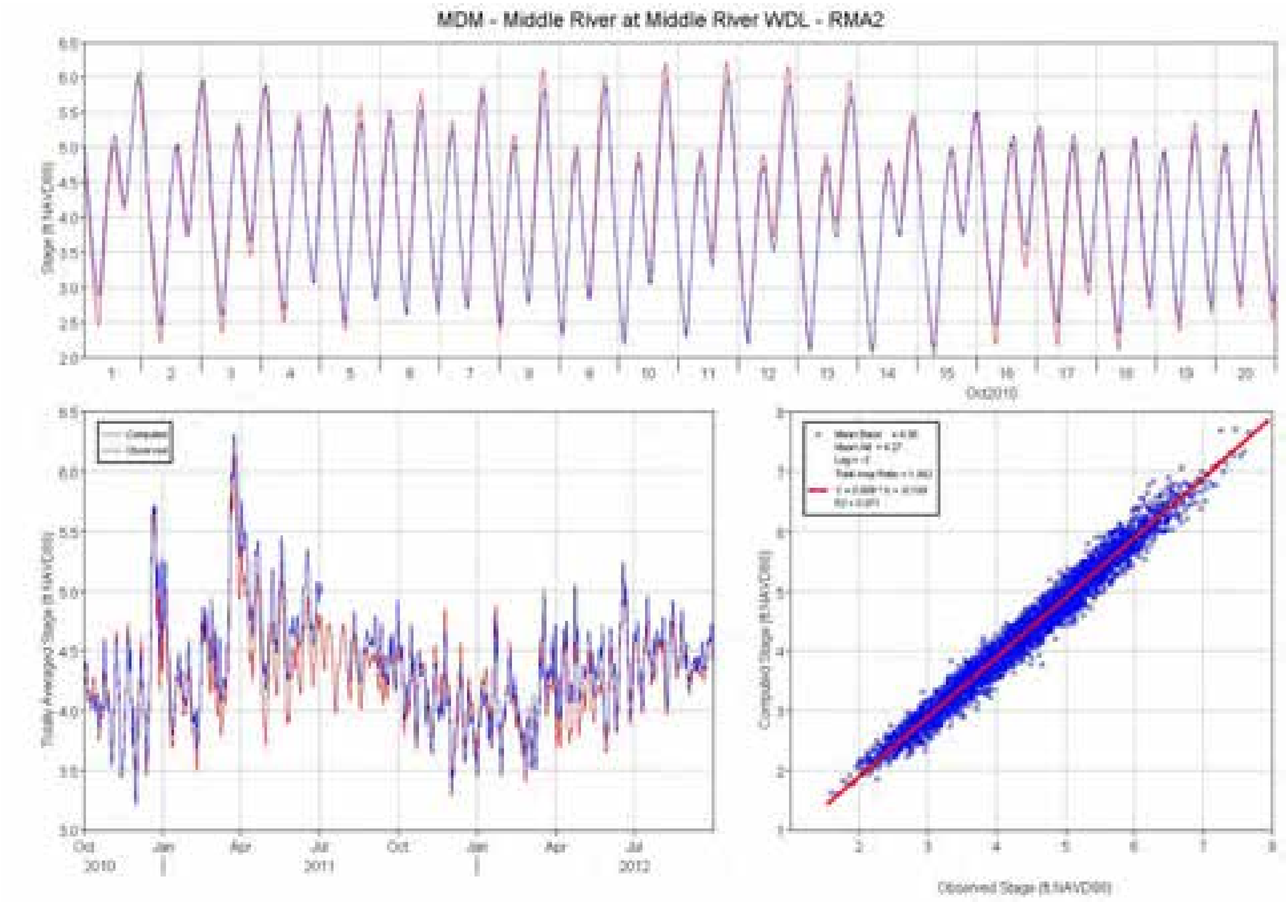


Figure 165 Computed (RMA2) and observed stage comparison plots for Middle River at Middle River.

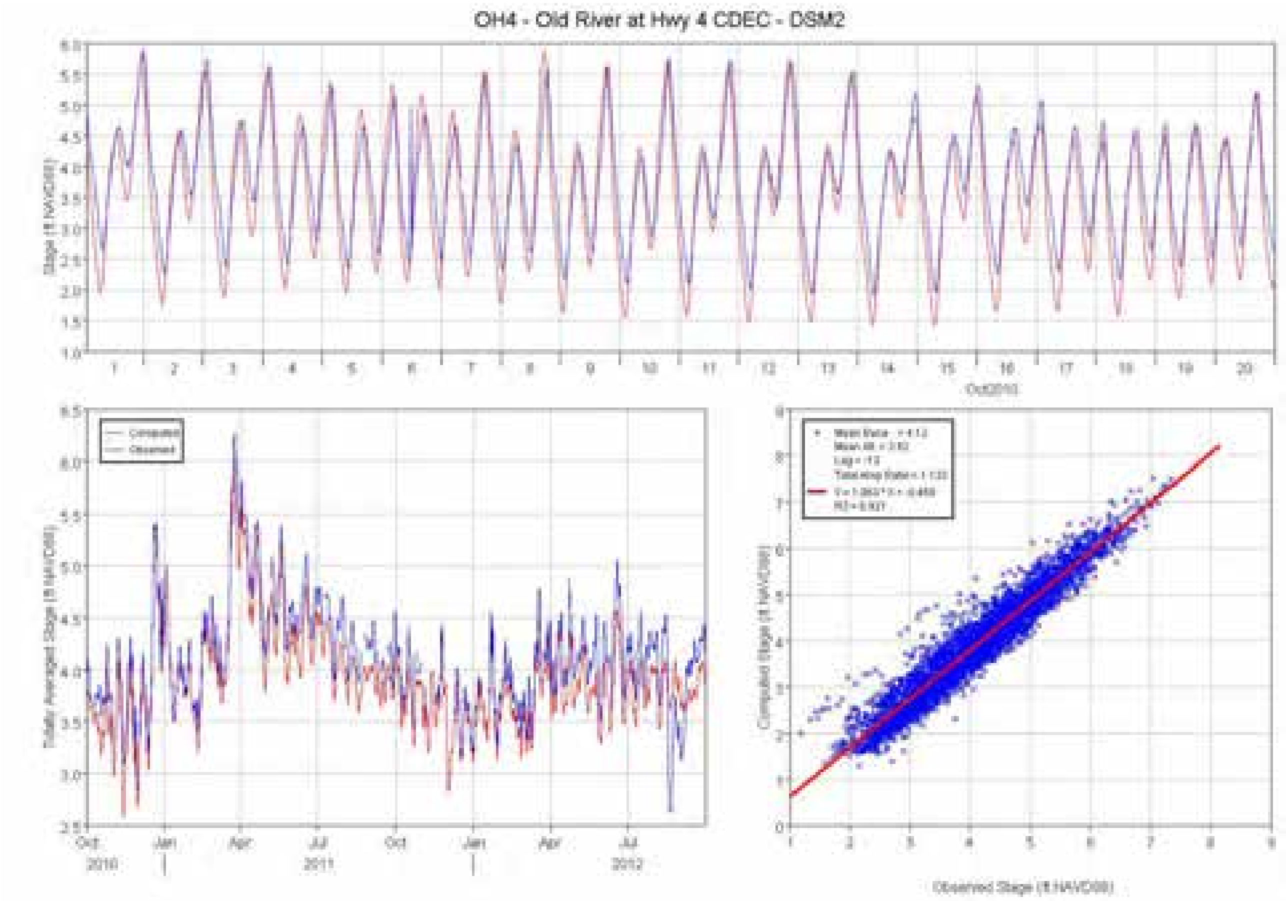


Figure 166 Computed (DSM2) and observed stage comparison plots for Old River at Hwy 4.

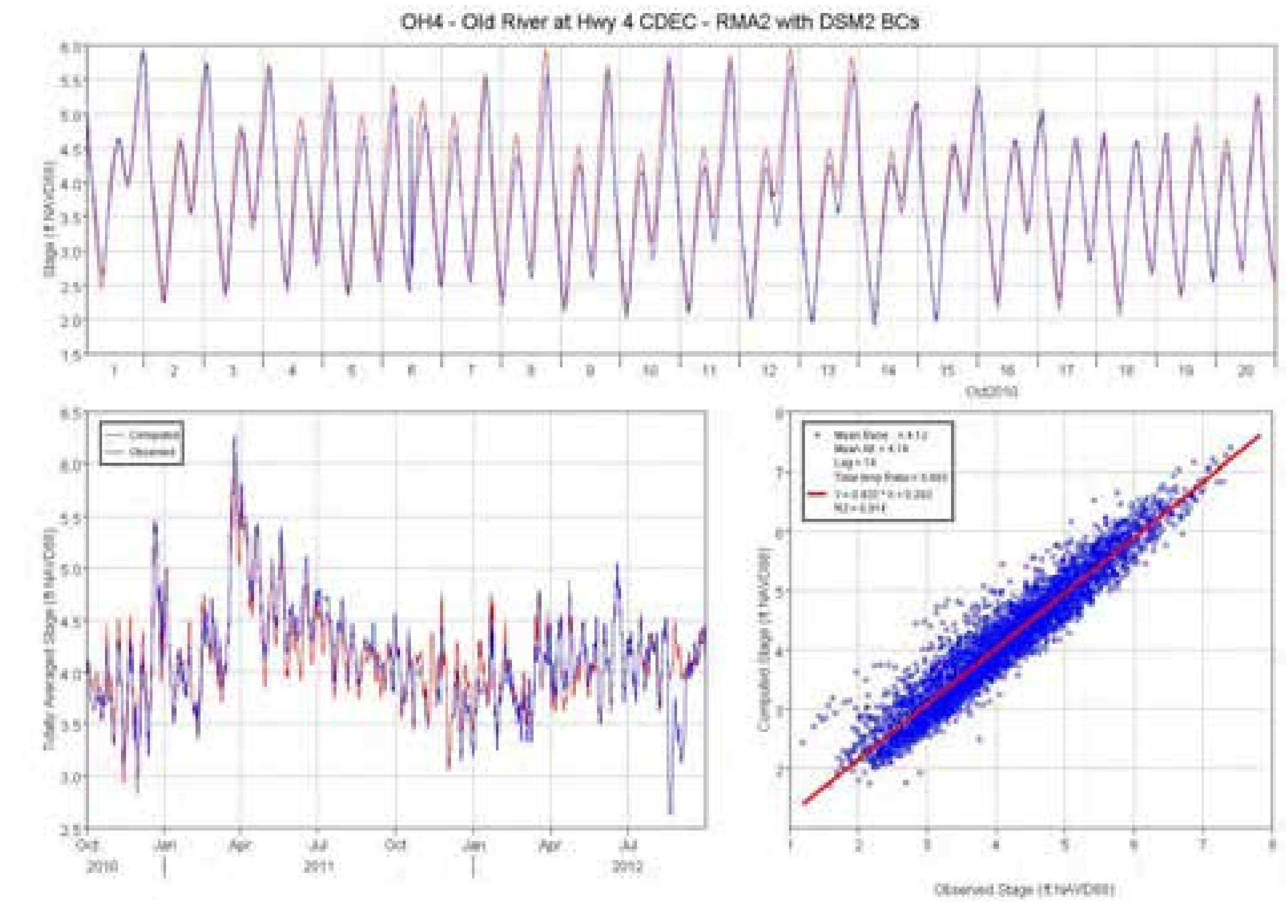


Figure 167 Computed (RMA2 with DSM2 BCs) and observed stage comparison plots for Old River at Hwy 4.

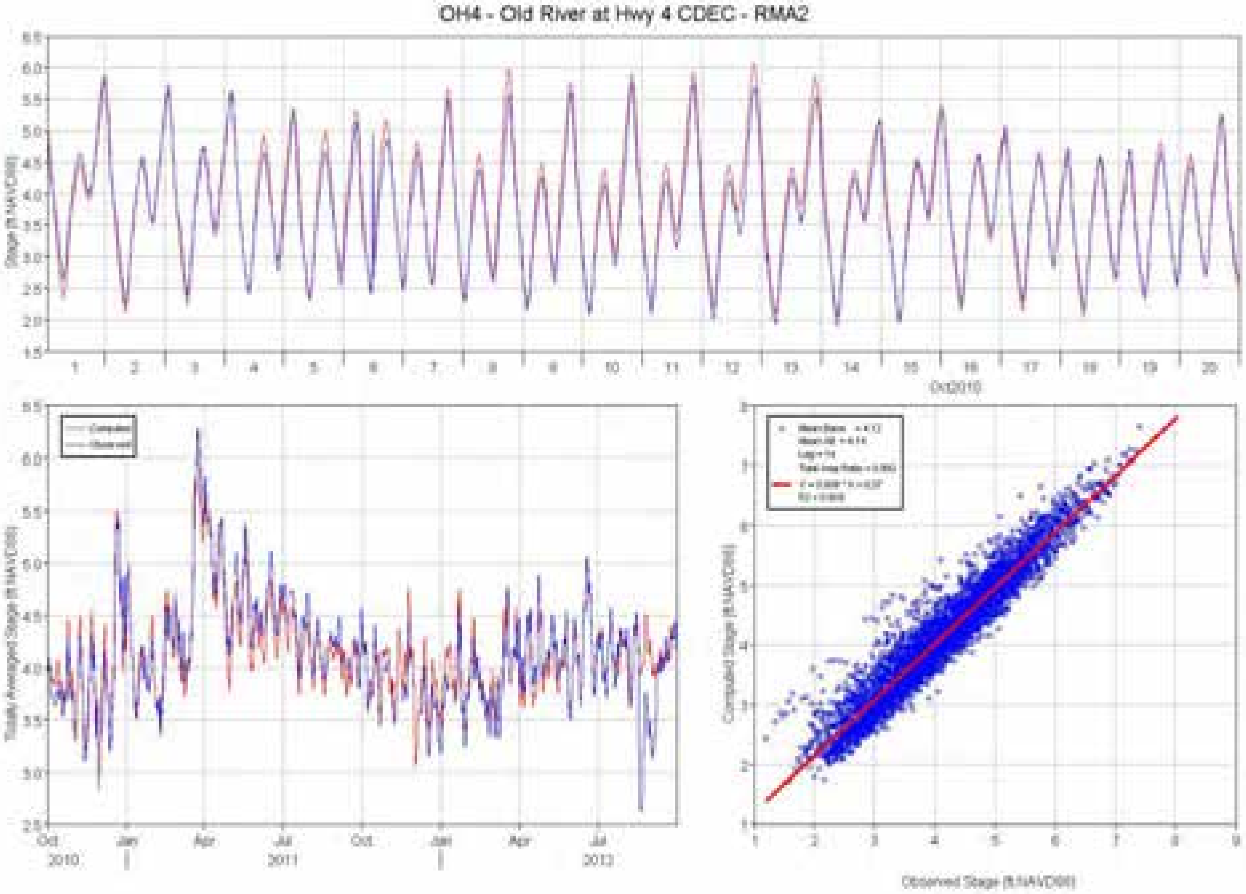


Figure 168 Computed (RMA2) and observed stage comparison plots for Old River at Hwy 4.

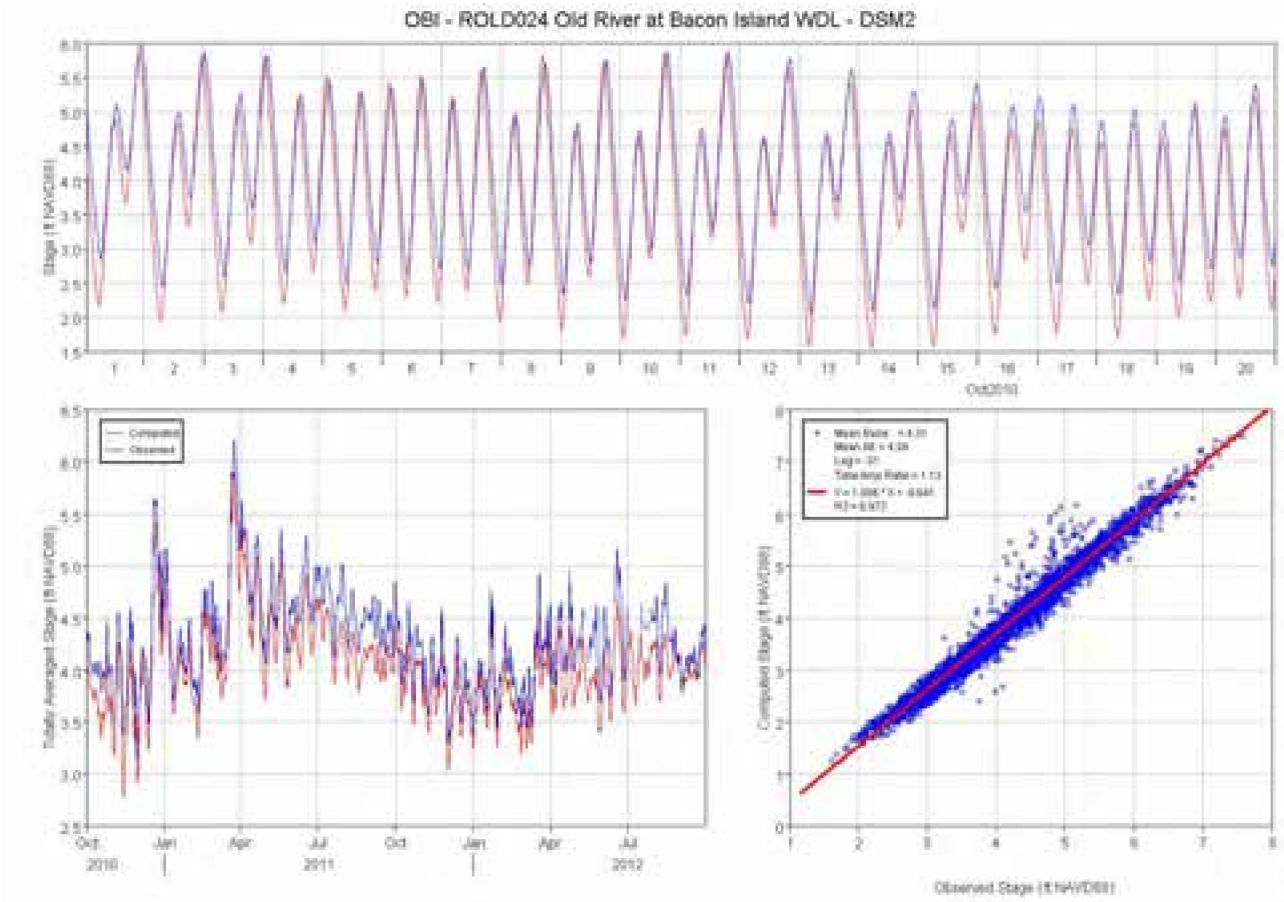
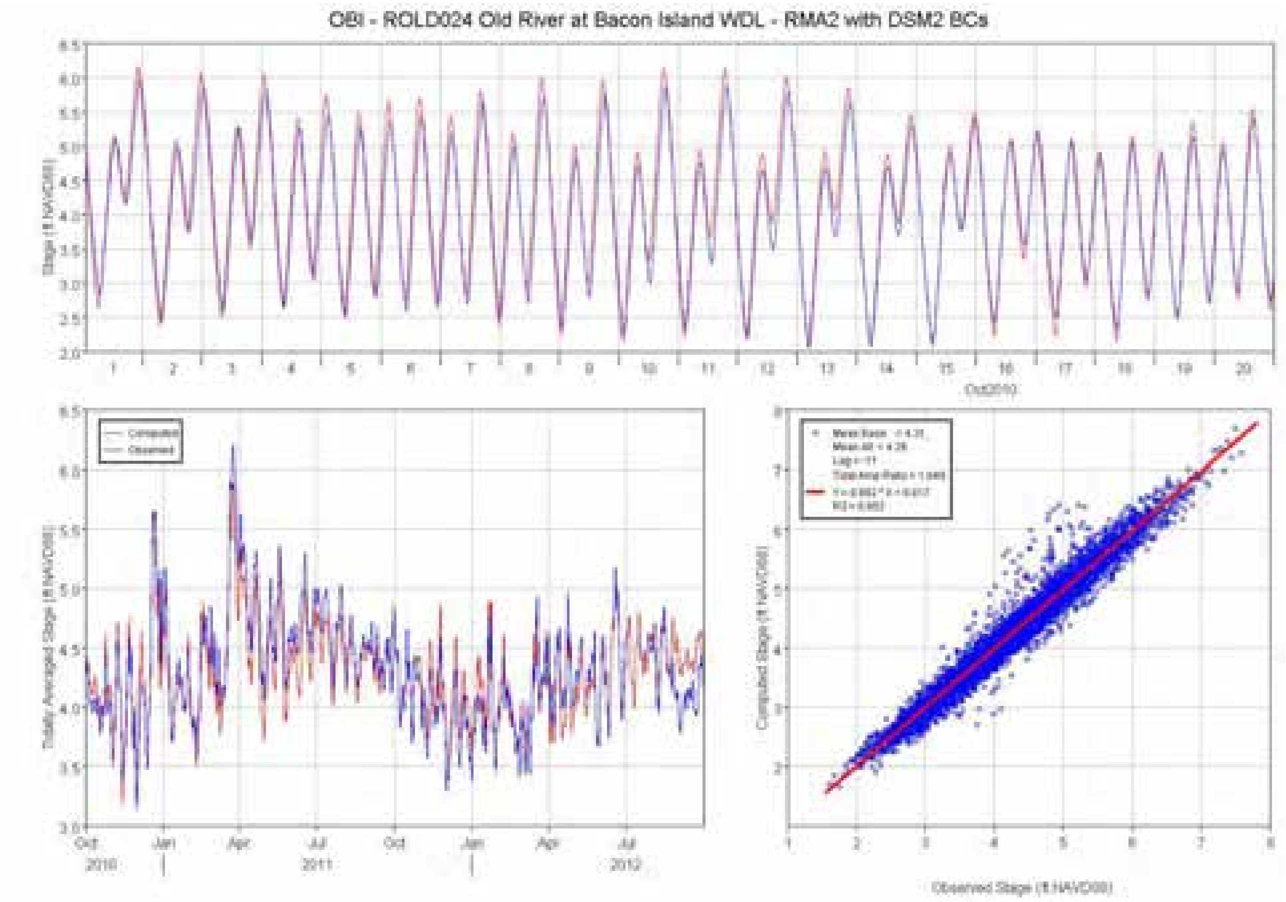


Figure 169 Computed (DSM2) and observed stage comparison plots for Old River at Bacon Island.



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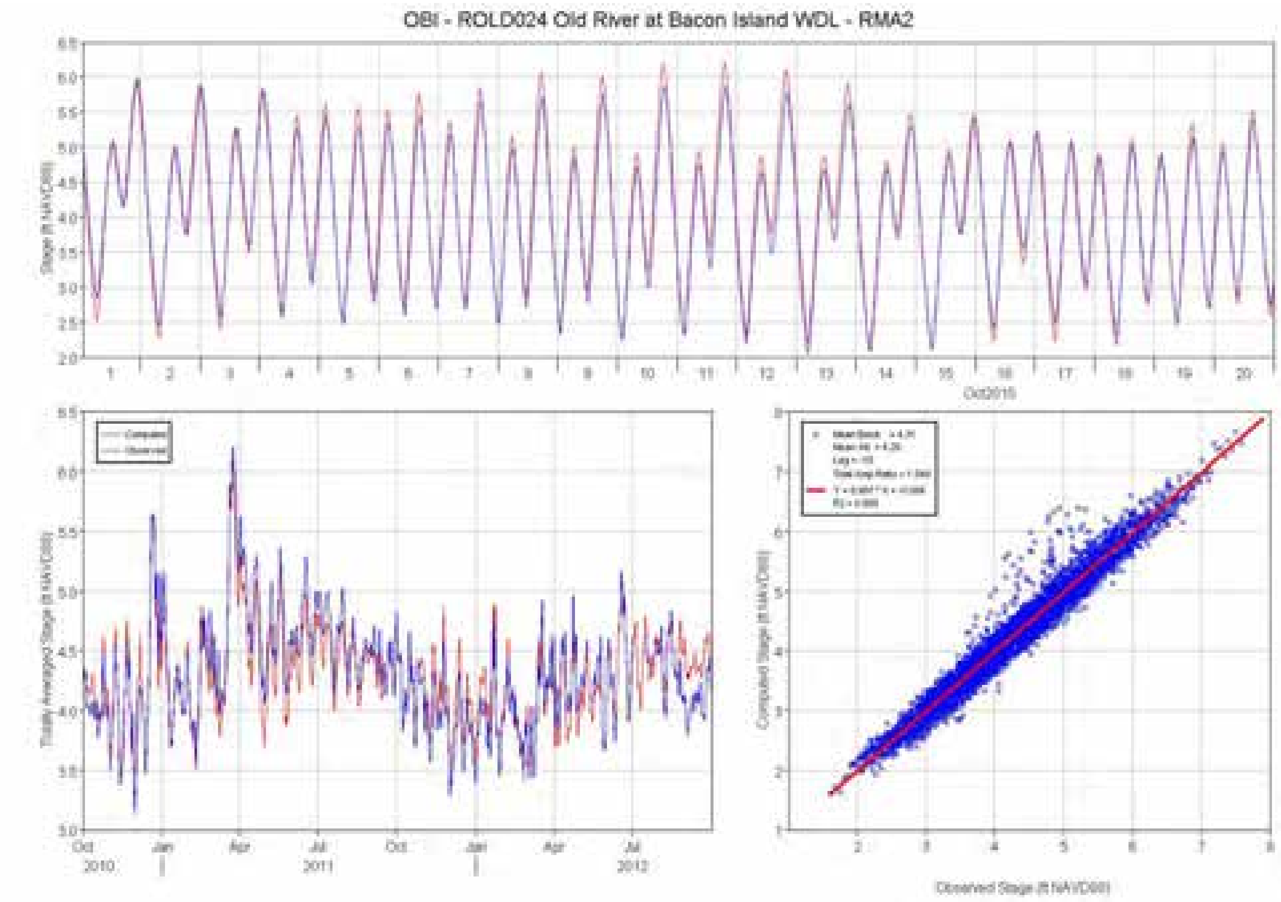

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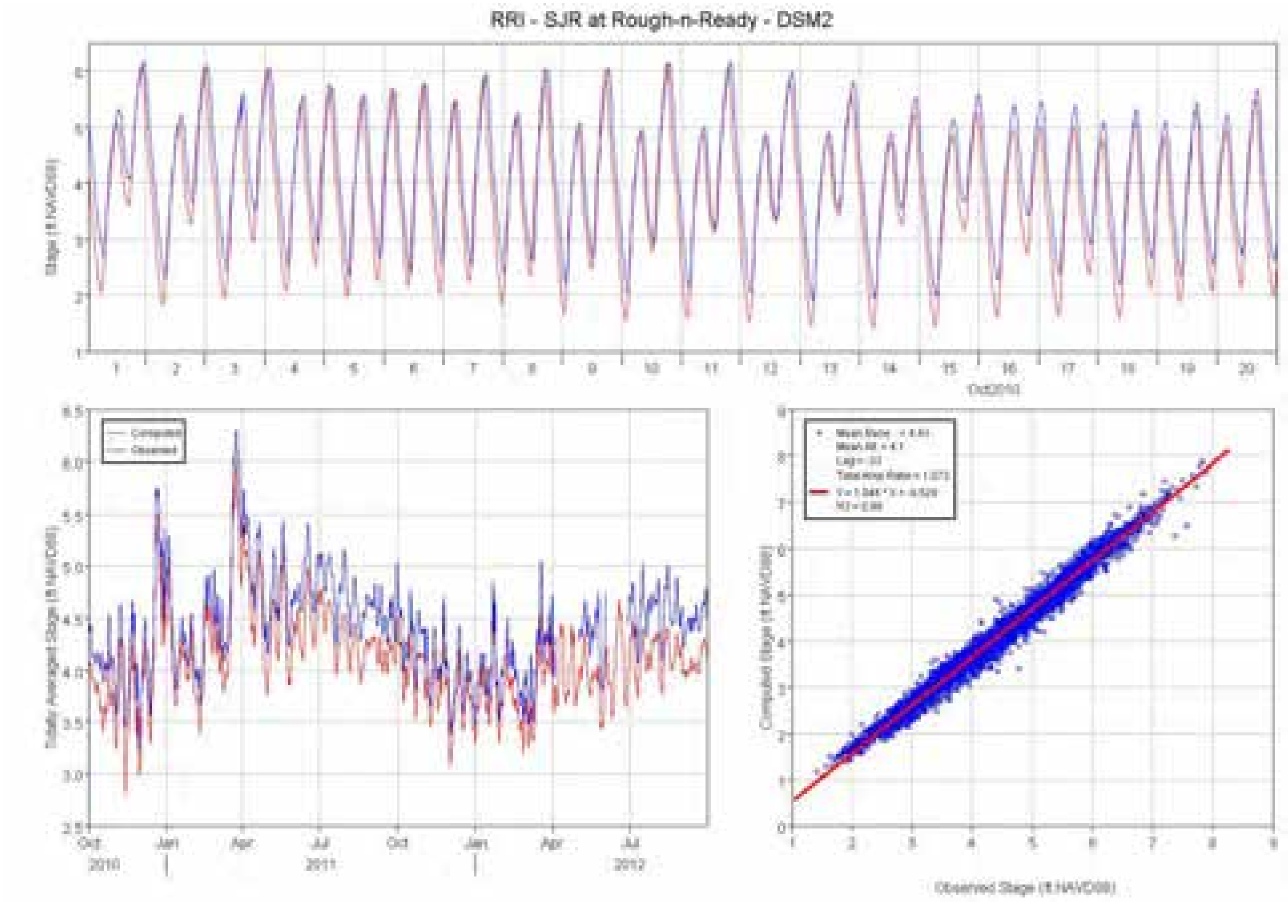


Figure 172 Computed (DSM2) and observed stage comparison plots for SJR at Rough-n-Ready.

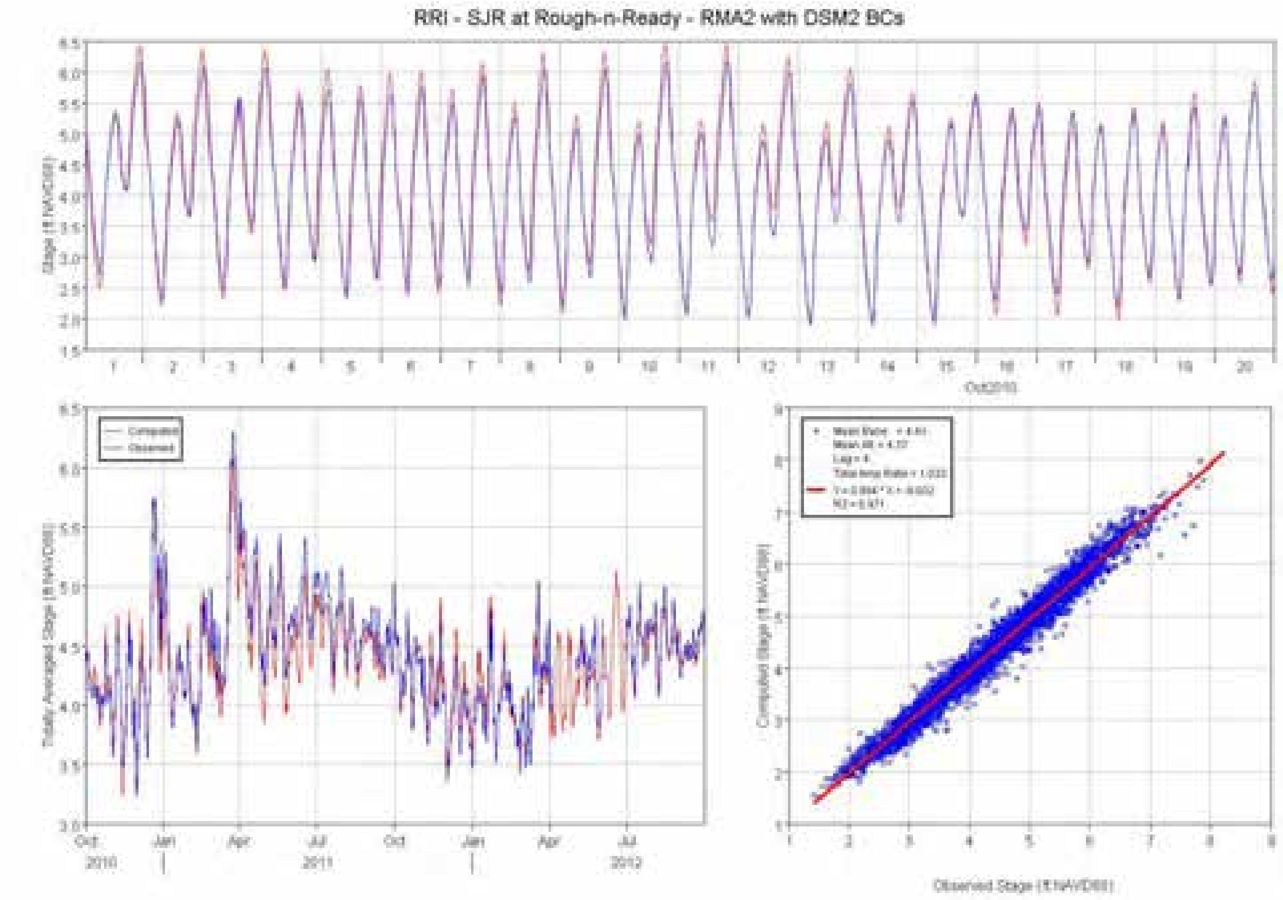
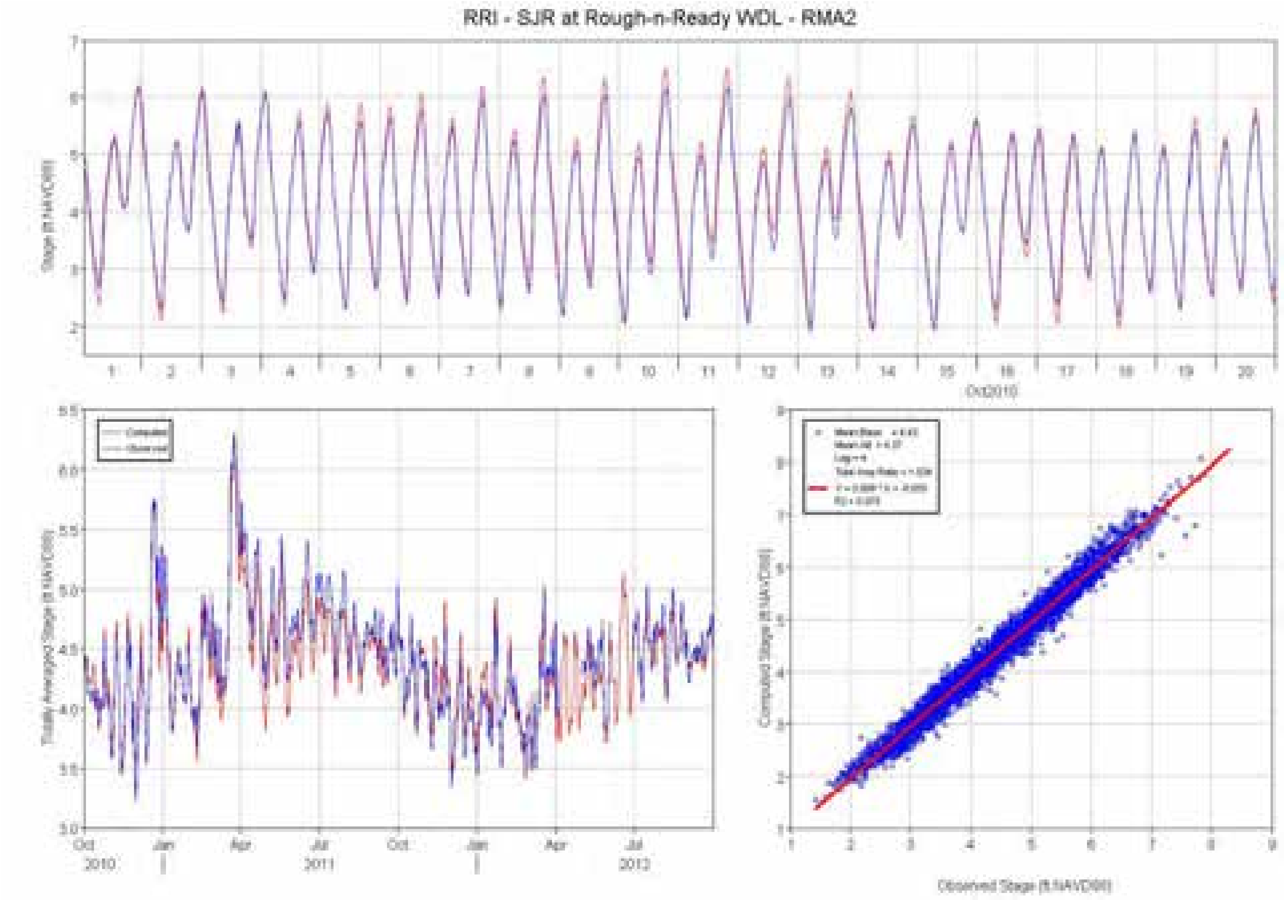


Figure 173 Computed (RMA2 with DSM2 BCs) and observed stage comparison plots for SJR at Rough-n-Ready.



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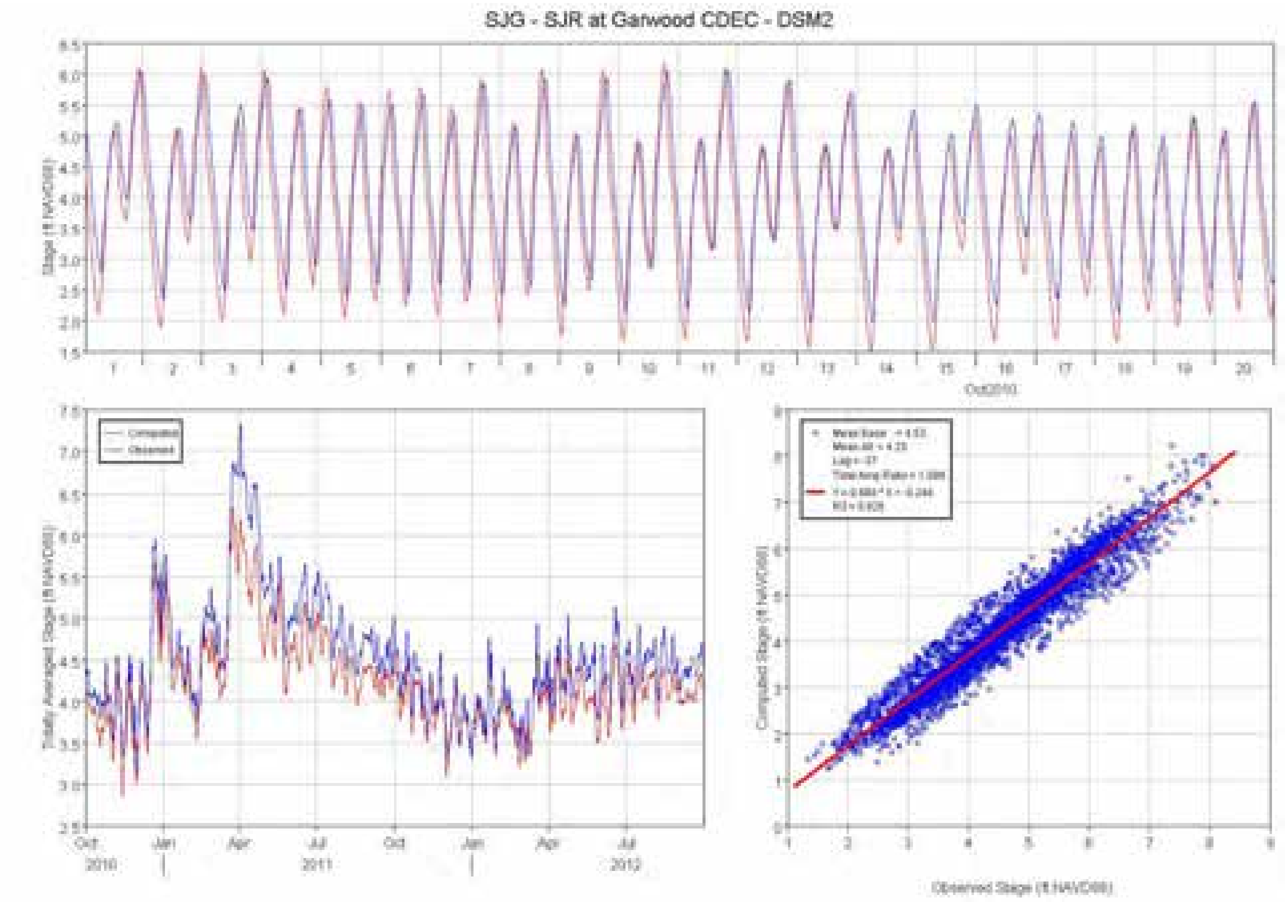


Figure 175 Computed (DSM2) and observed stage comparison plots for SJR at Garwood.

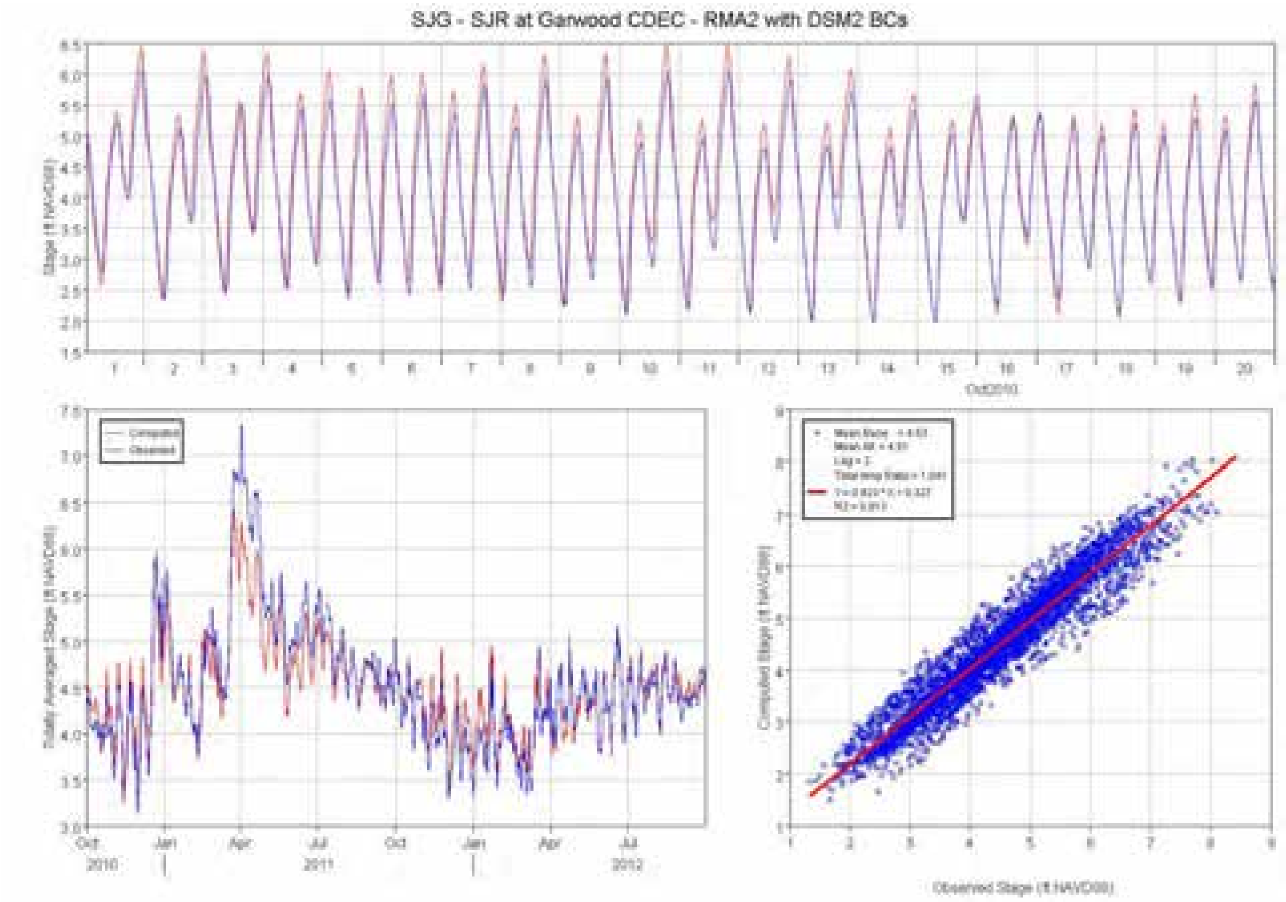


Figure 176 Computed (RMA2 with DSM2 BCs) and observed stage comparison plots for SJR at Garwood.

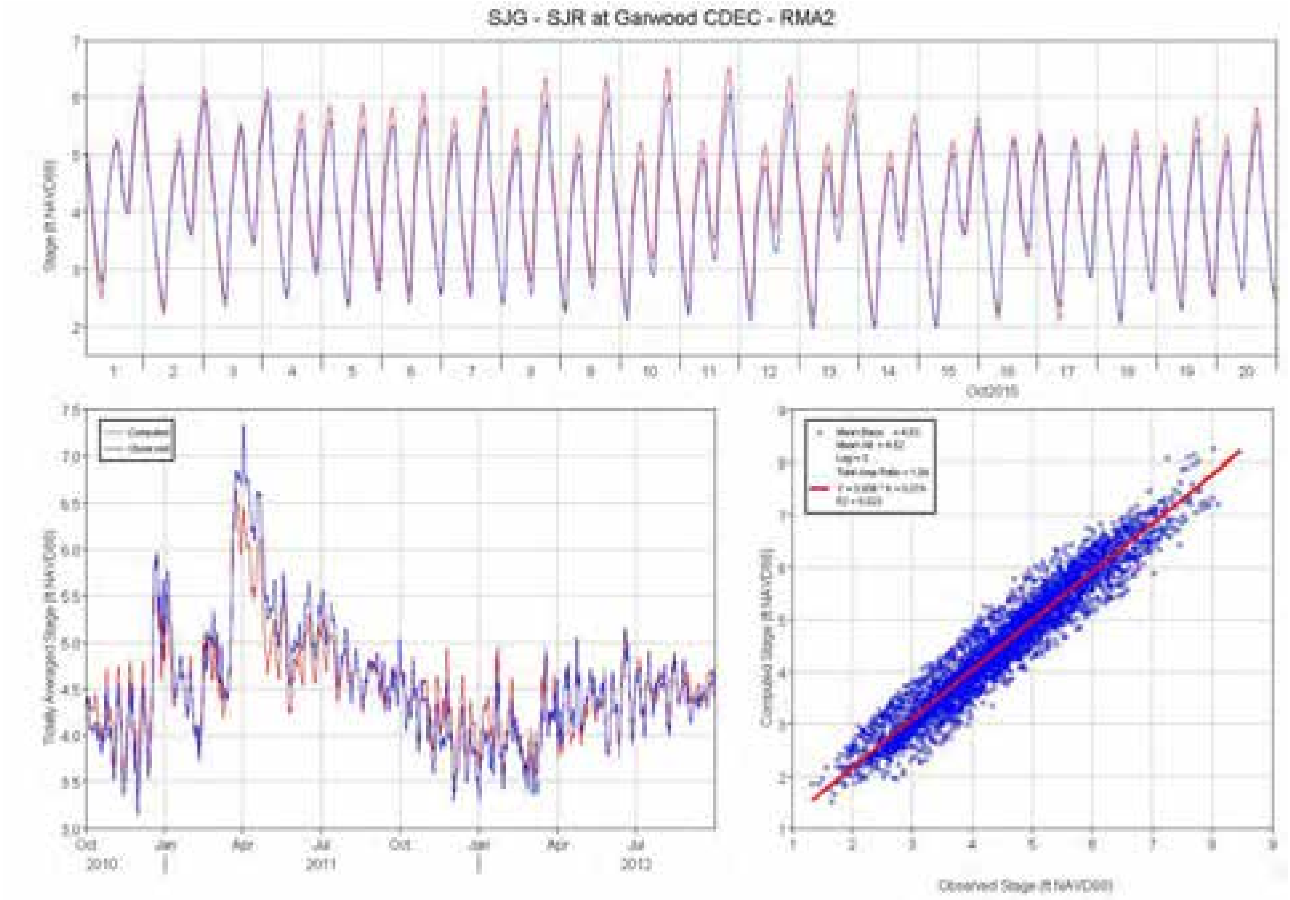


Figure 177 Computed (RMA2) and observed stage comparison plots for SJR at Garwood.

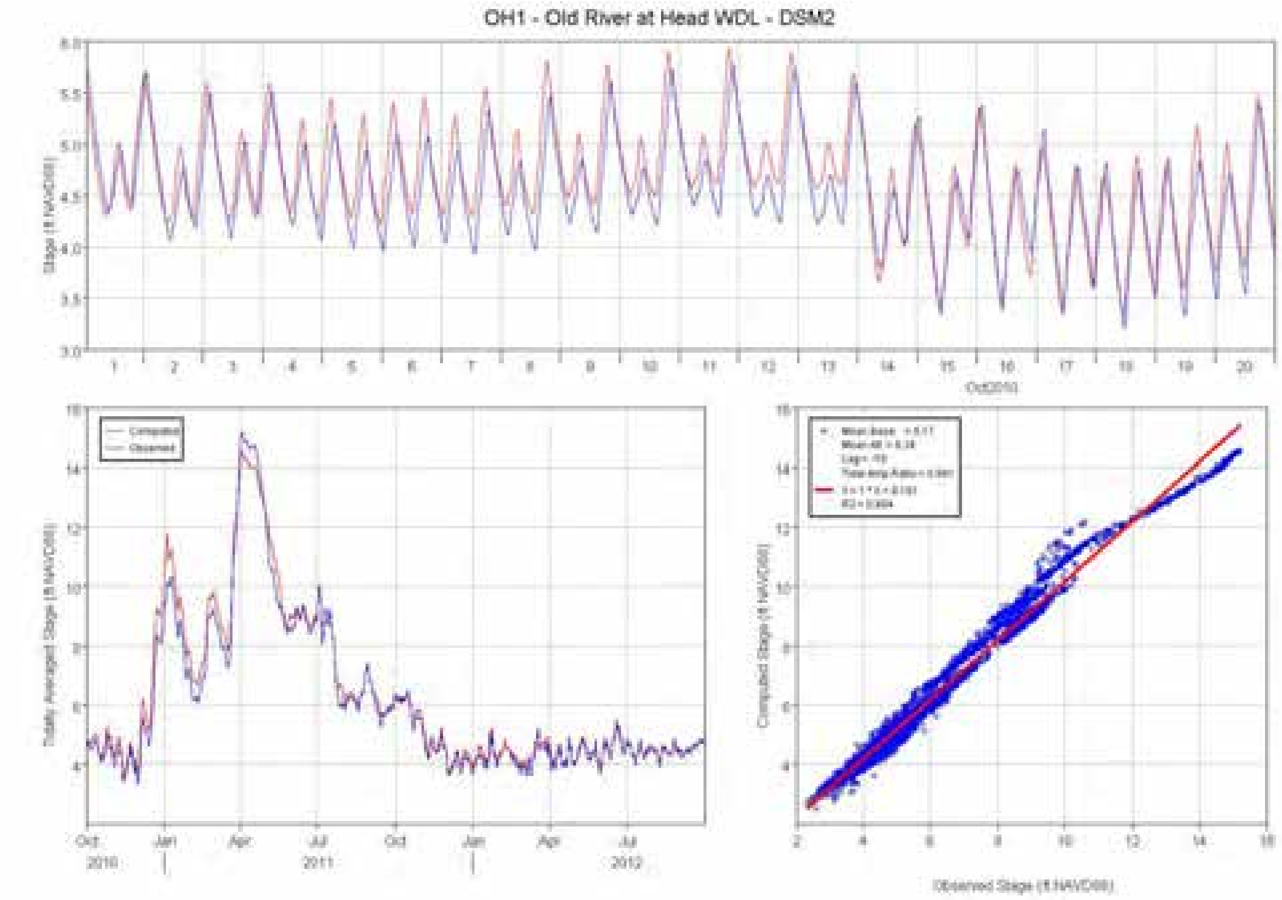


Figure 178 Computed (DSM2) and observed stage comparison plots for Old River at Head.

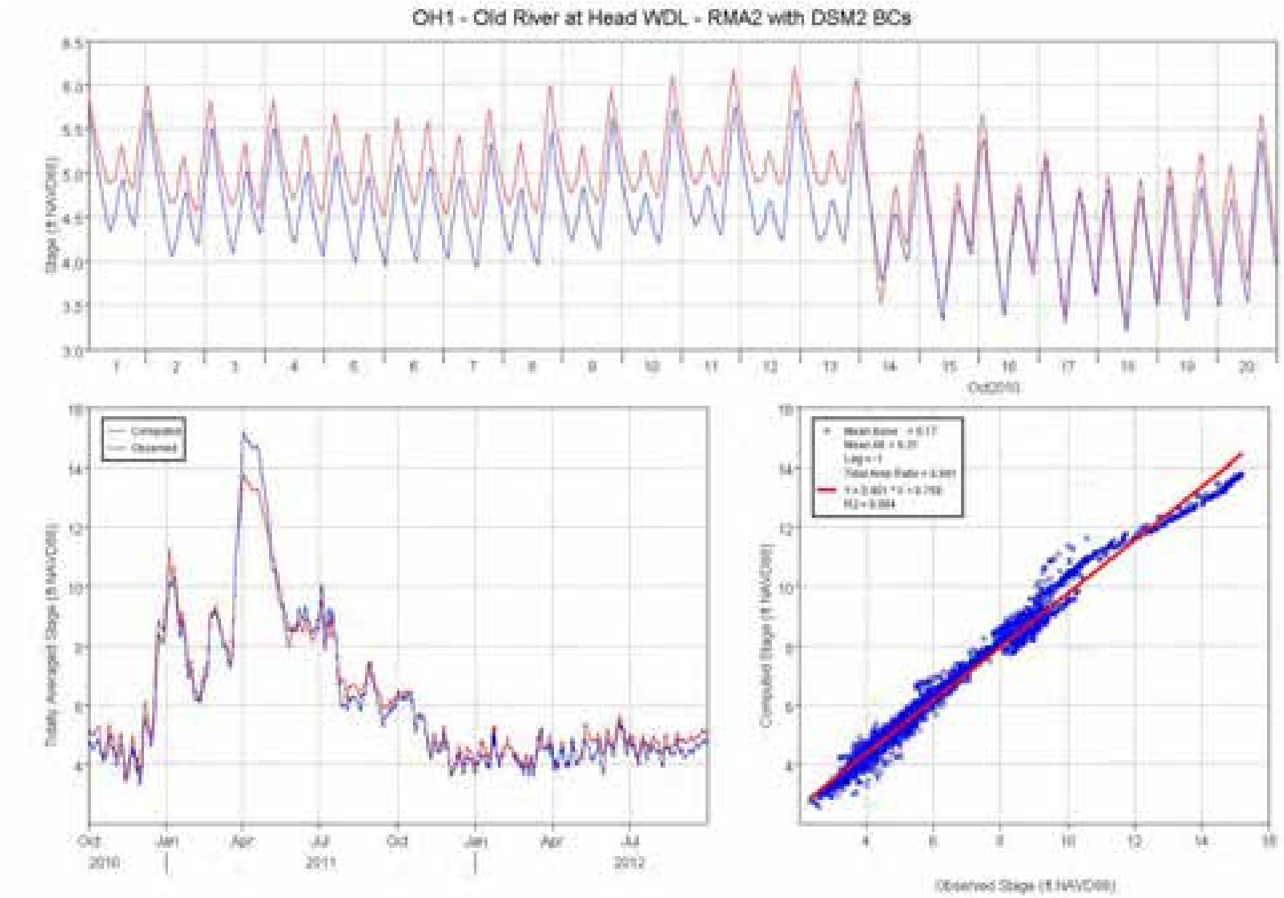


Figure 179 Computed (RMA2 with DSM2 BCs) and observed stage comparison plots for Old River at Head.

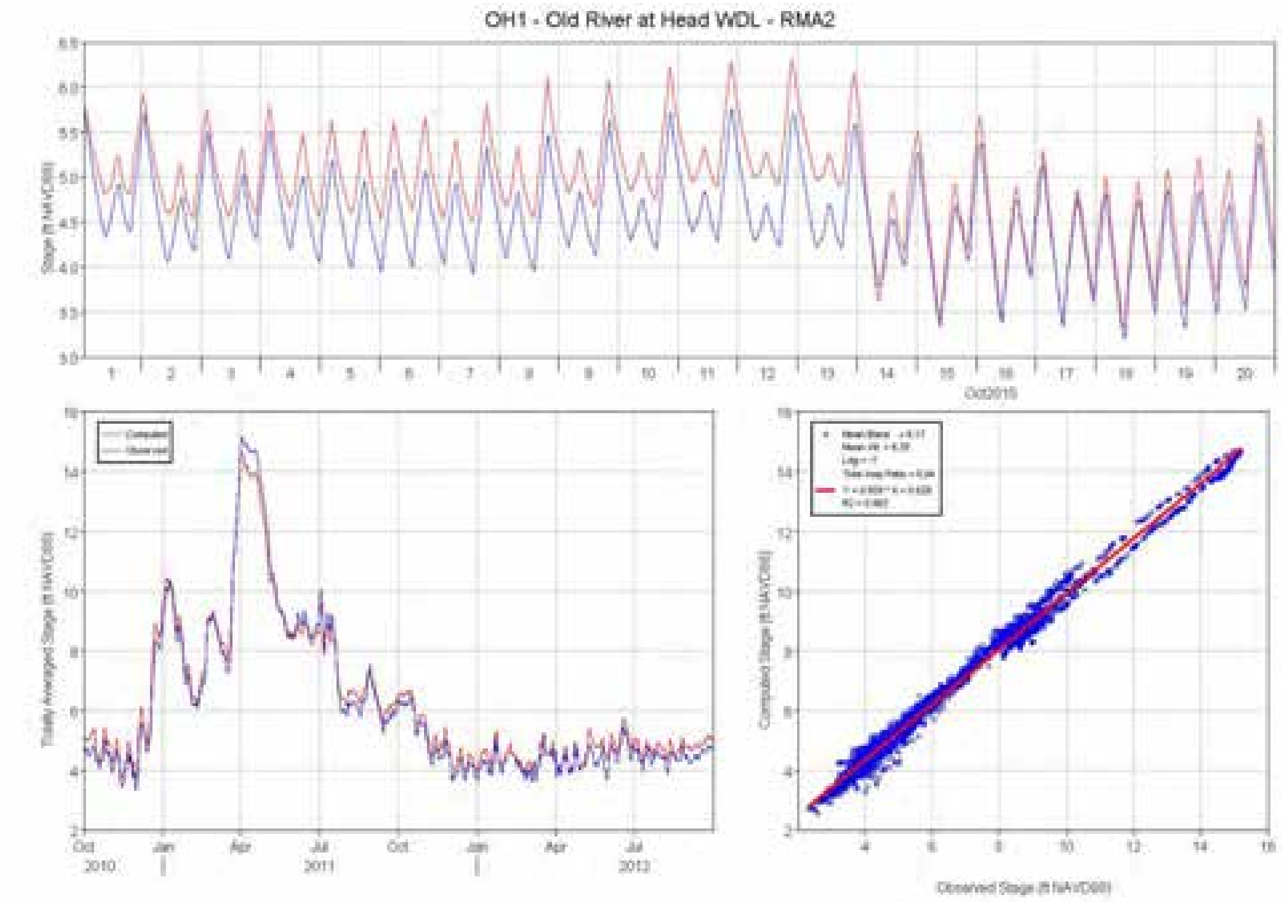


Figure 180 Computed (RMA2) and observed stage comparison plots for Old River at Head.

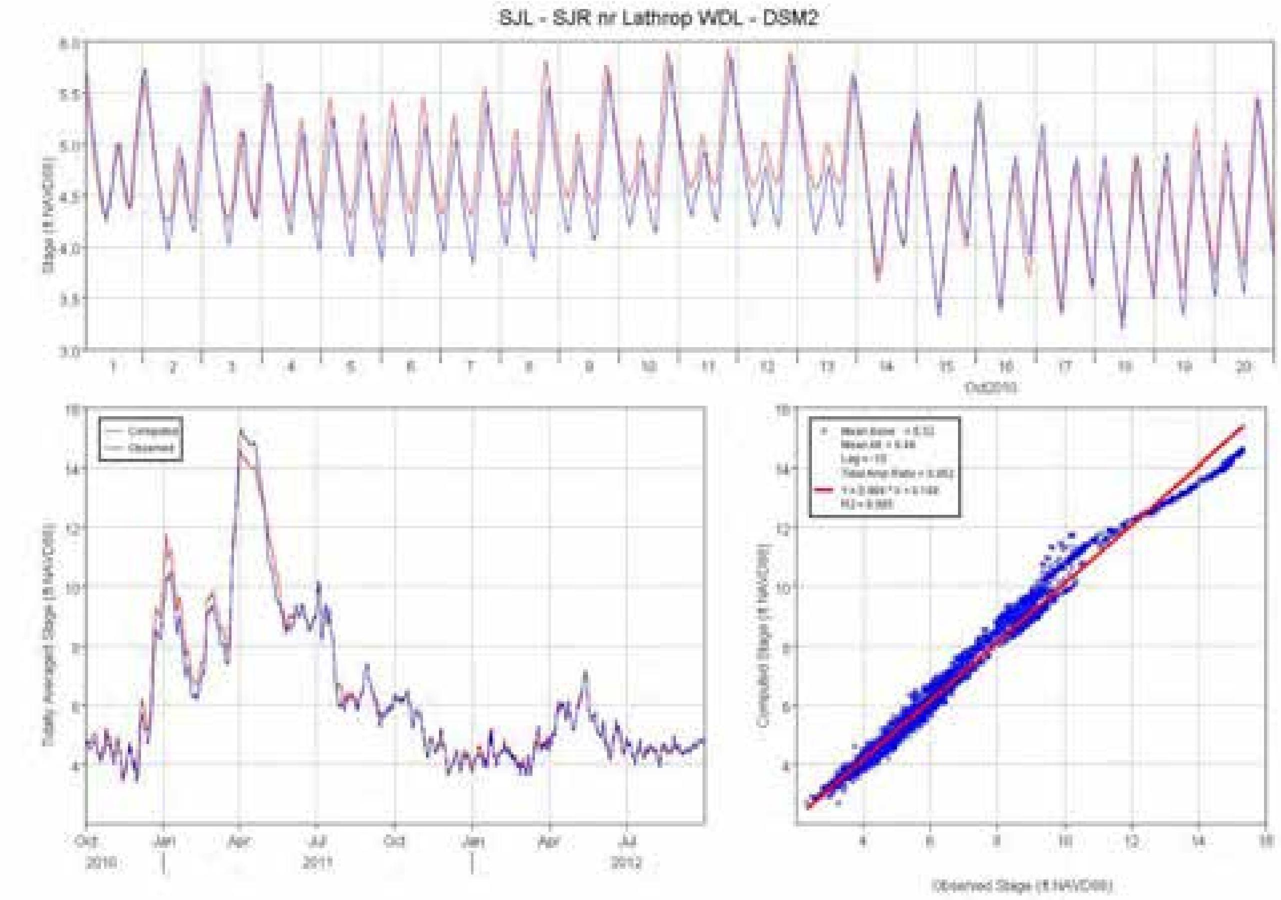


Figure 181 Computed (DSM2) and observed stage comparison plots for SJR near Lathrop.

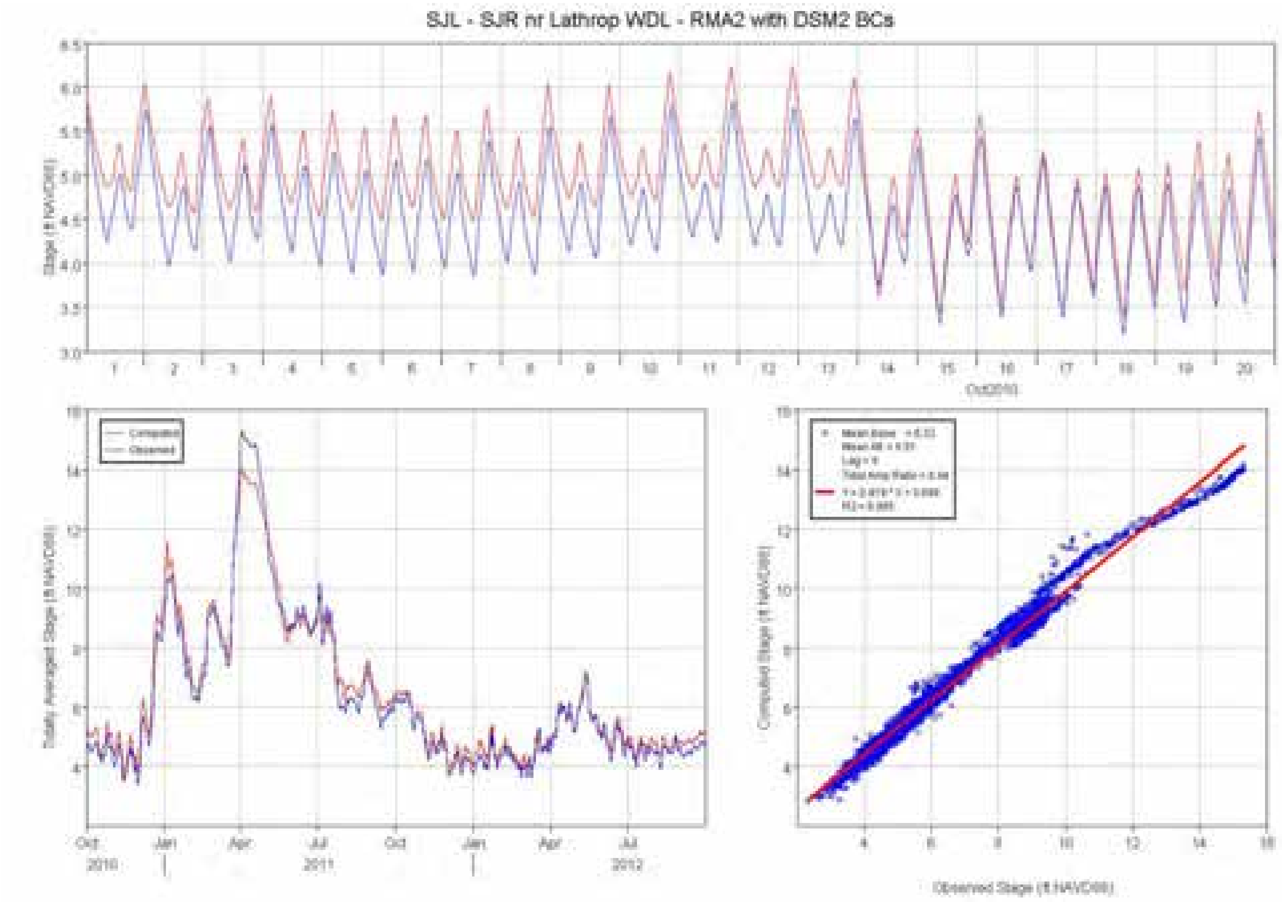


Figure 182 Computed (RMA2 with DSM2 BCs) and observed stage comparison plots for SJR near Lathrop.

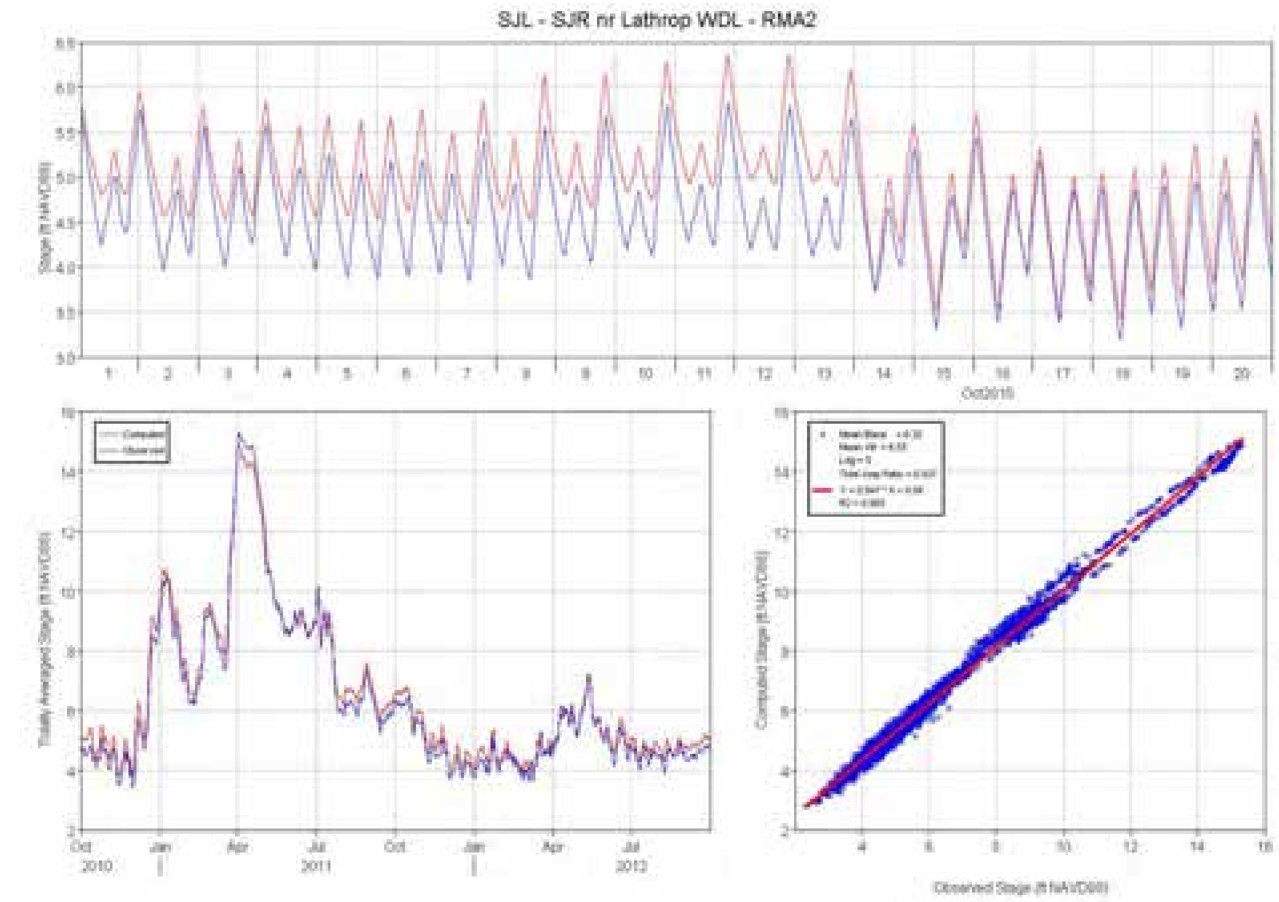


Figure 183 Computed (RMA2) and observed stage comparison plots for SJR near Lathrop.

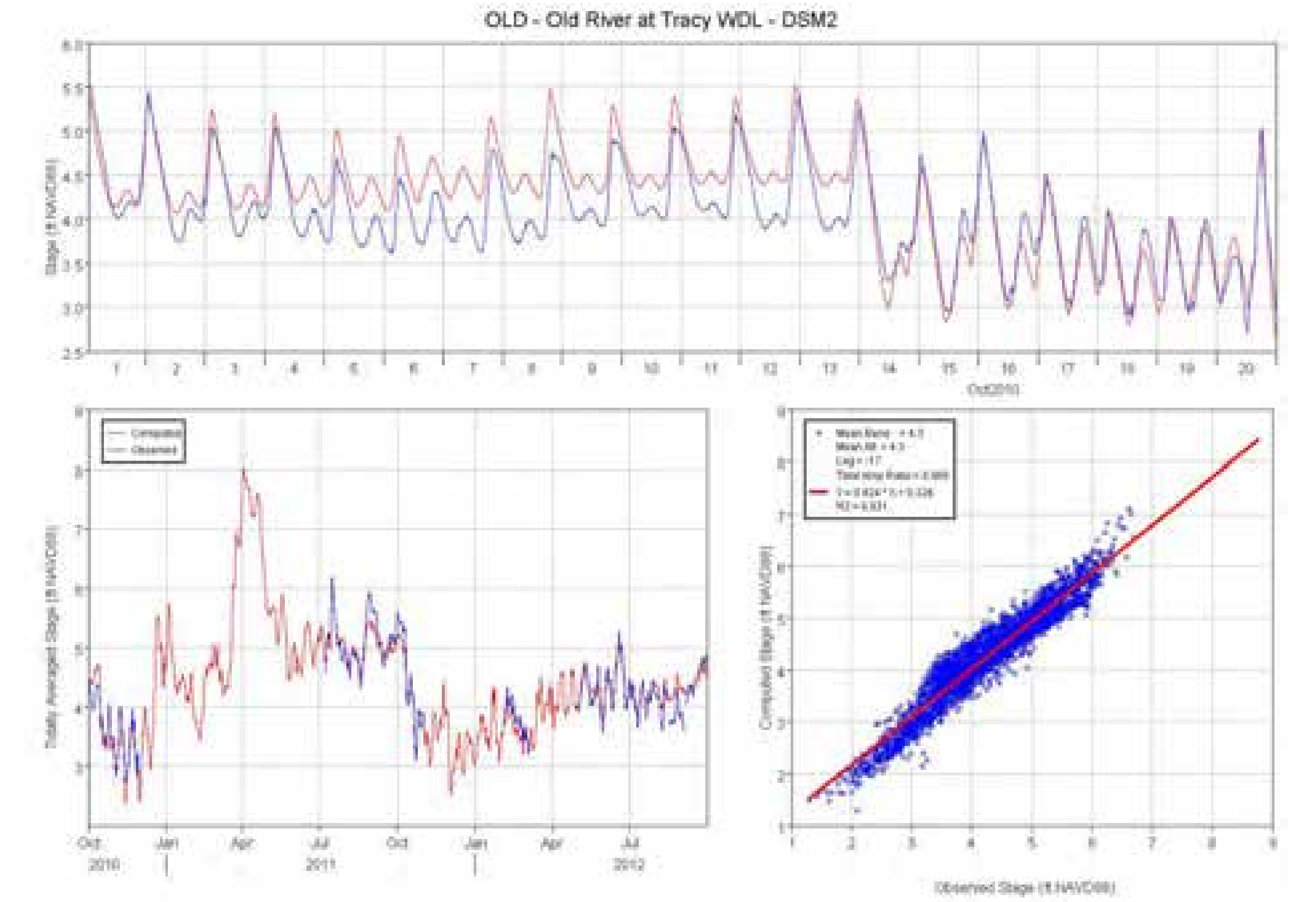


Figure 184 Computed (DSM2) and observed stage comparison plots for Old River at Tracy.

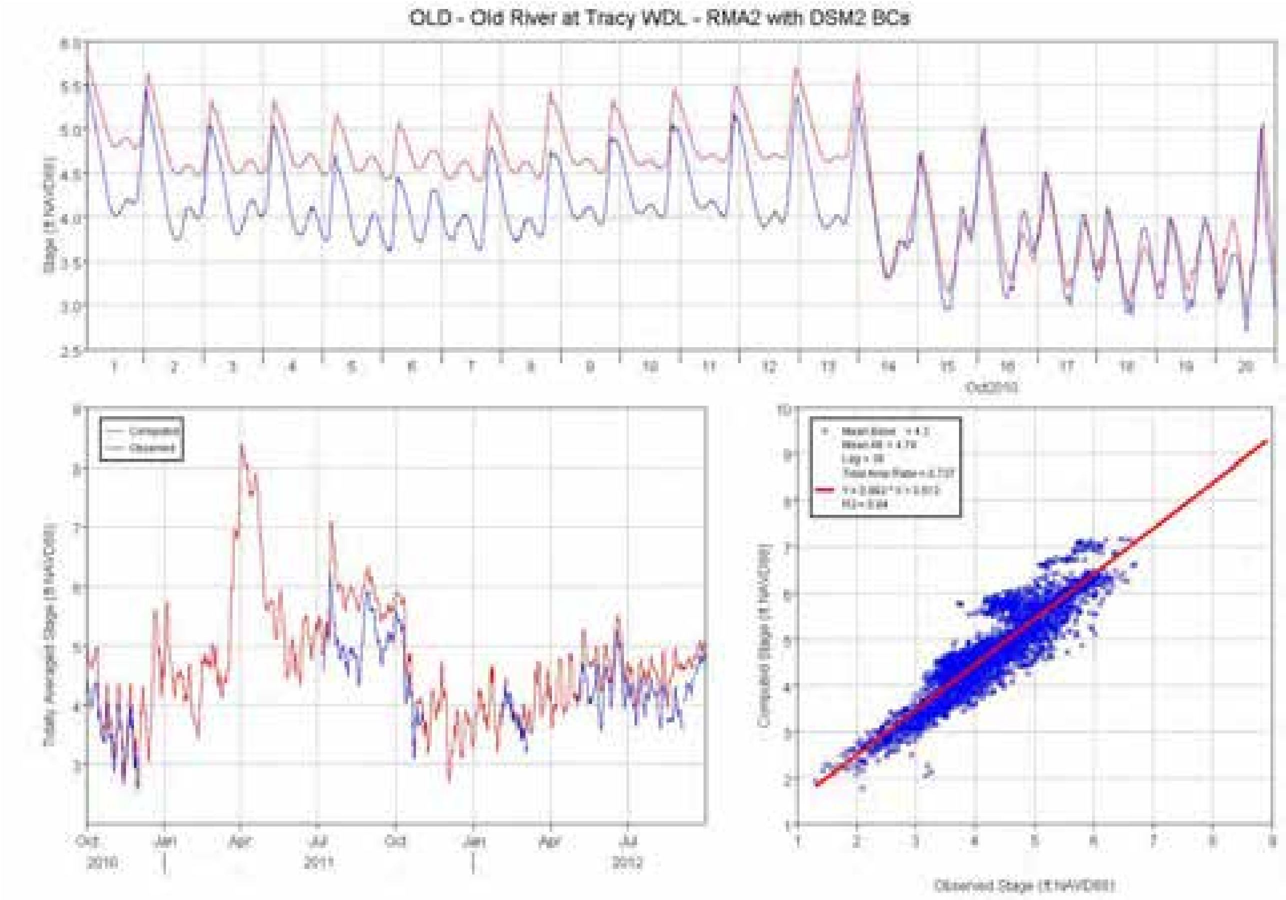


Figure 185 Computed (RMA2 with DSM2 BCs) and observed stage comparison plots for Old River at Tracy.

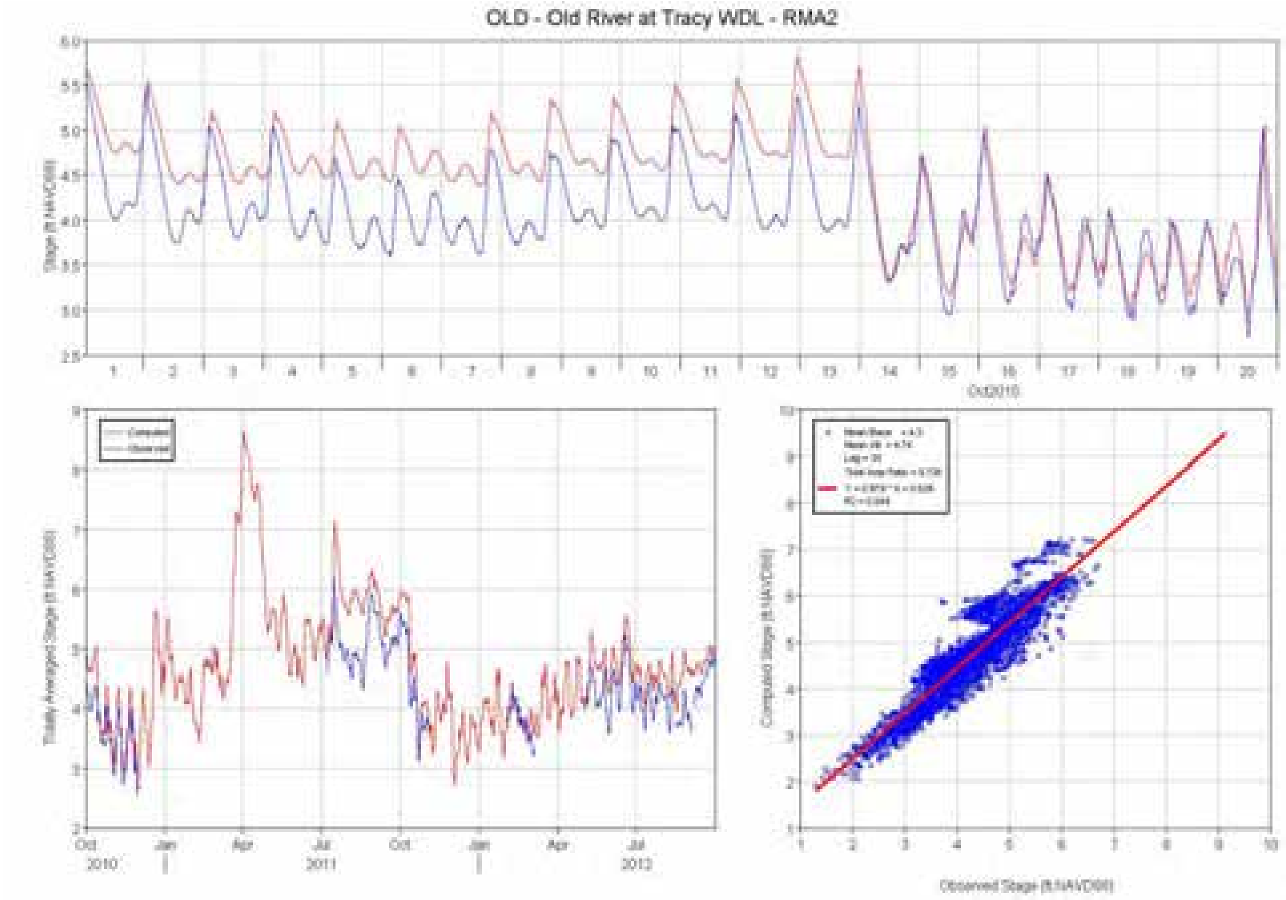


Figure 186 Computed (RMA2) and observed stage comparison plots for Old River at Tracy.

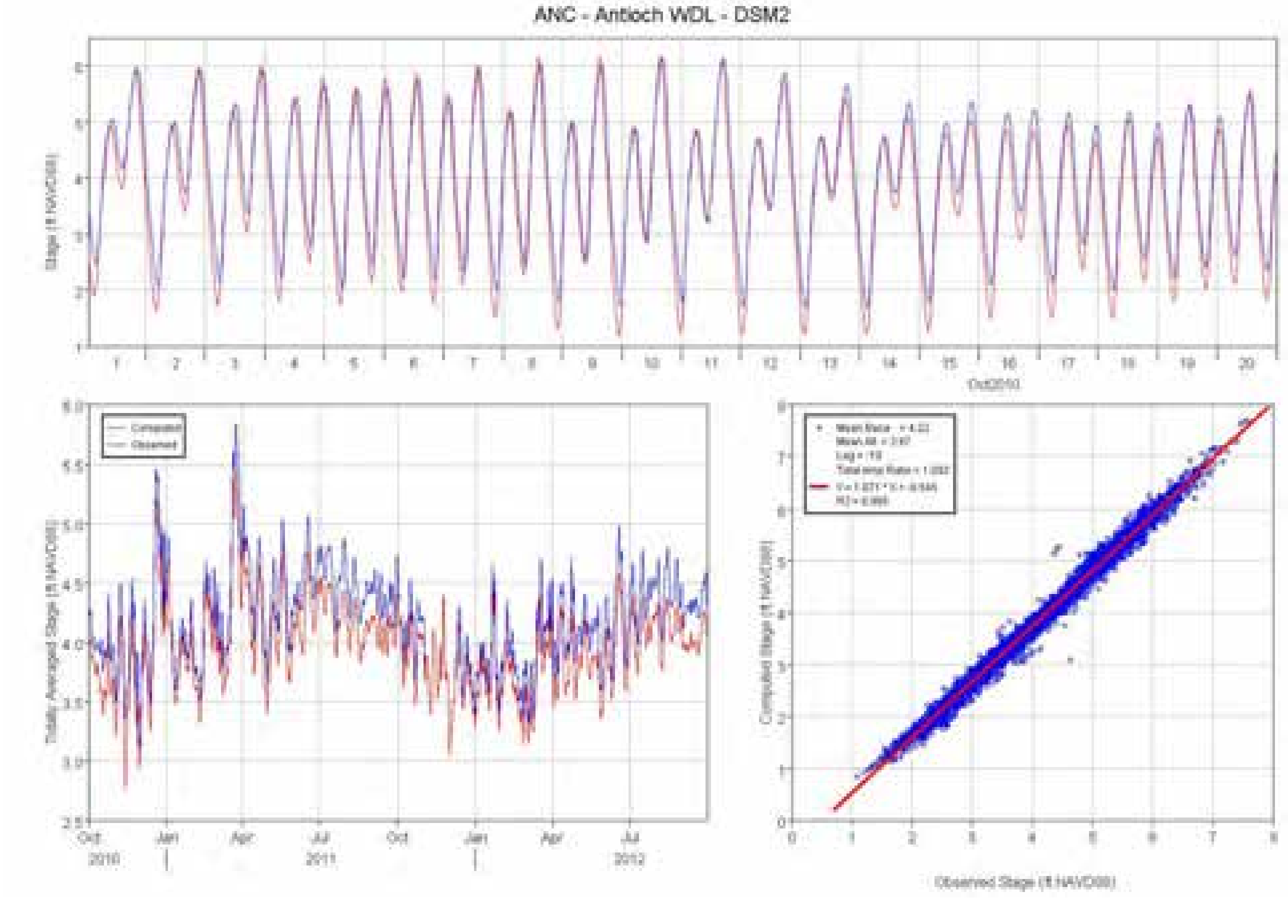


Figure 187 Computed (DSM2) and observed stage comparison plots for Antioch.

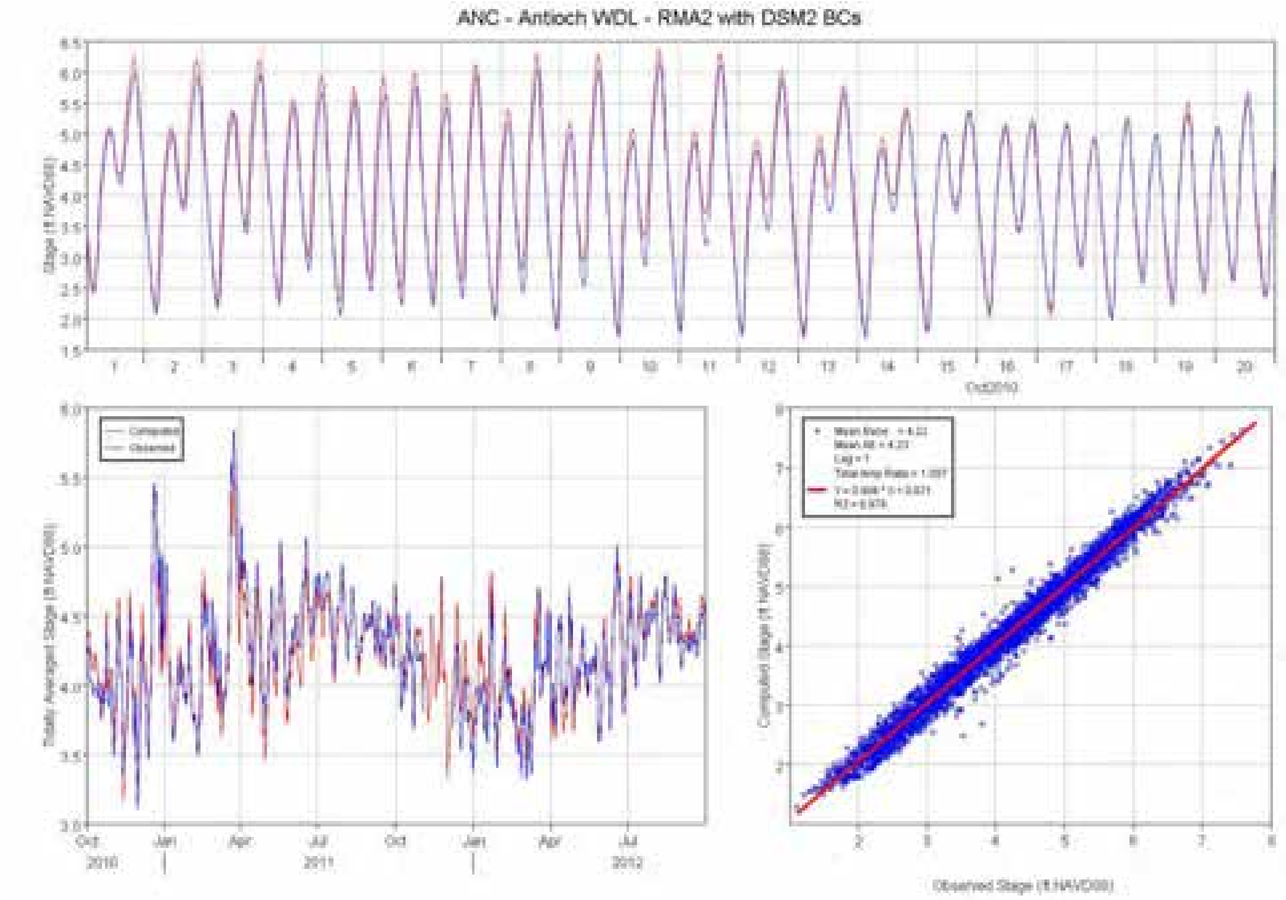


Figure 188 Computed (RMA2 with DSM2 BCs) and observed stage comparison plots for Antioch.

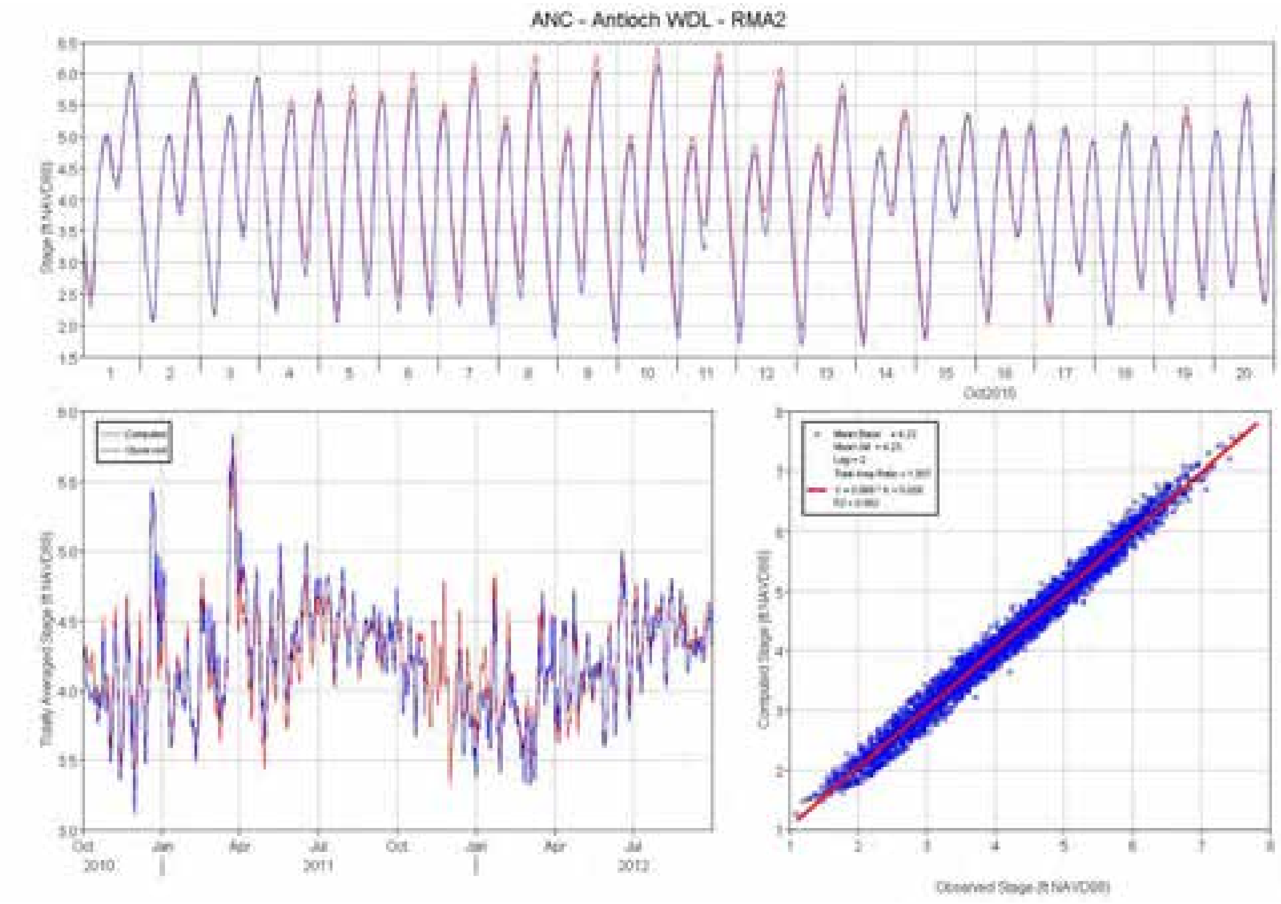


Figure 189 Computed (RMA2) and observed stage comparison plots for Antioch.

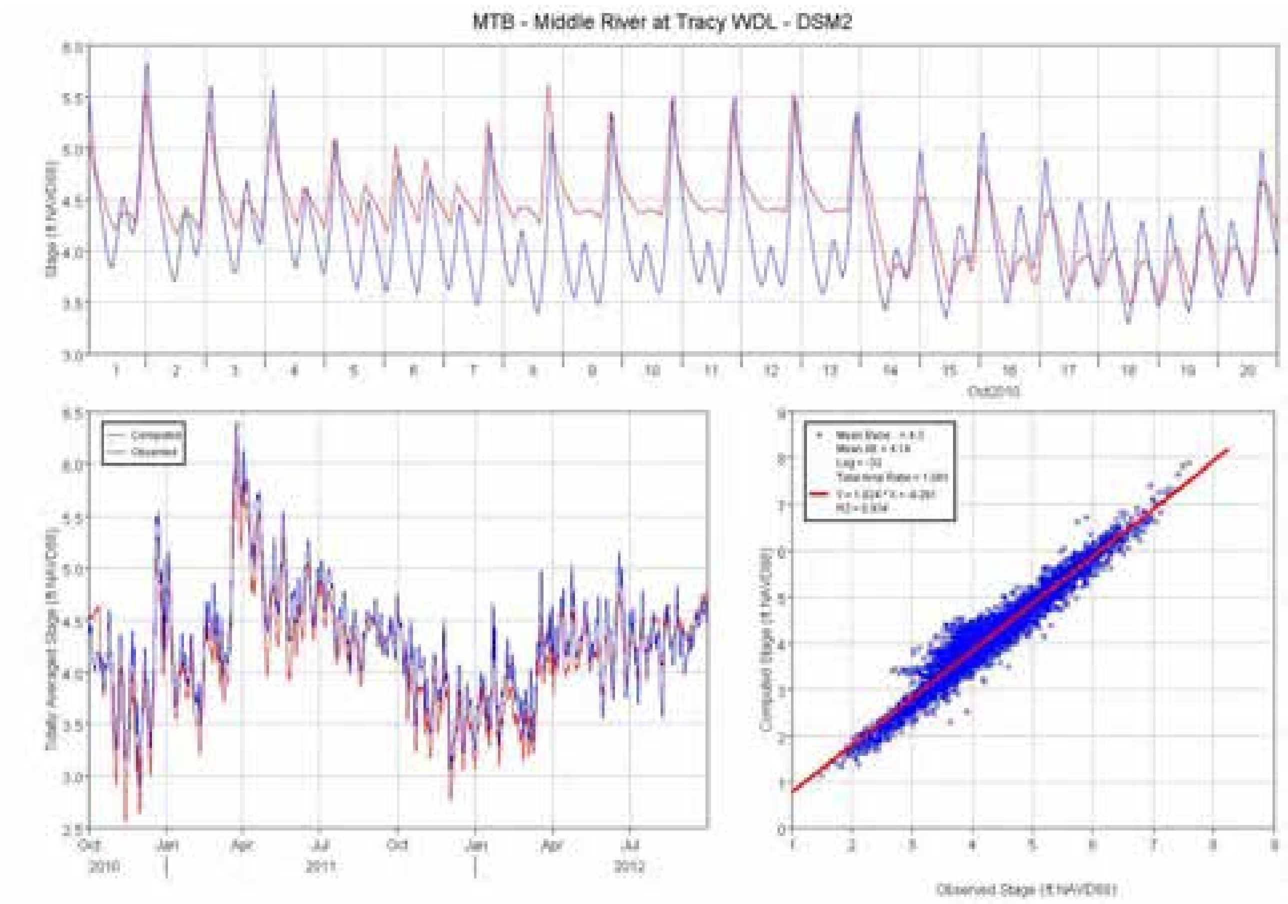


Figure 190 Computed (DSM2) and observed stage comparison plots for Middle River at Tracy.

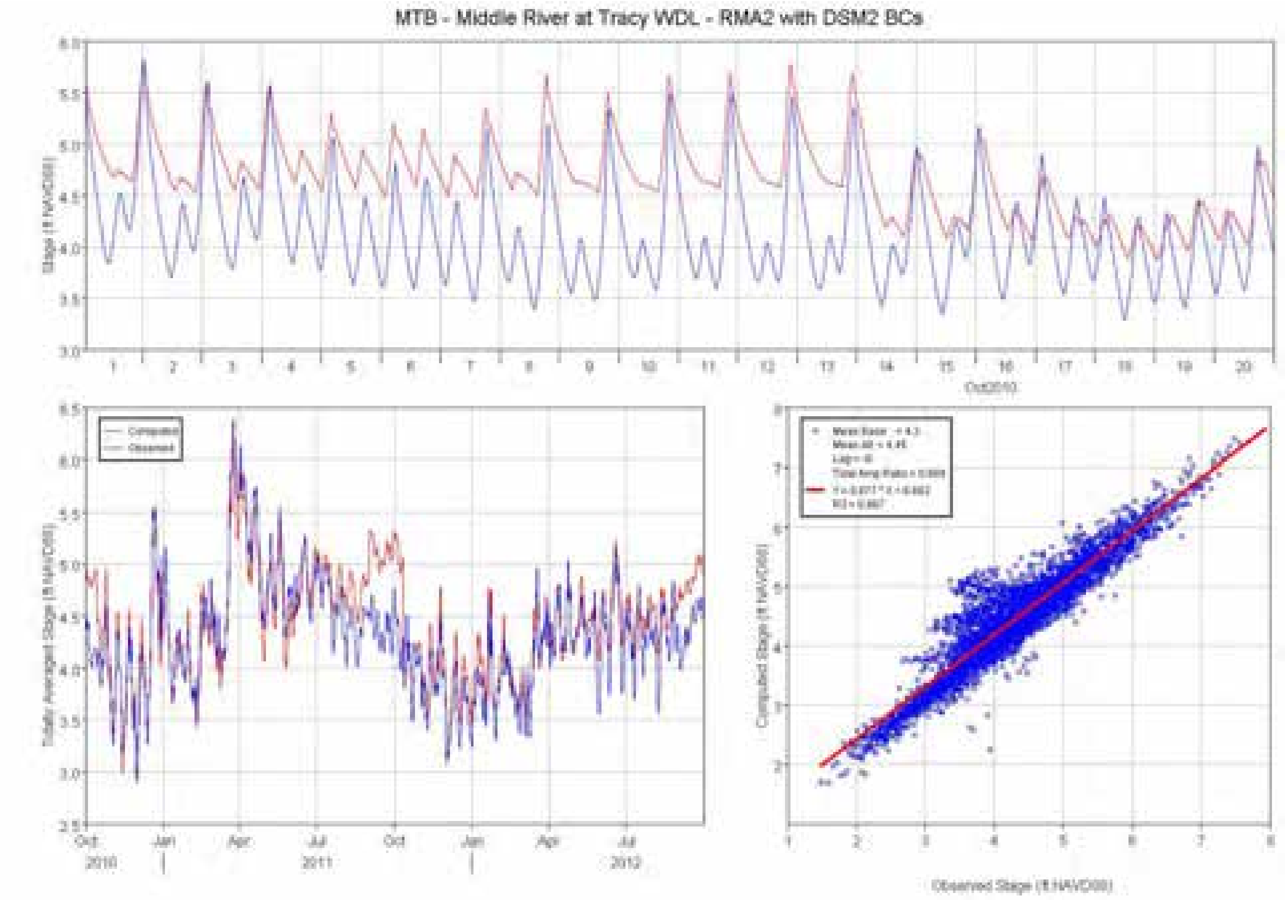


Figure 191 Computed (RMA2 with DSM2 BCs) and observed stage comparison plots for Middle River at Tracy.

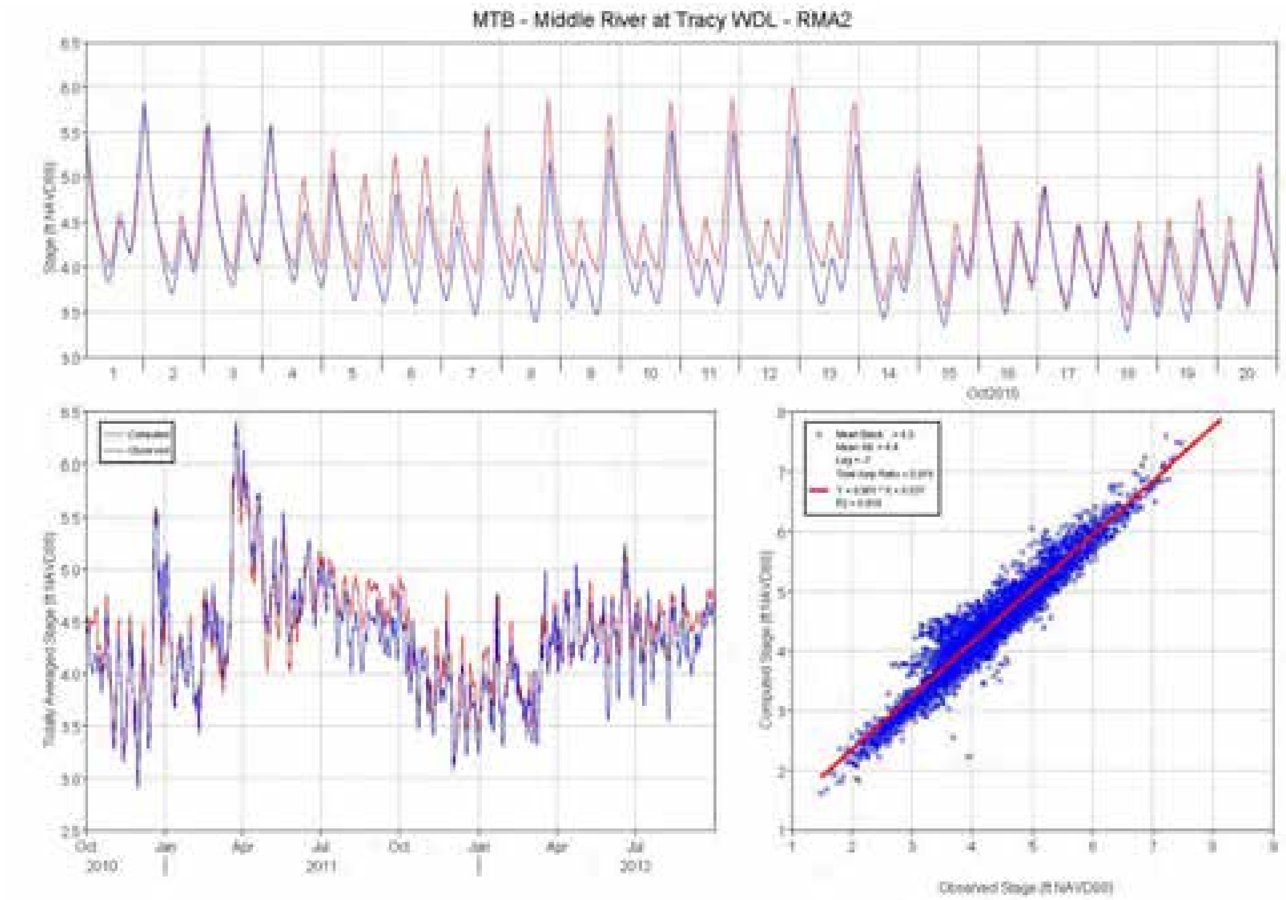


Figure 192 Computed (RMA2) and observed stage comparison plots for Middle River at Tracy.

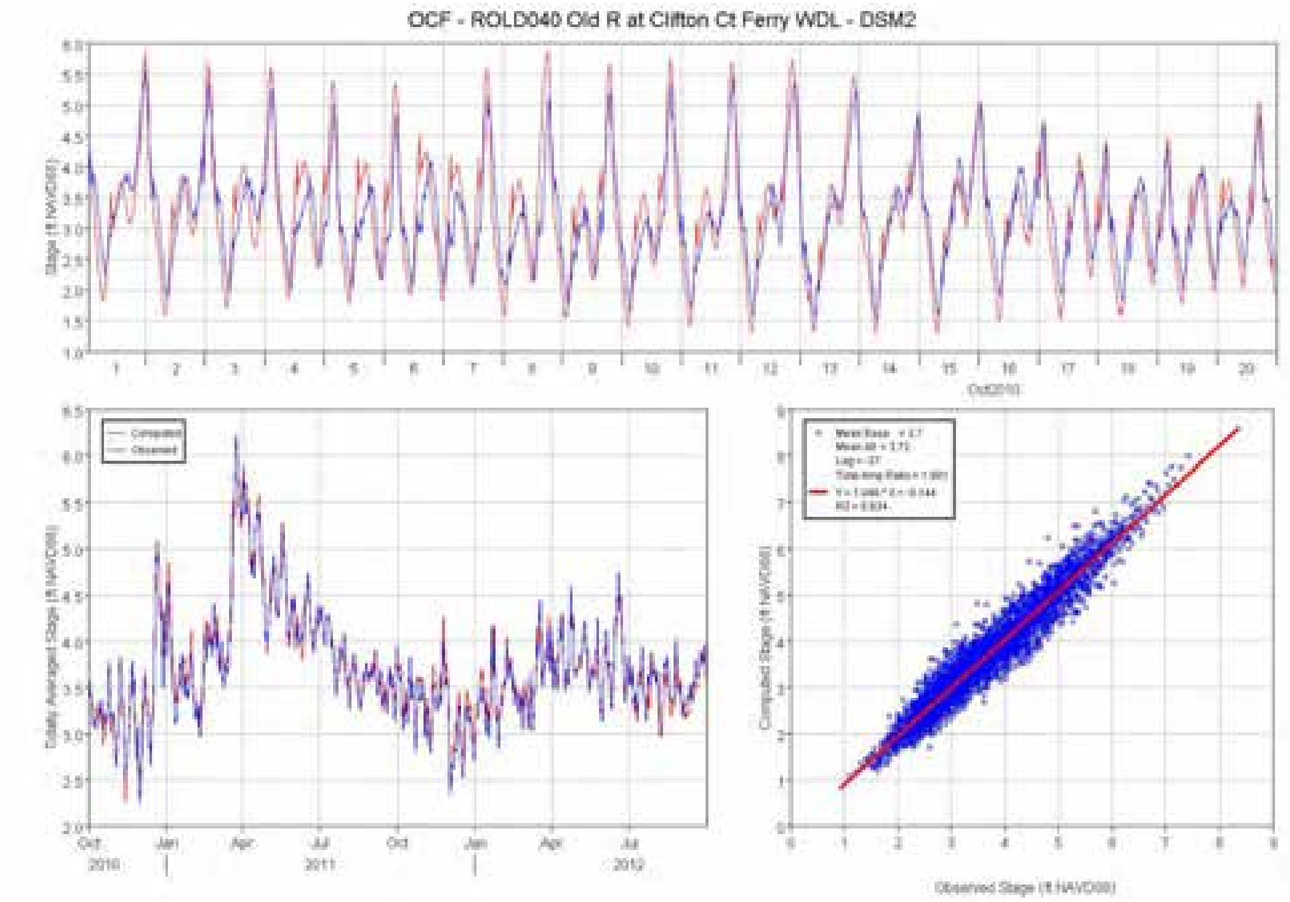


Figure 193 Computed (DSM2) and observed stage comparison plots for Old River at Clifton Court Ferry.

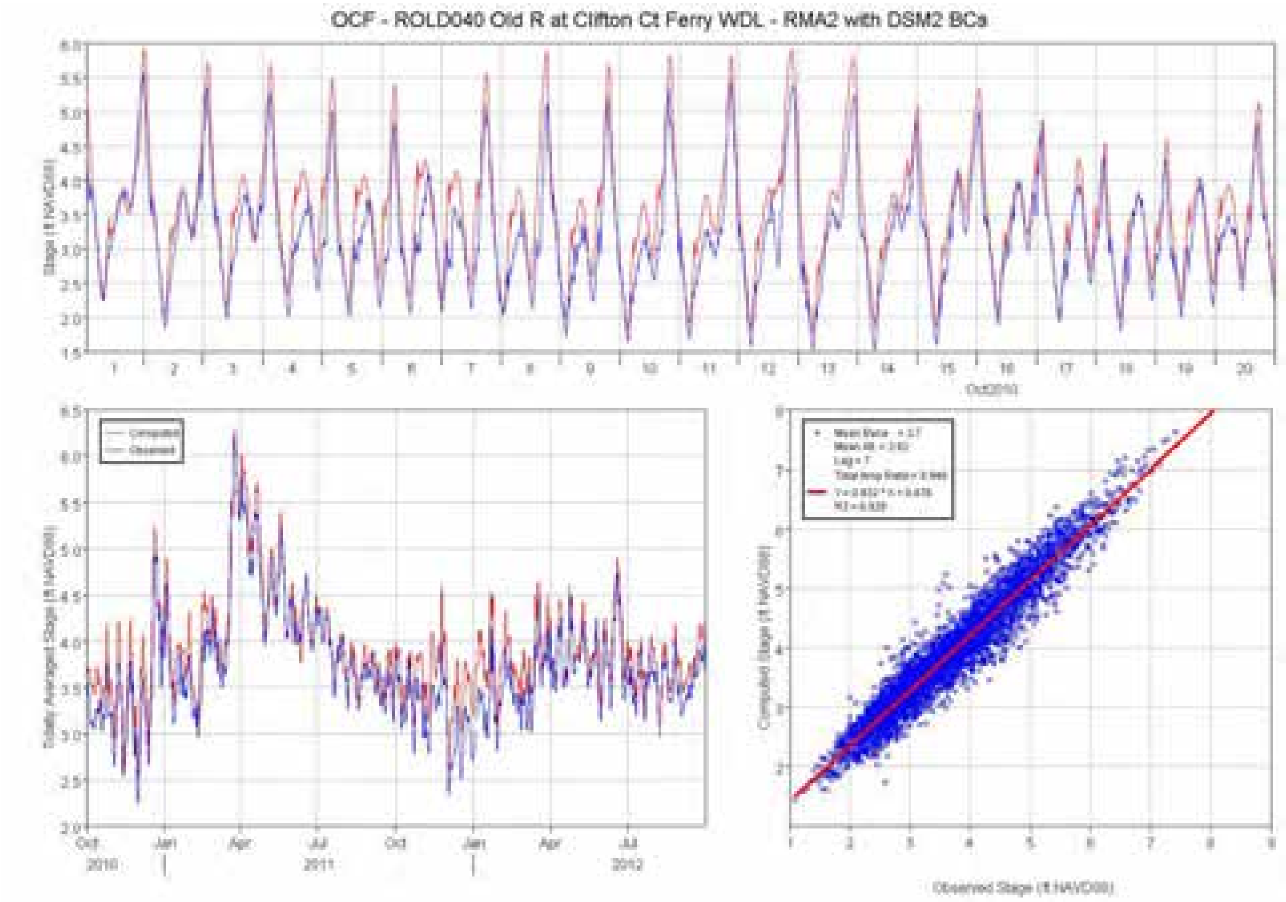


Figure 194 Computed (RMA2 with DSM2 BCs) and observed stage comparison plots for Old River at Clifton Court Ferry.

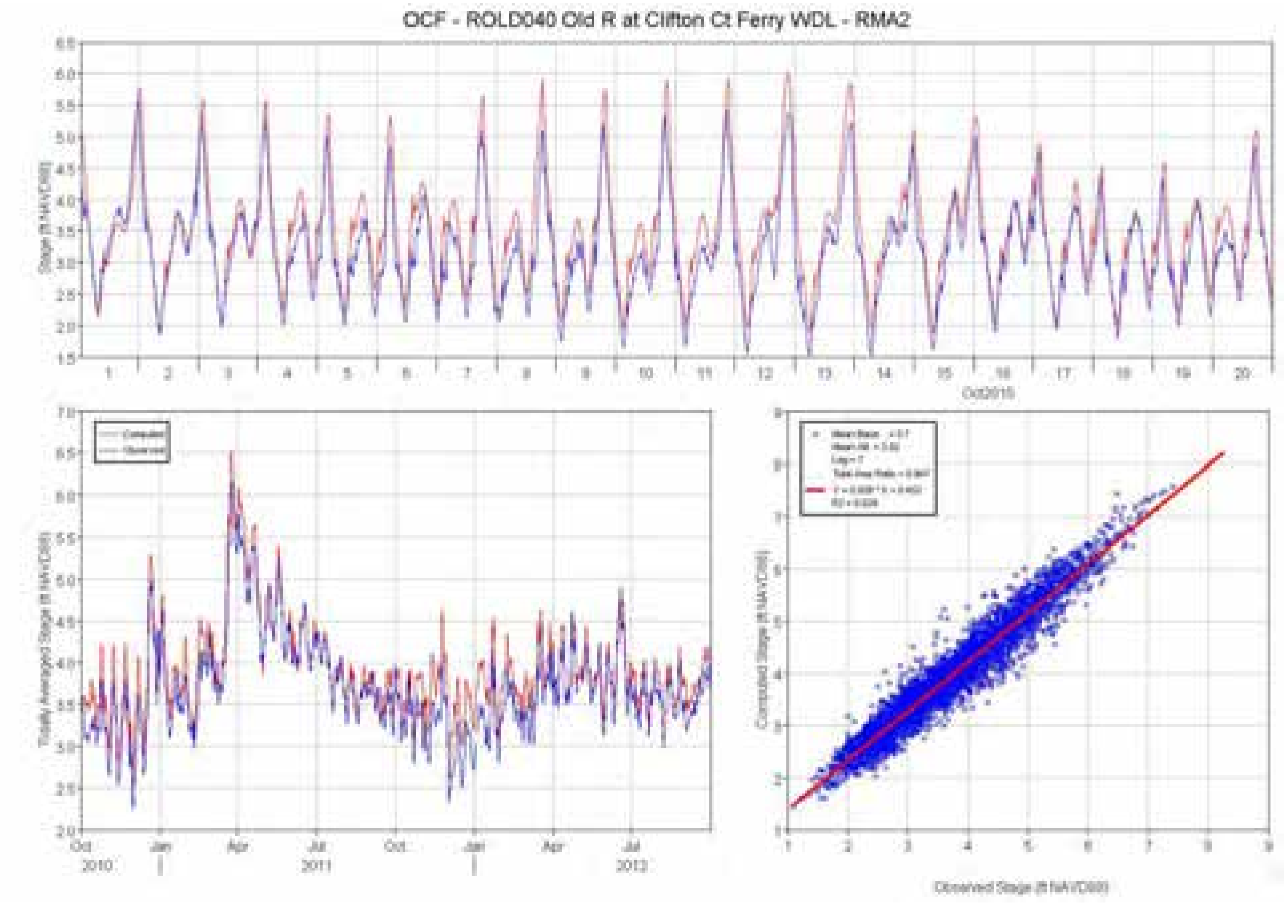


Figure 195 Computed (RMA2) and observed stage comparison plots for Old River at Clifton Court Ferry.

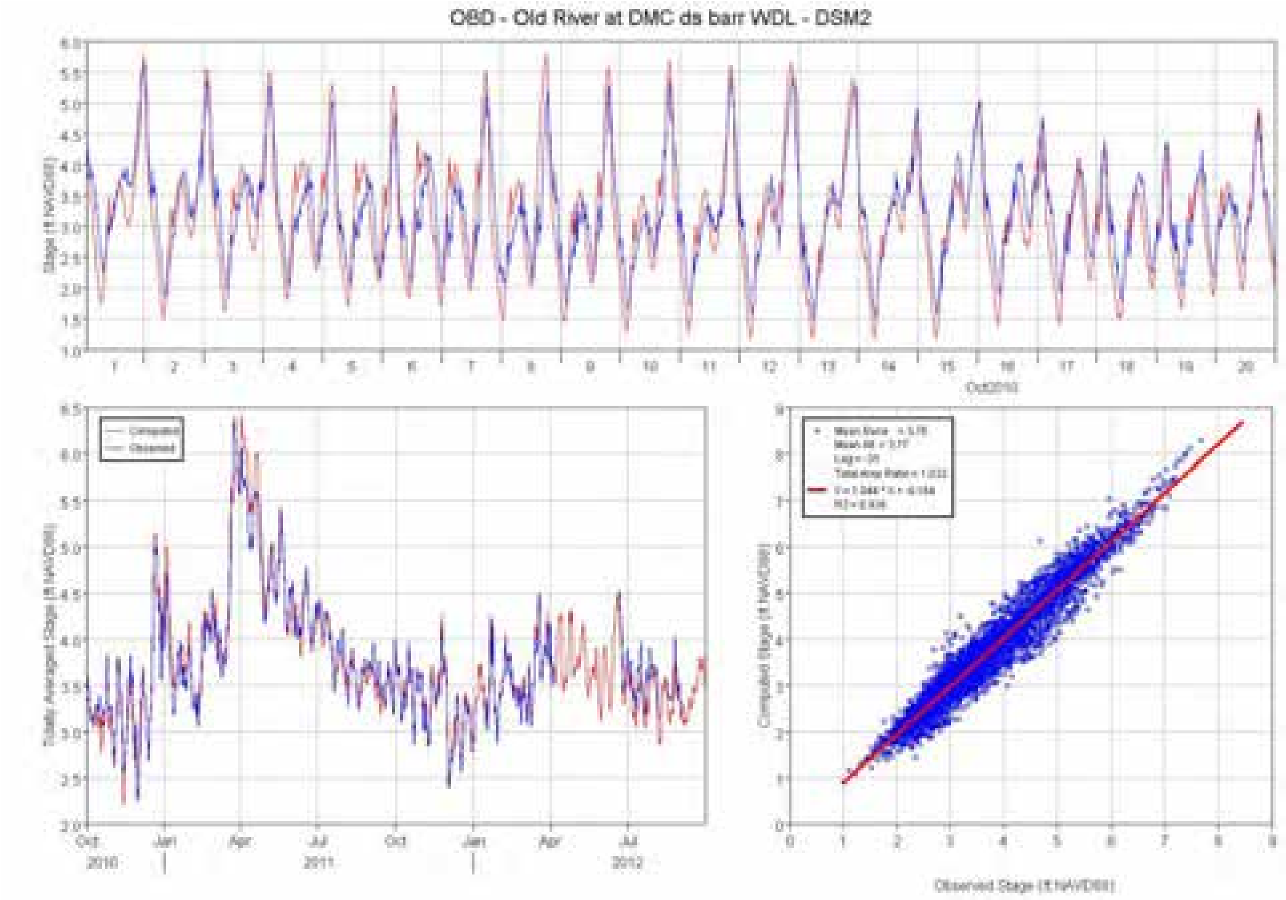
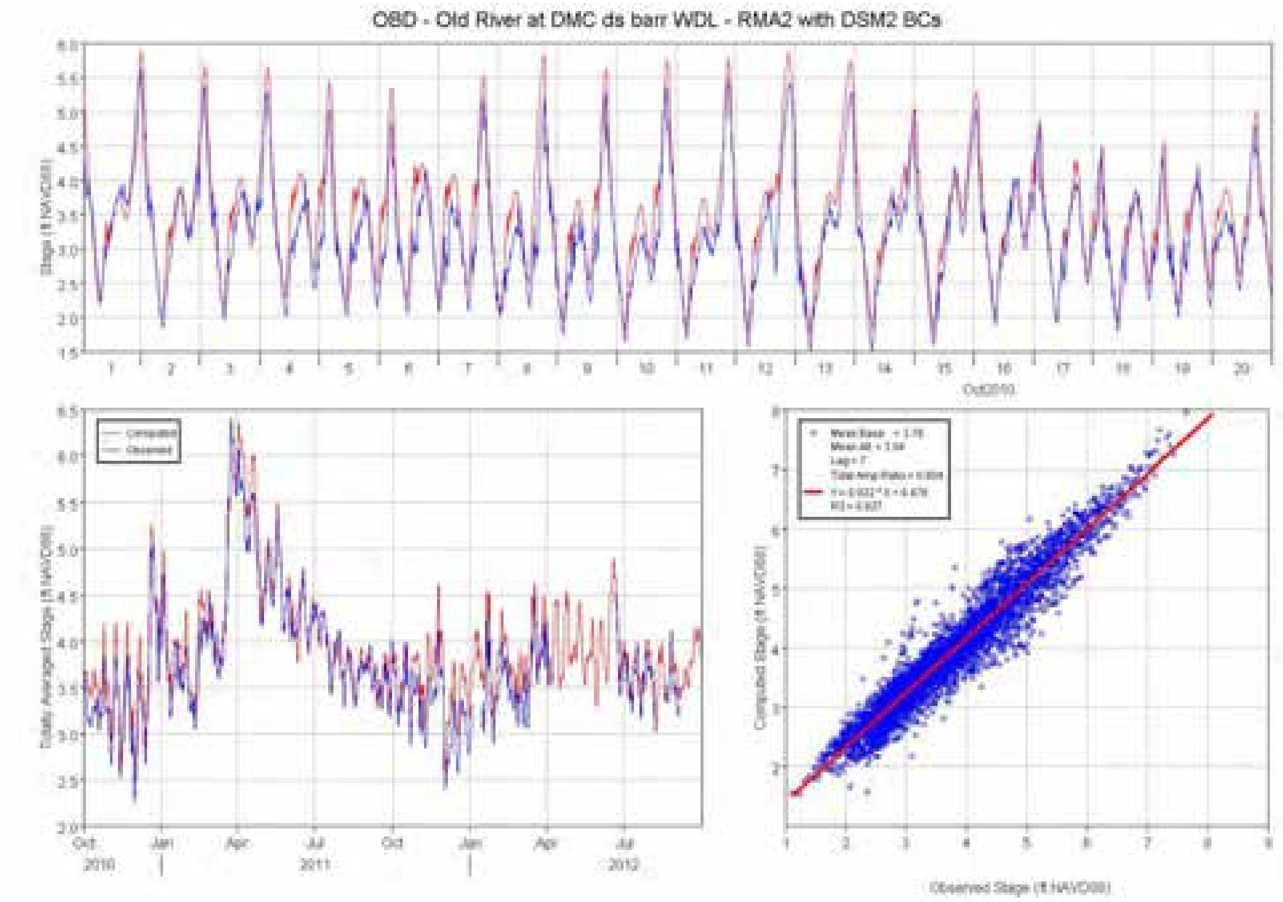


Figure 196 Computed (DSM2) and observed stage comparison plots for Old River at DMC downstream of Barrier.



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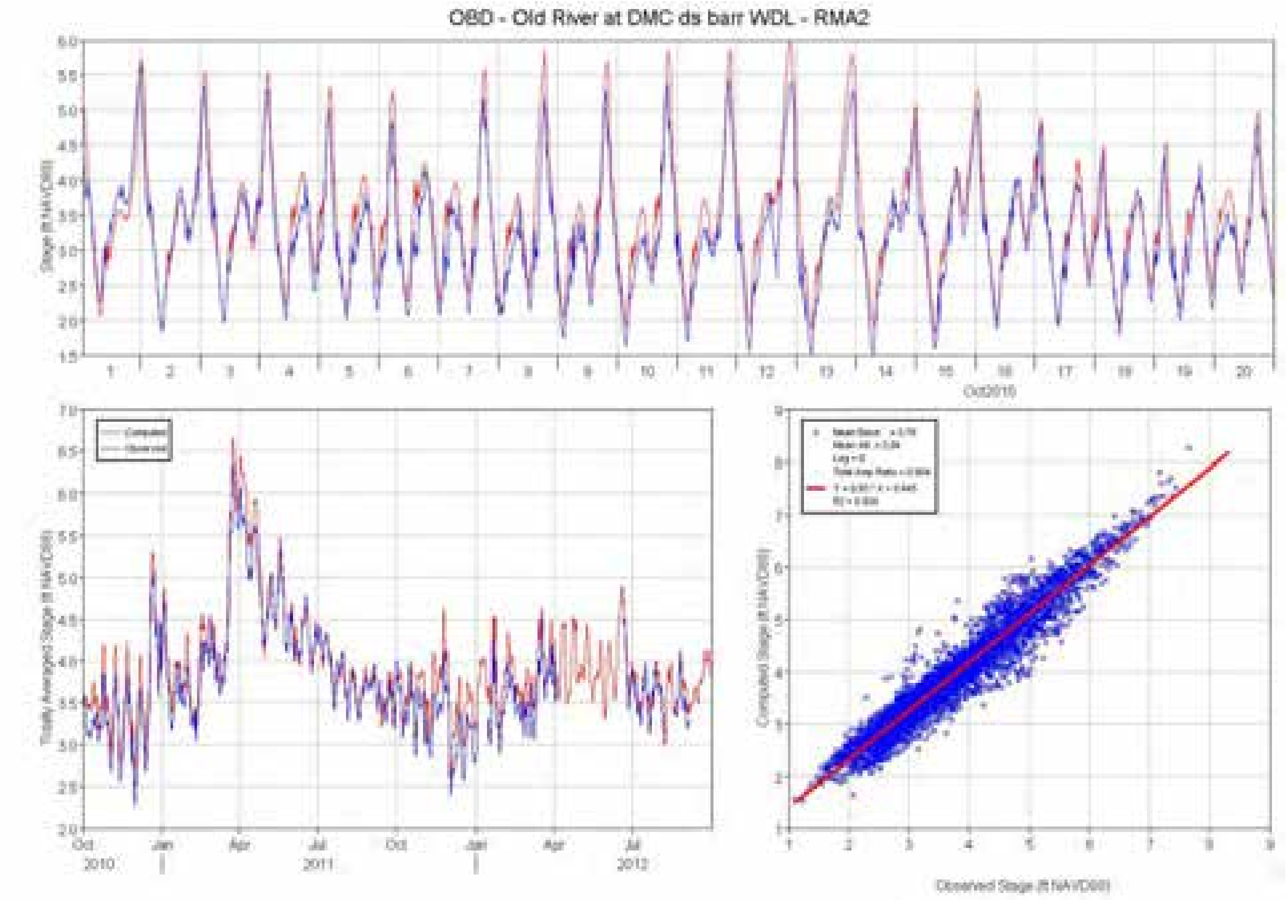

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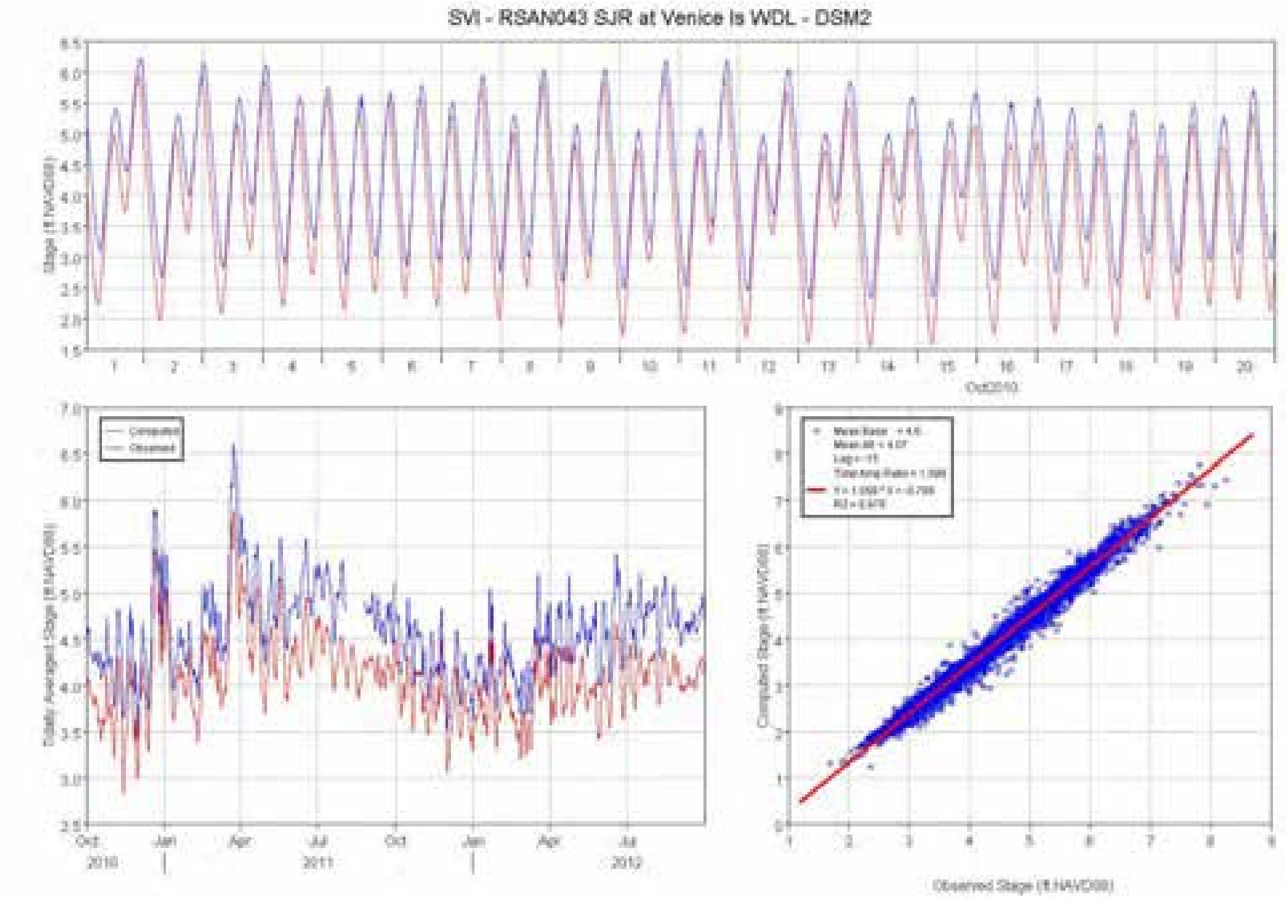
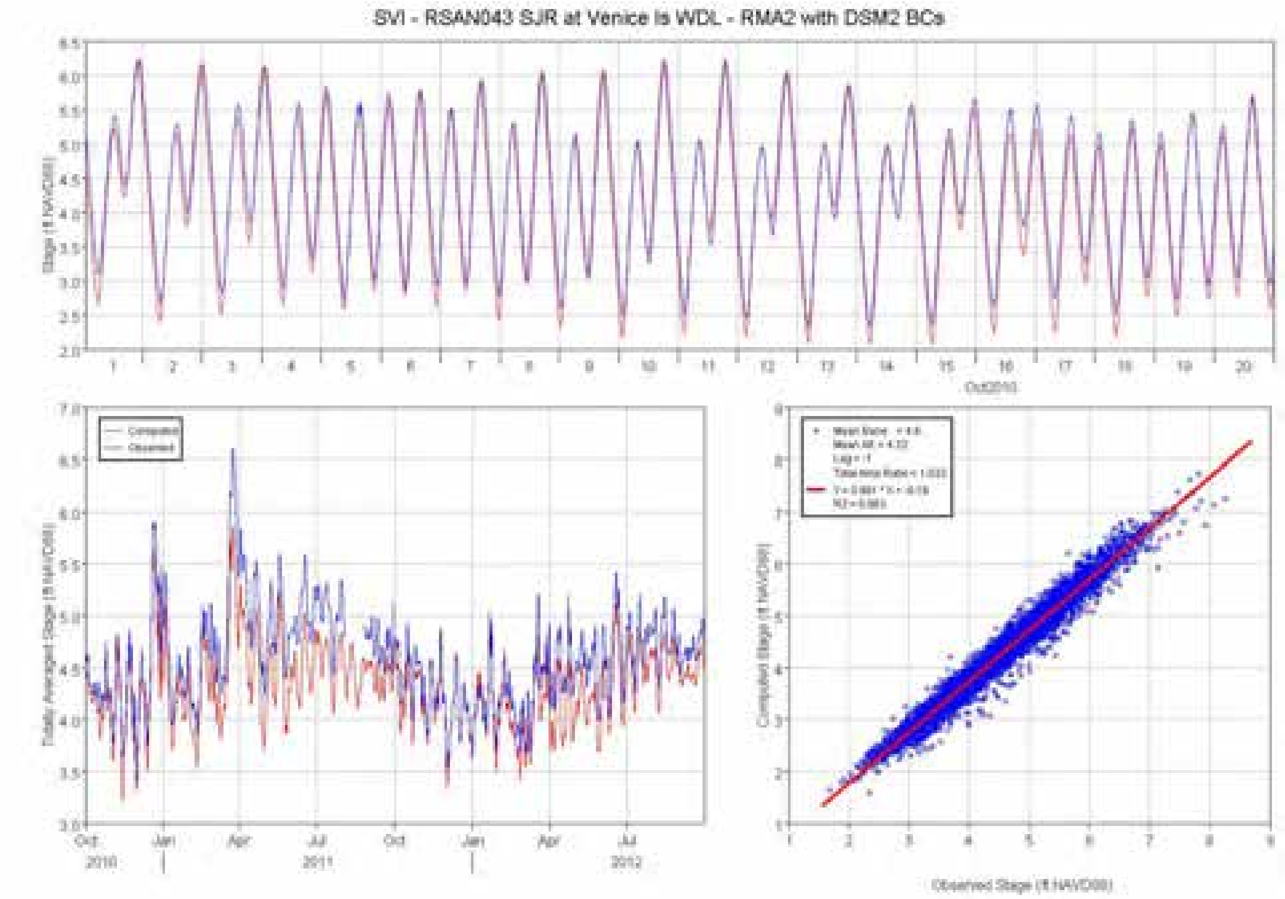


Figure 199 Computed (DSM2) and observed stage comparison plots for SJR at Venice Island.



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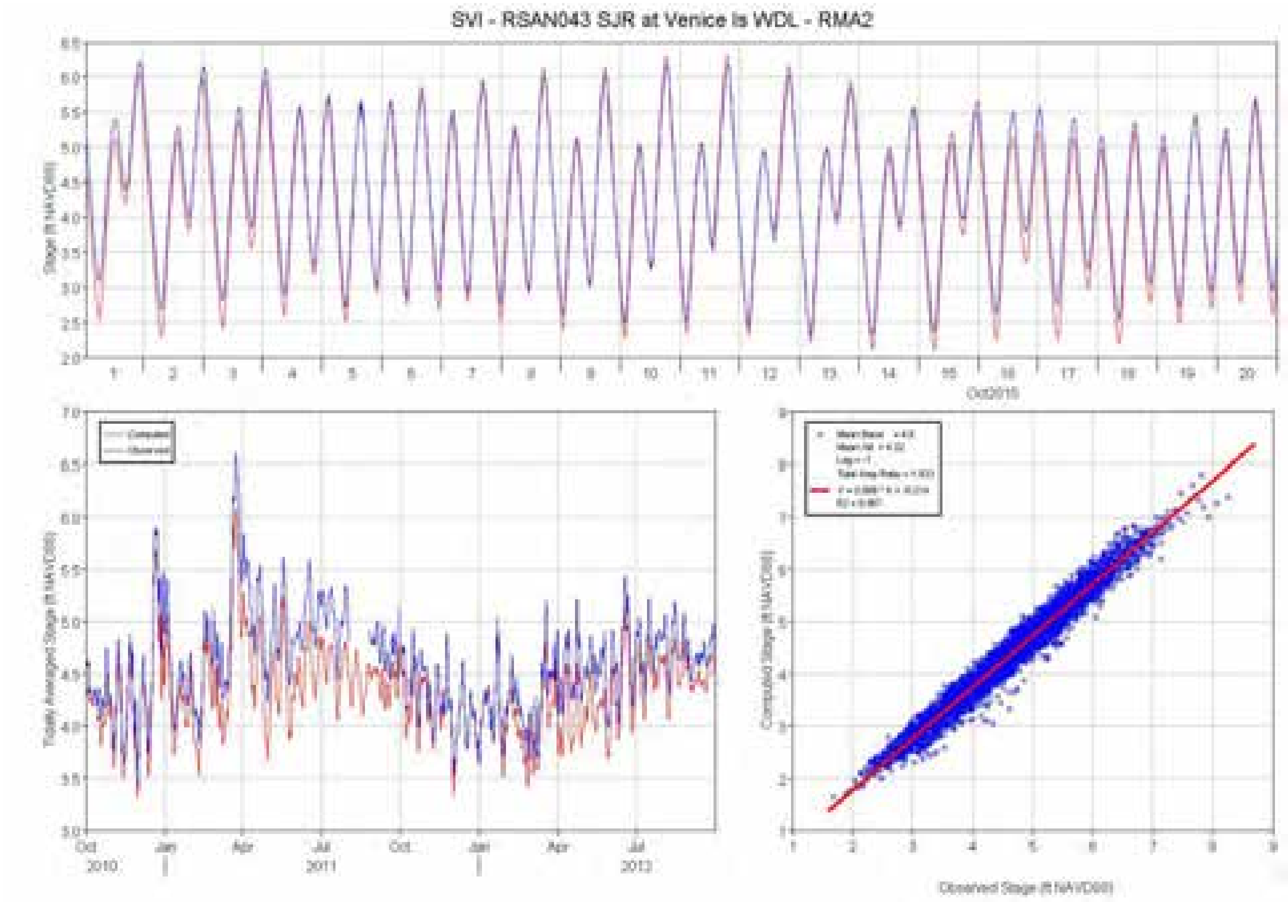


Figure 201 Computed (RMA2) and observed stage comparison plots for SJR at Venice Island.

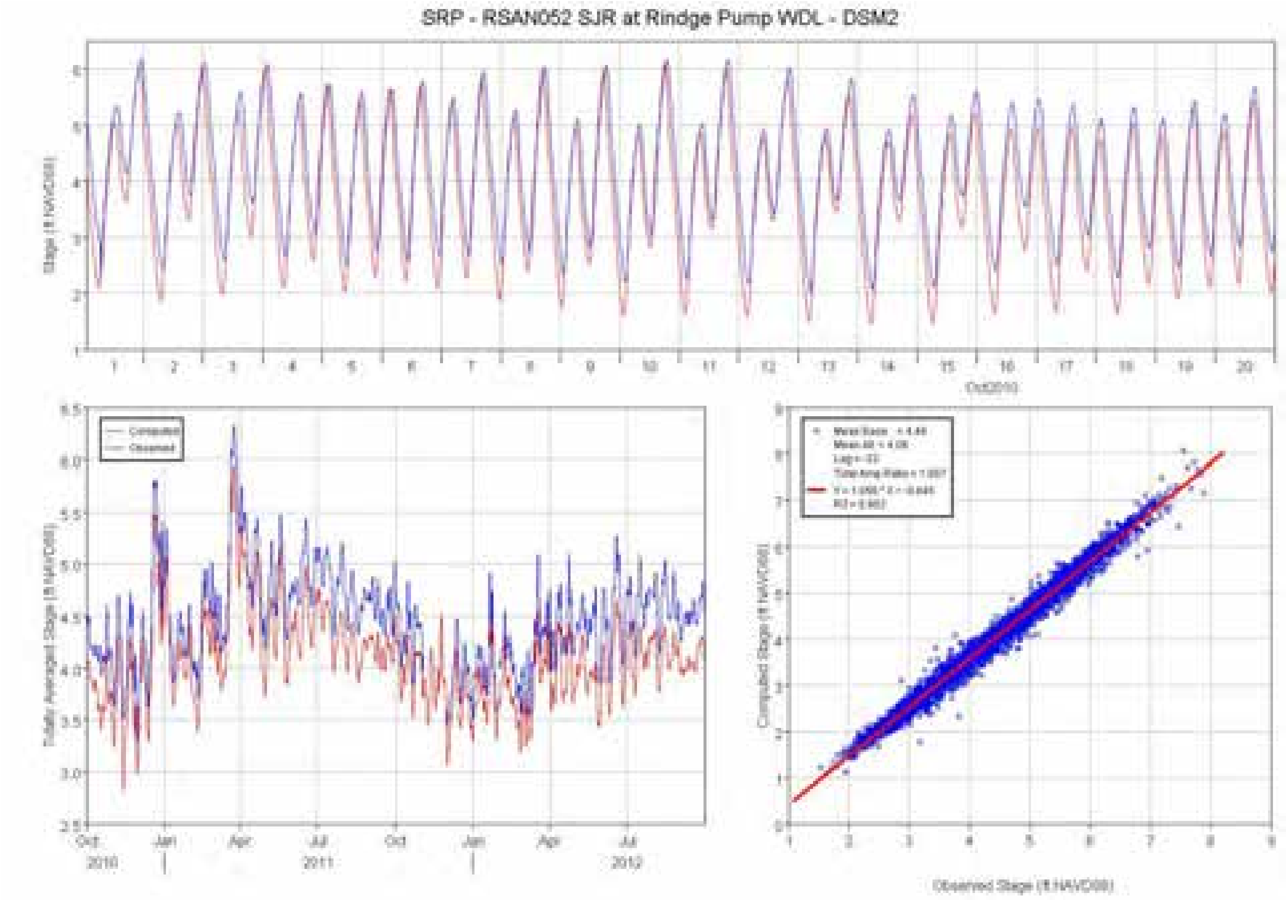


Figure 202 Computed (DSM2) and observed stage comparison plots for SJR at Rindge Pump.

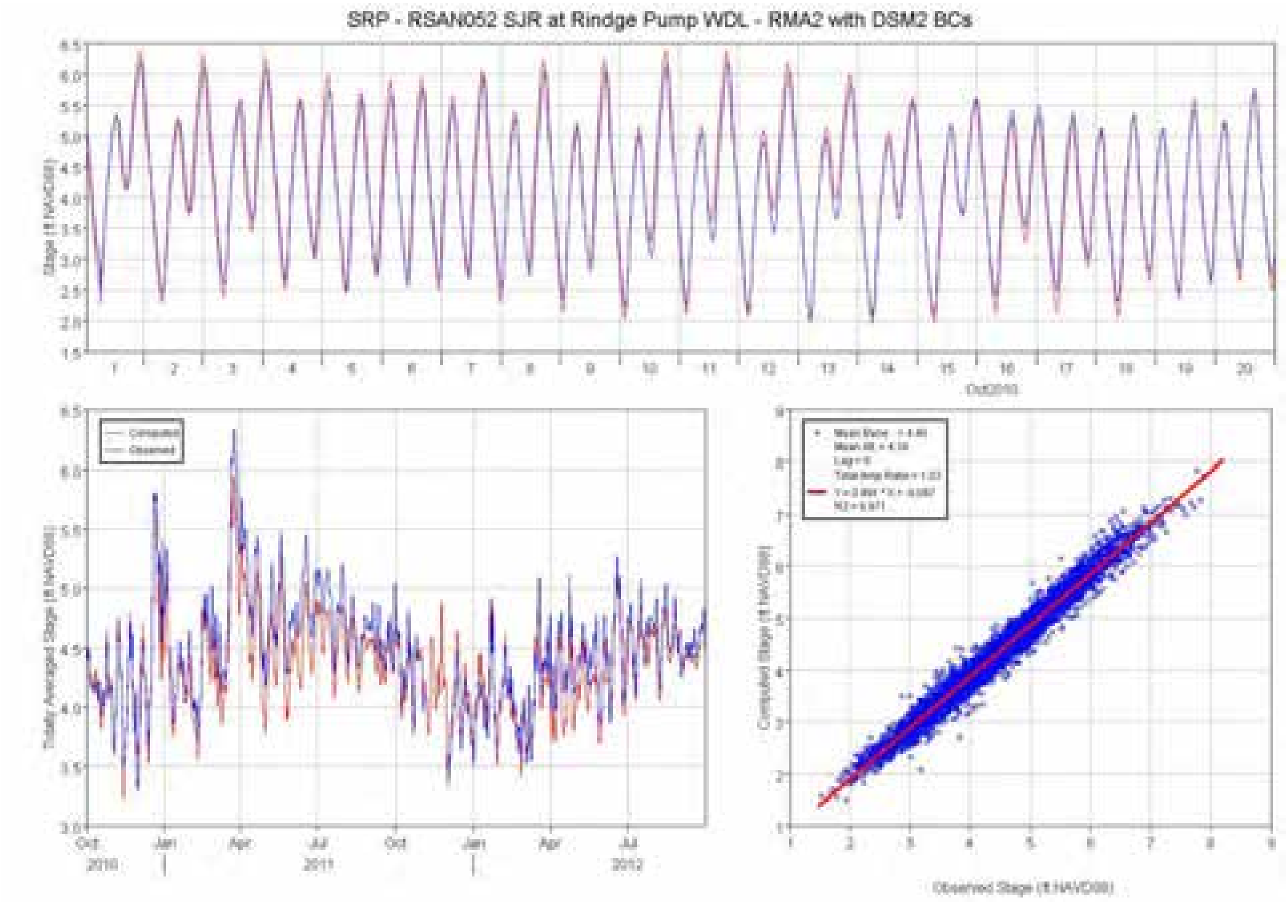


Figure 203 Computed (RMA2 with DSM2 BCs) and observed stage comparison plots for SJR at Rindge Pump.

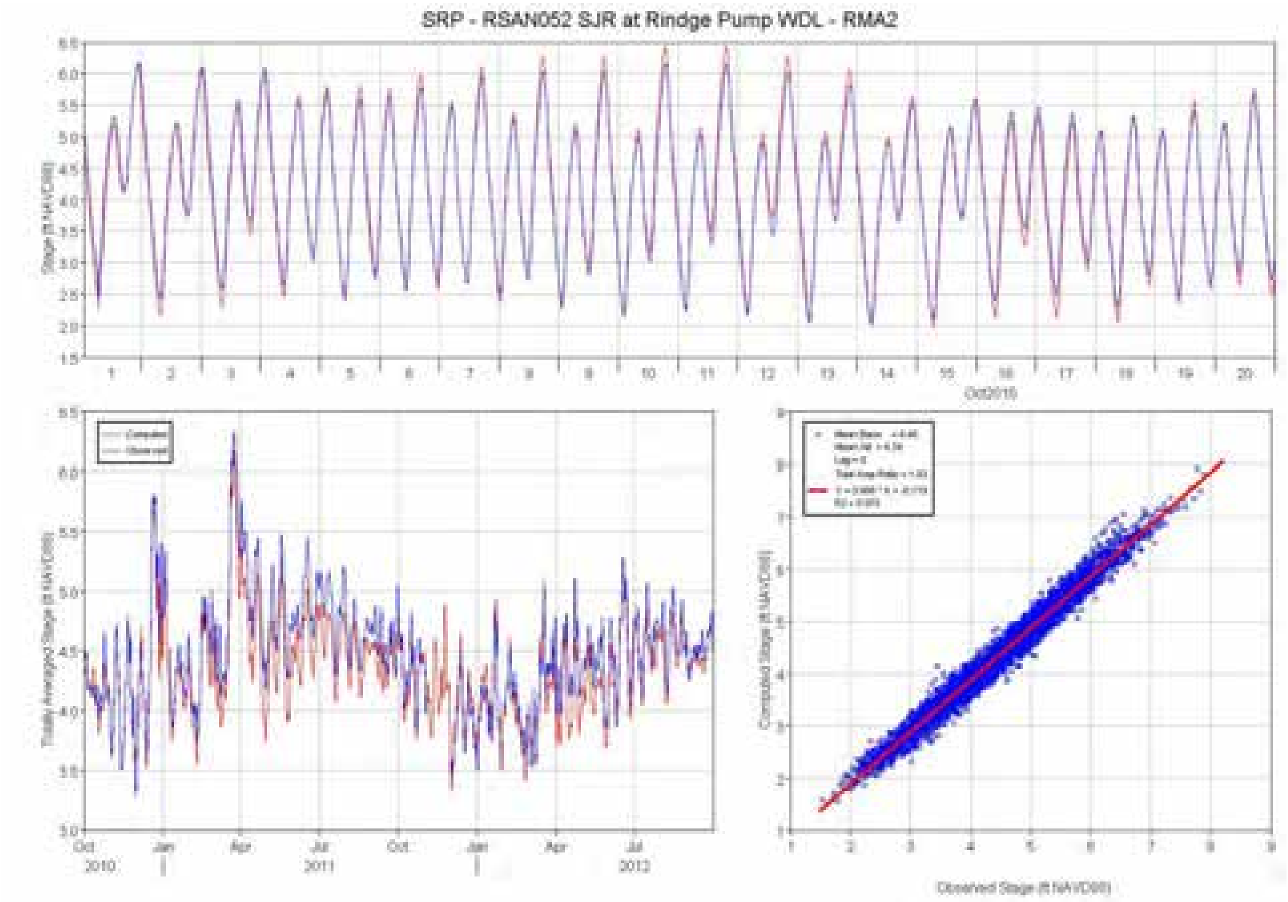


Figure 204 Computed (RMA2) and observed stage comparison plots for SJR at Rindge Pump.

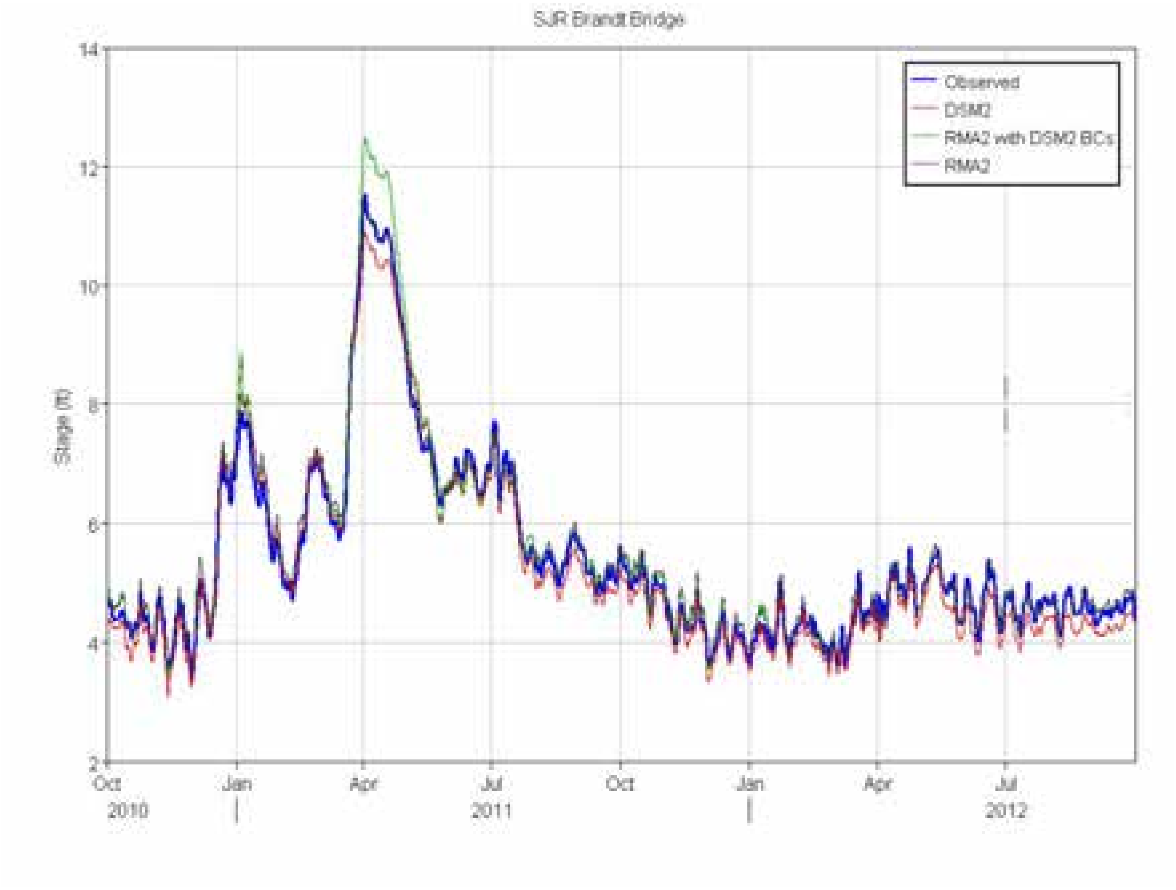


Figure 205 Computed (DSM2) and observed stage comparison plots for San Joaquin River at Brandt Bridge.

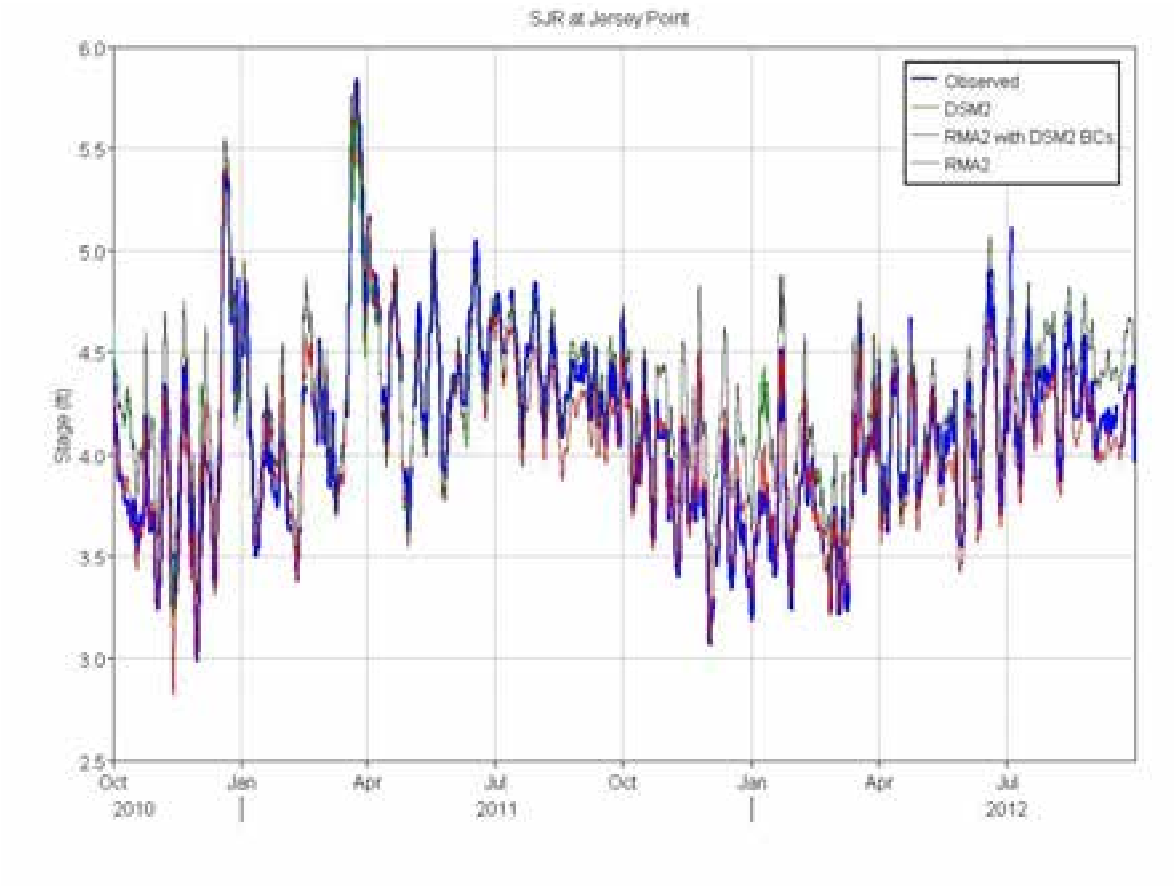
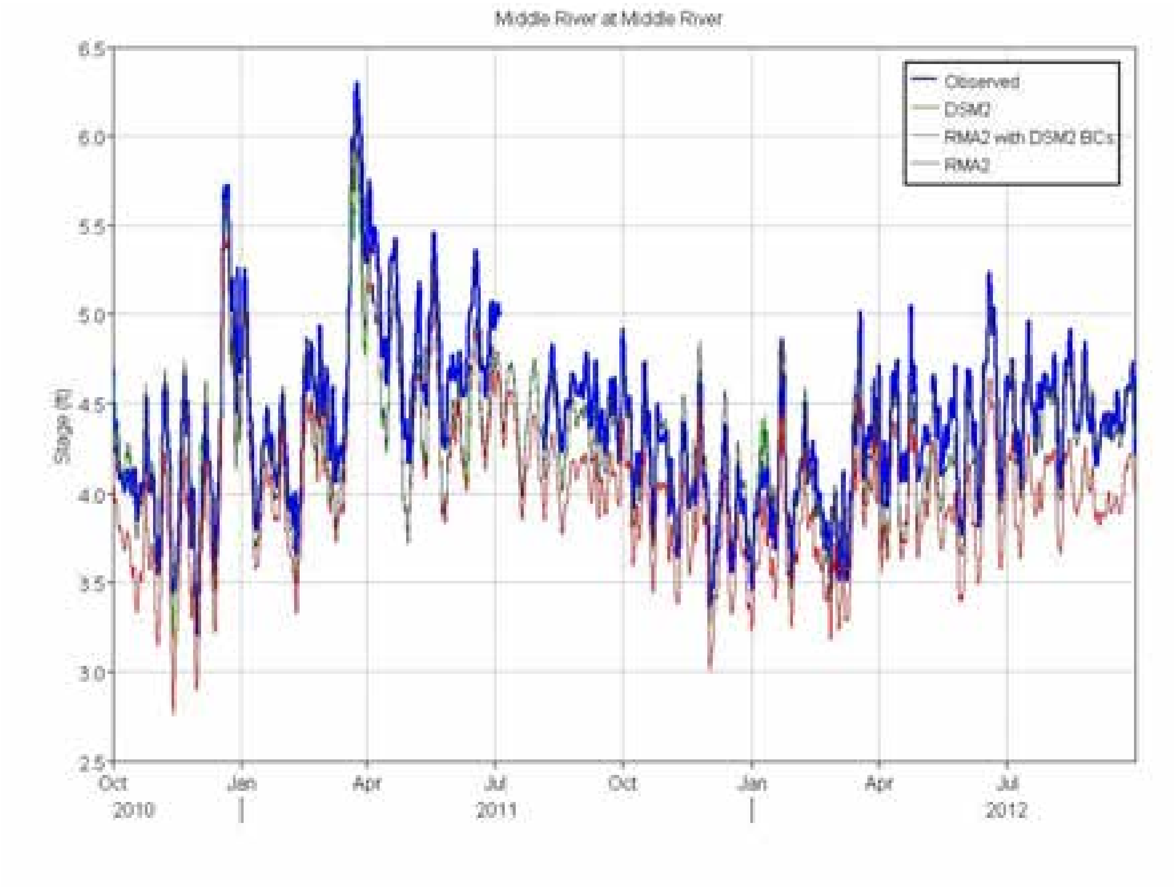


Figure 206 Computed (DSM2) and observed stage comparison plots for SJR at Jersey Point.



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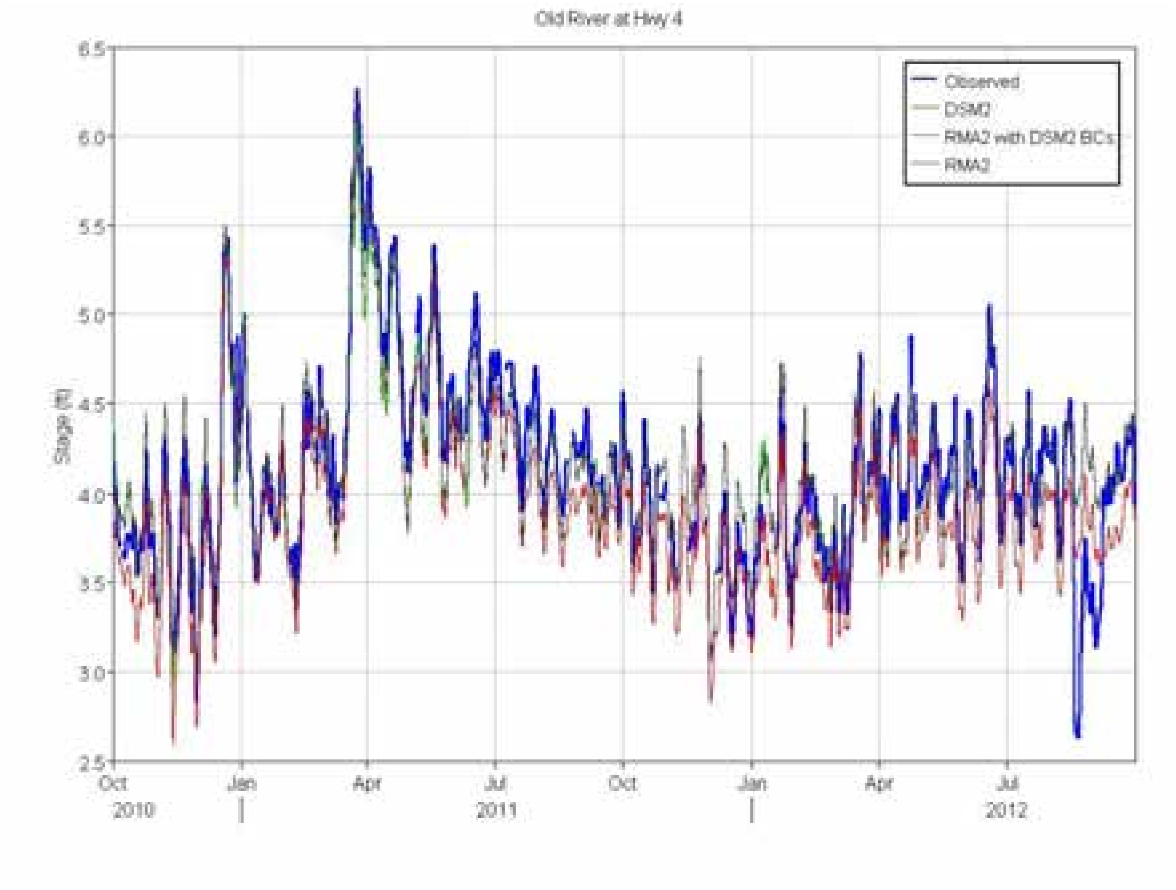

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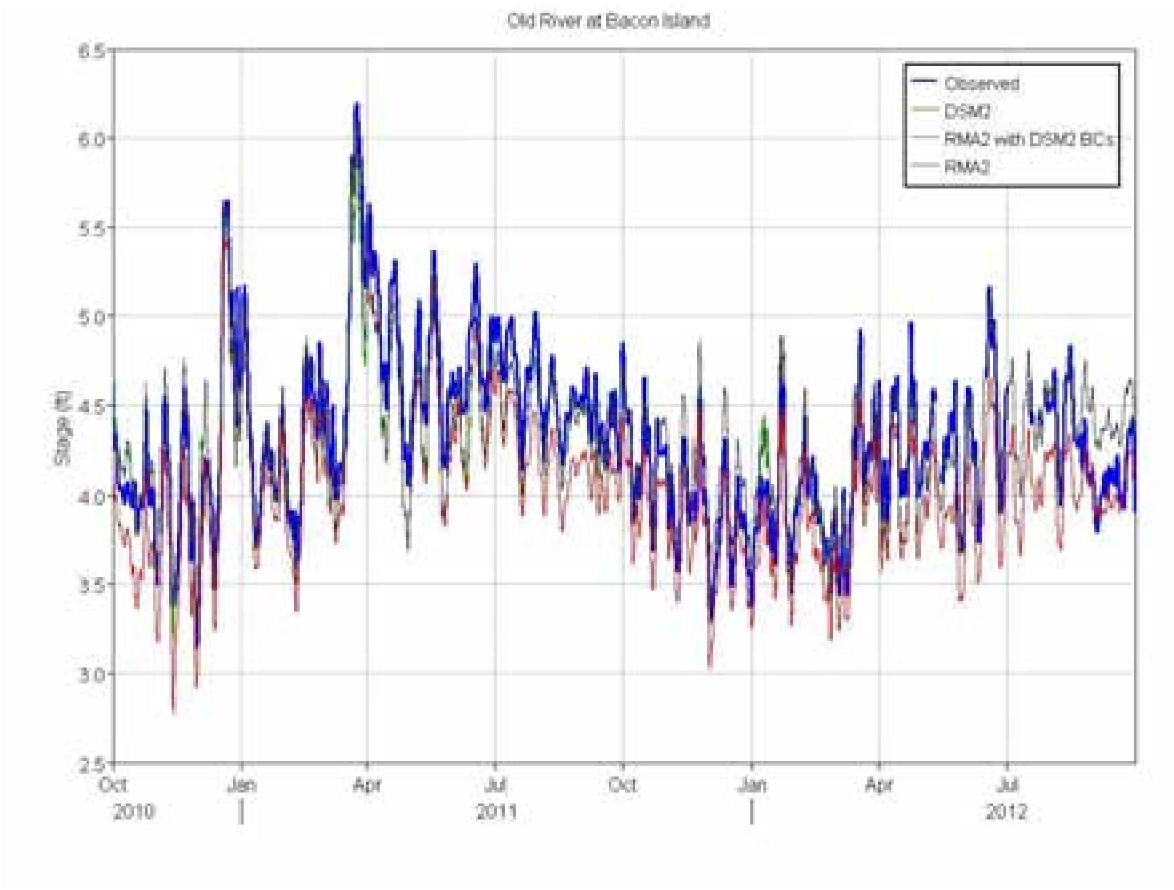
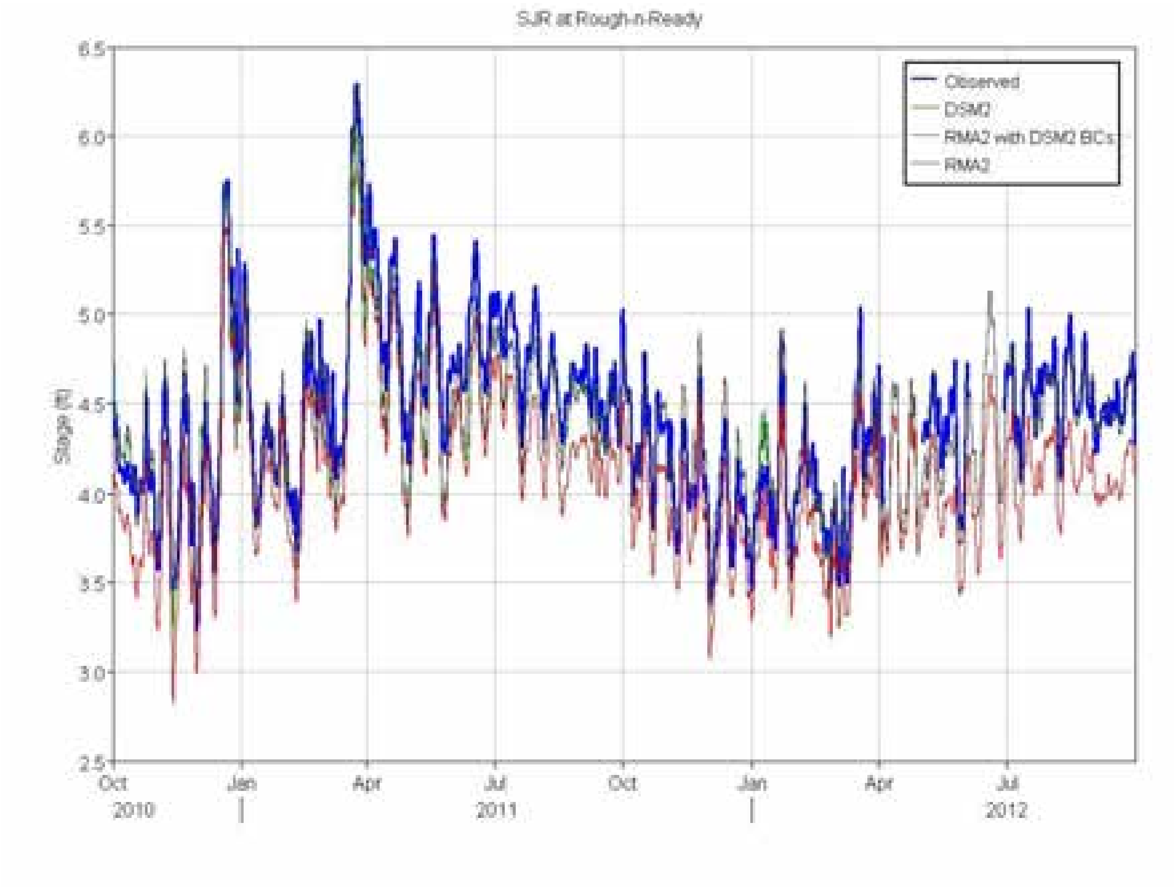


Figure 209 Computed (DSM2) and observed stage comparison plots for Old River at Bacon Island.



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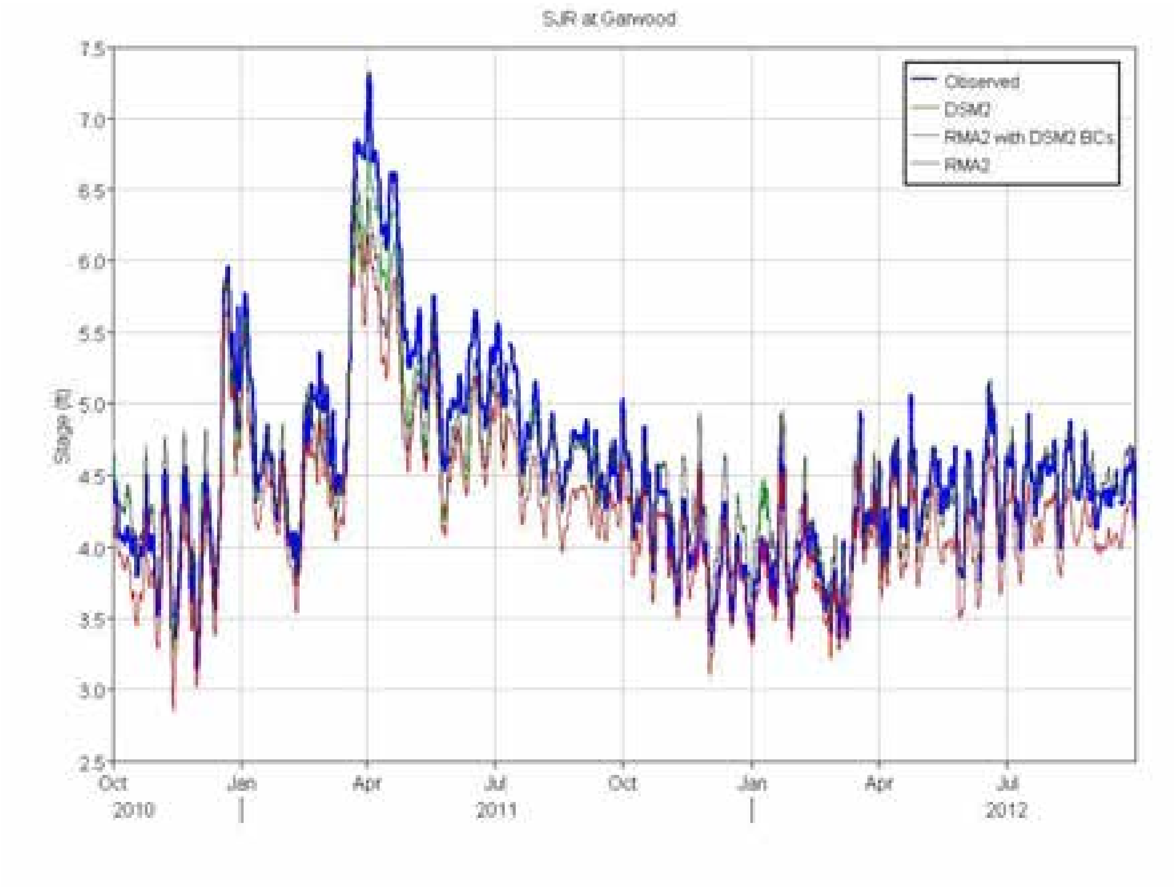


Figure 211 Computed (DSM2) and observed stage comparison plots for SJR at Garwood.

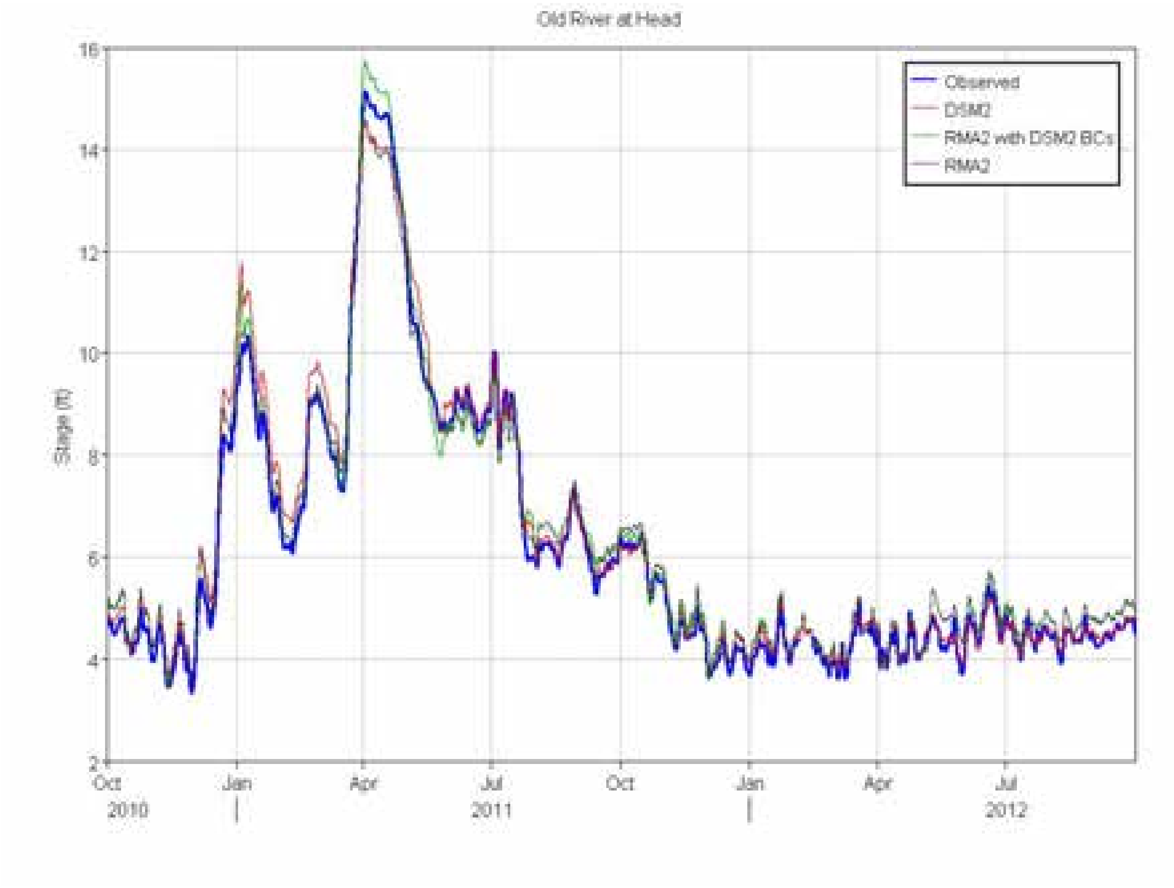


Figure 212 Computed (DSM2) and observed stage comparison plots for Old River at Head.

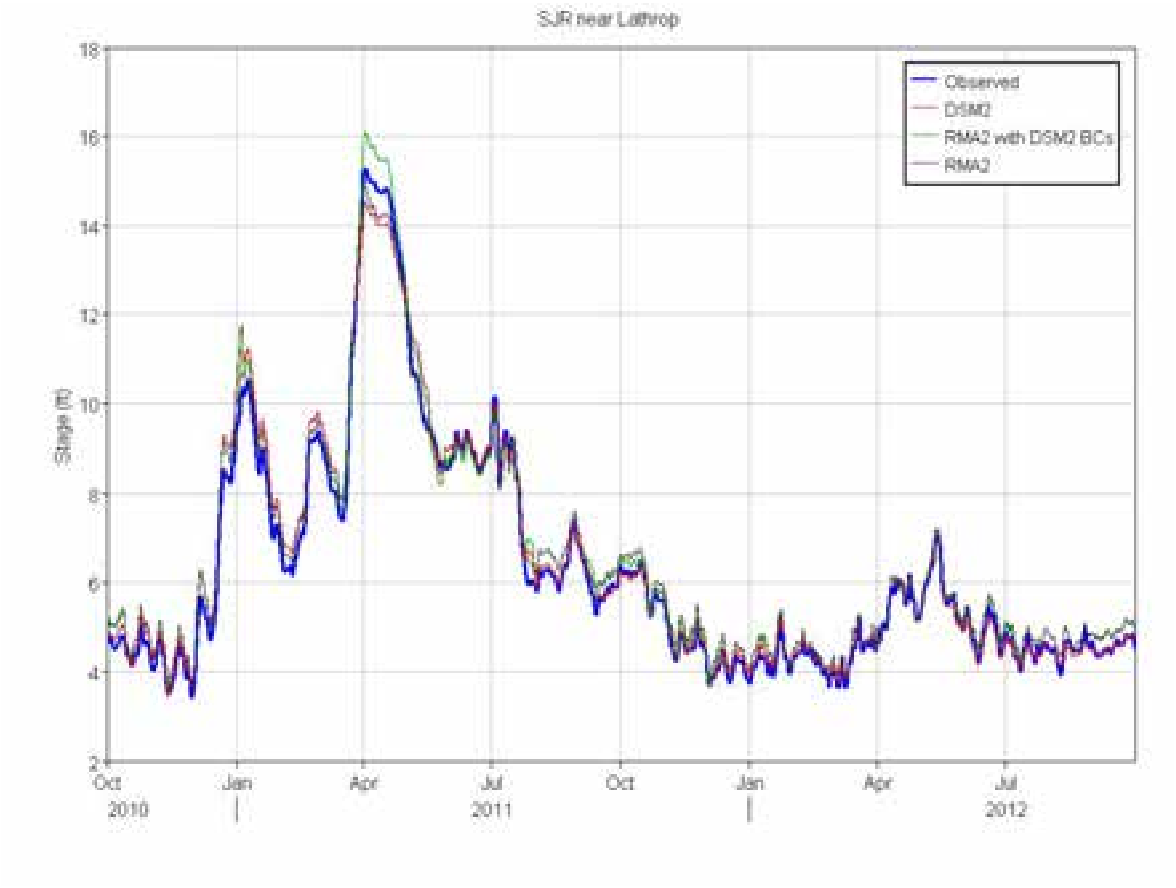
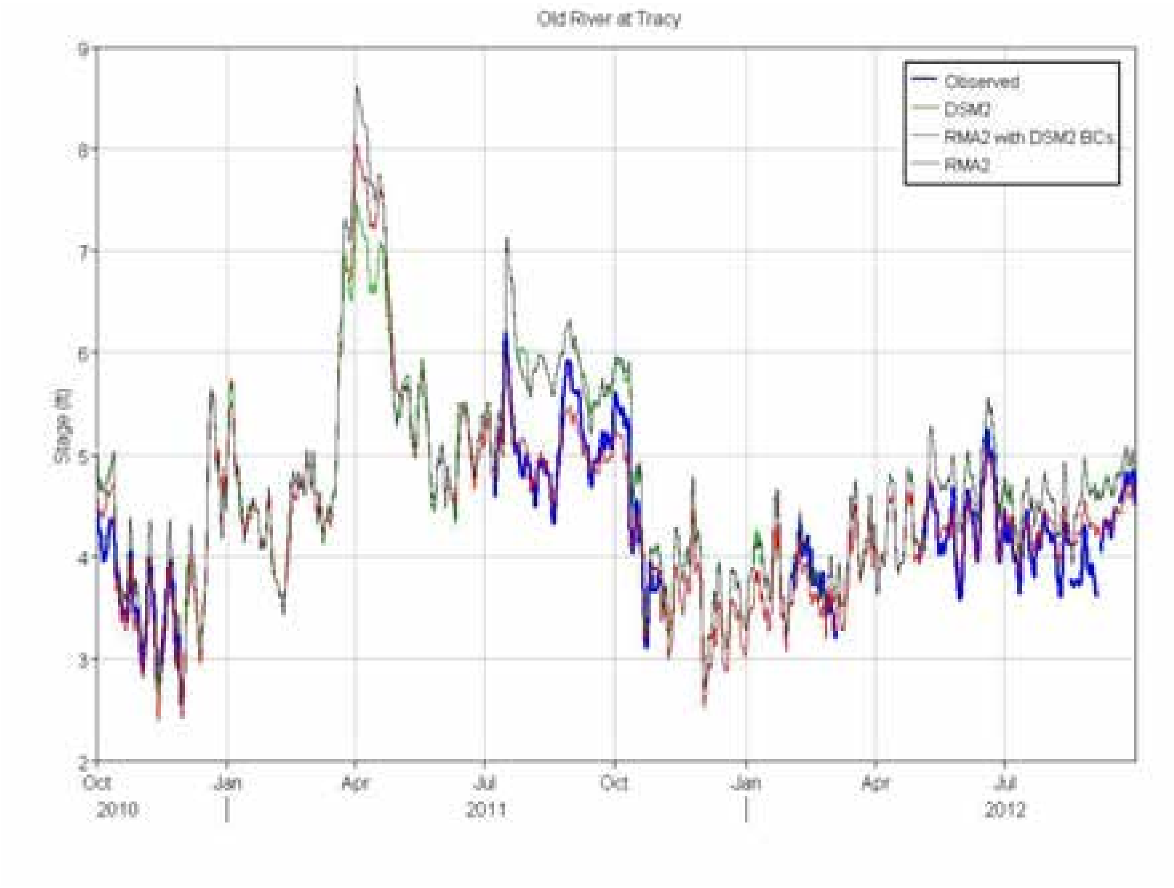


Figure 213 Computed (DSM2) and observed stage comparison plots for SJR near Lathrop.



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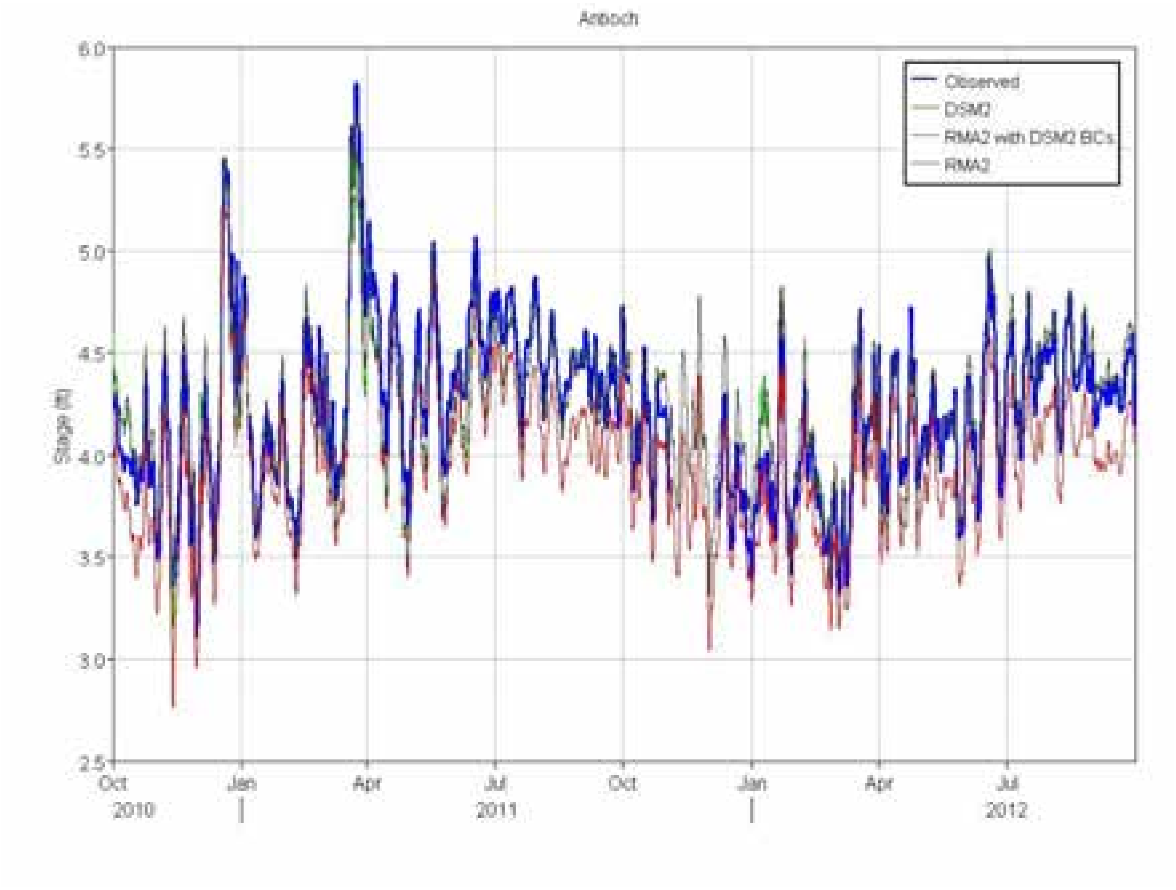

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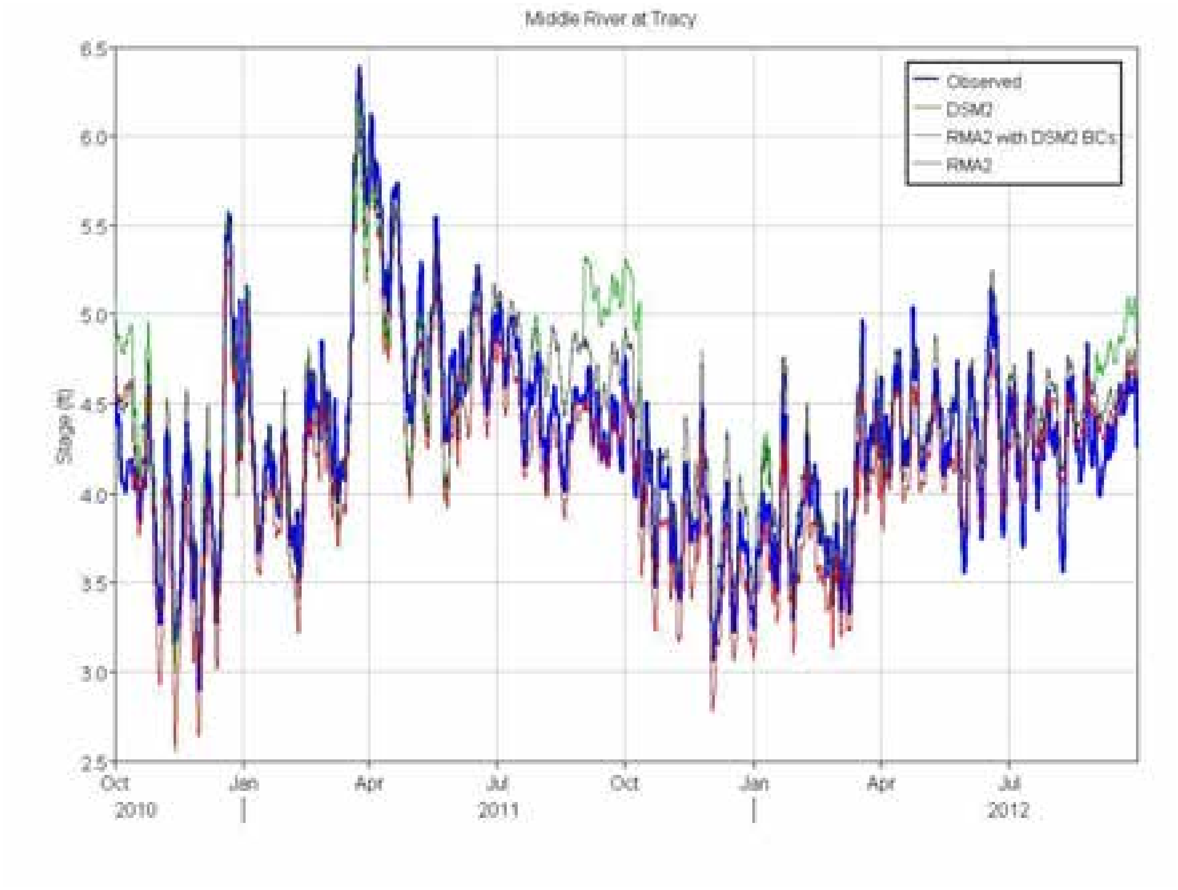

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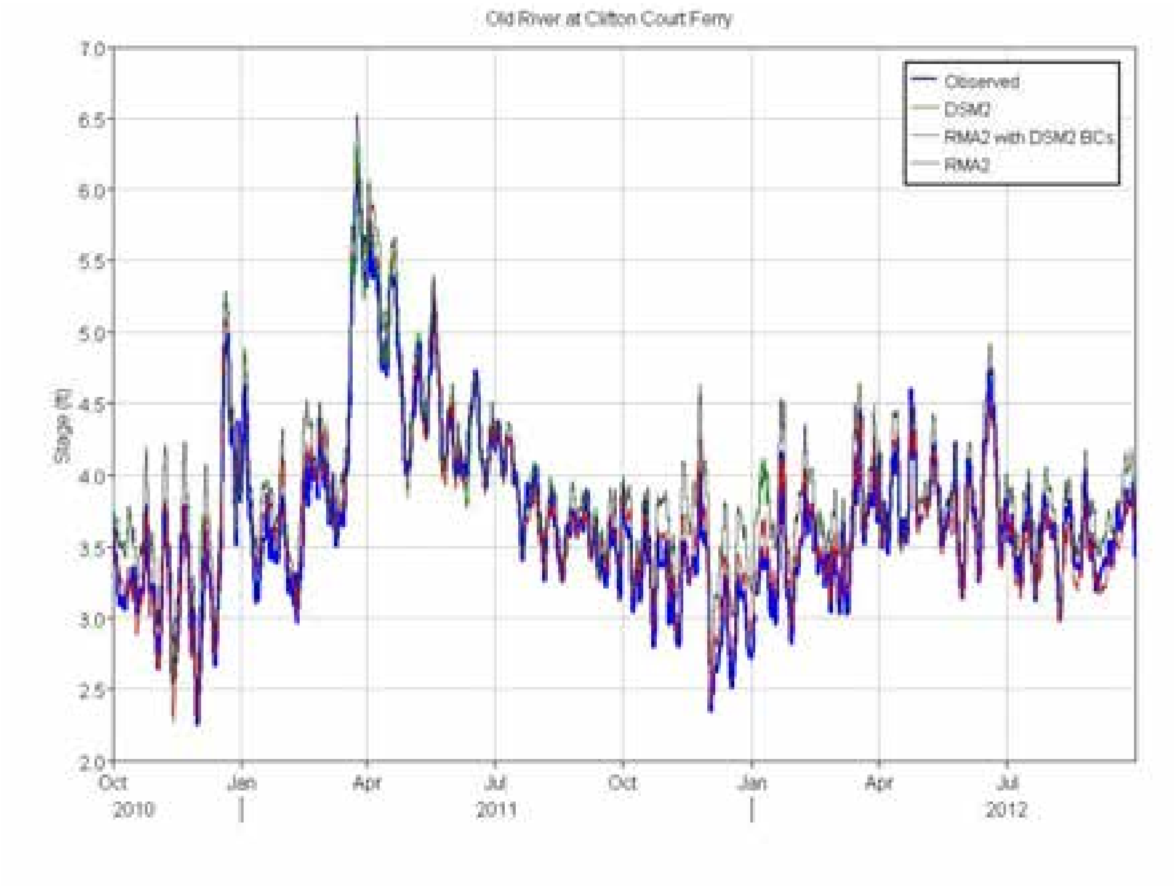


Figure 217 Computed (DSM2) and observed stage comparison plots for Old River at Clifton Court Ferry.

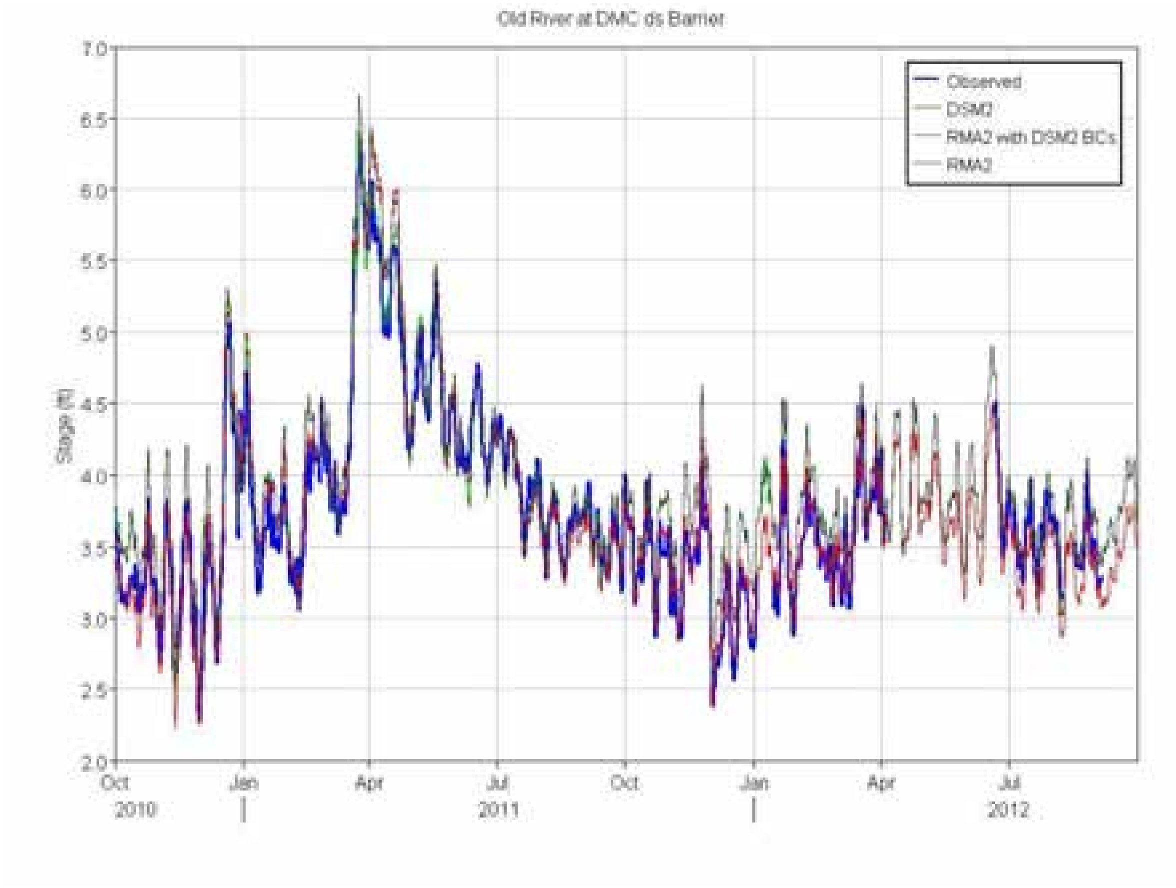
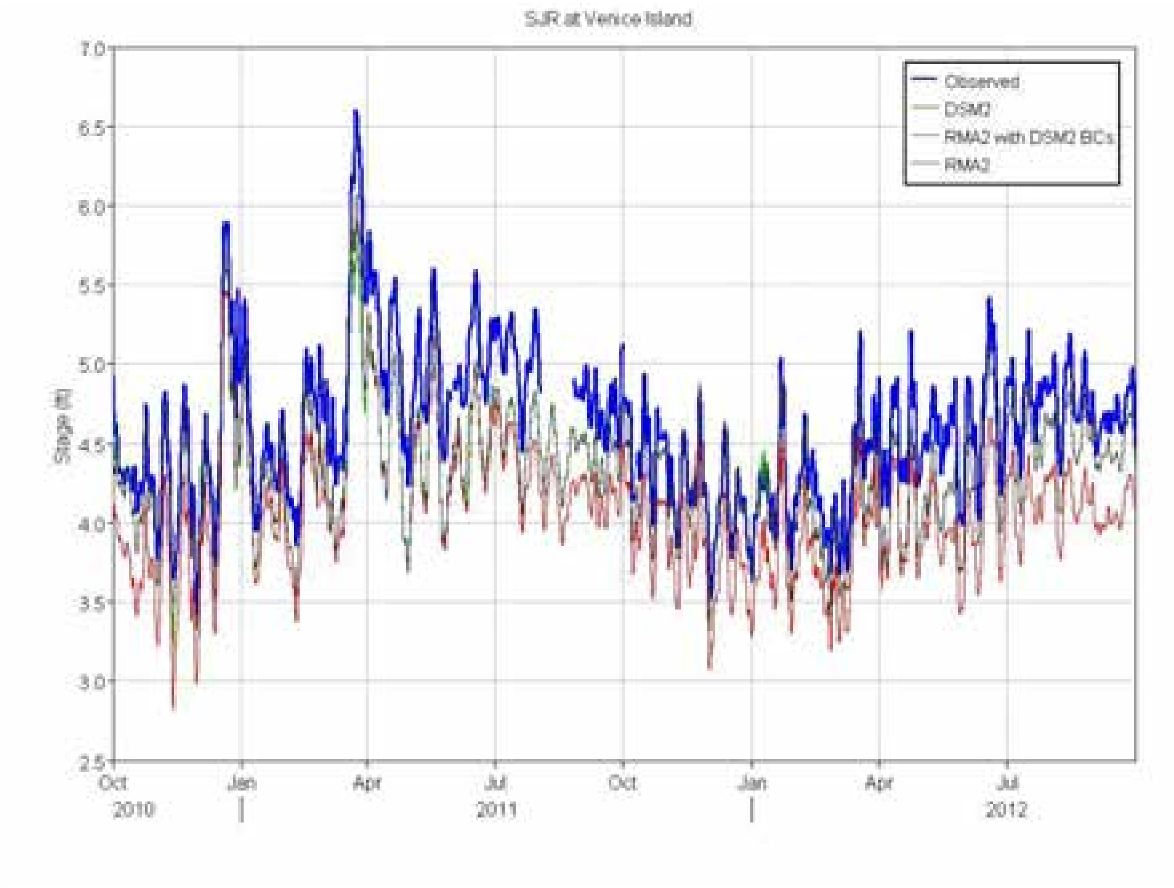


Figure 218 Computed (DSM2) and observed stage comparison plots for Old River at DMC ds Barrier.



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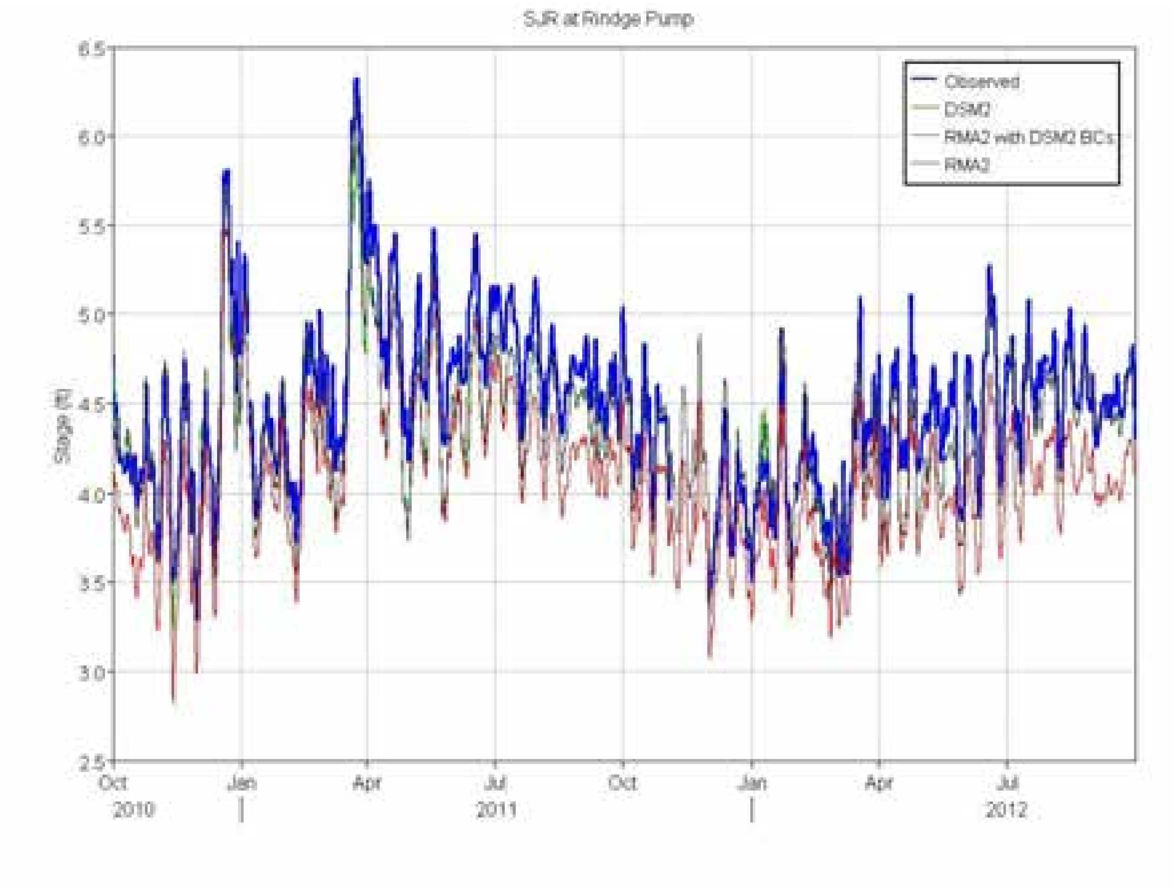

Figure 220 Computed (DSM2) and observed stage comparison plots for SJR at Rindge Pump.

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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.

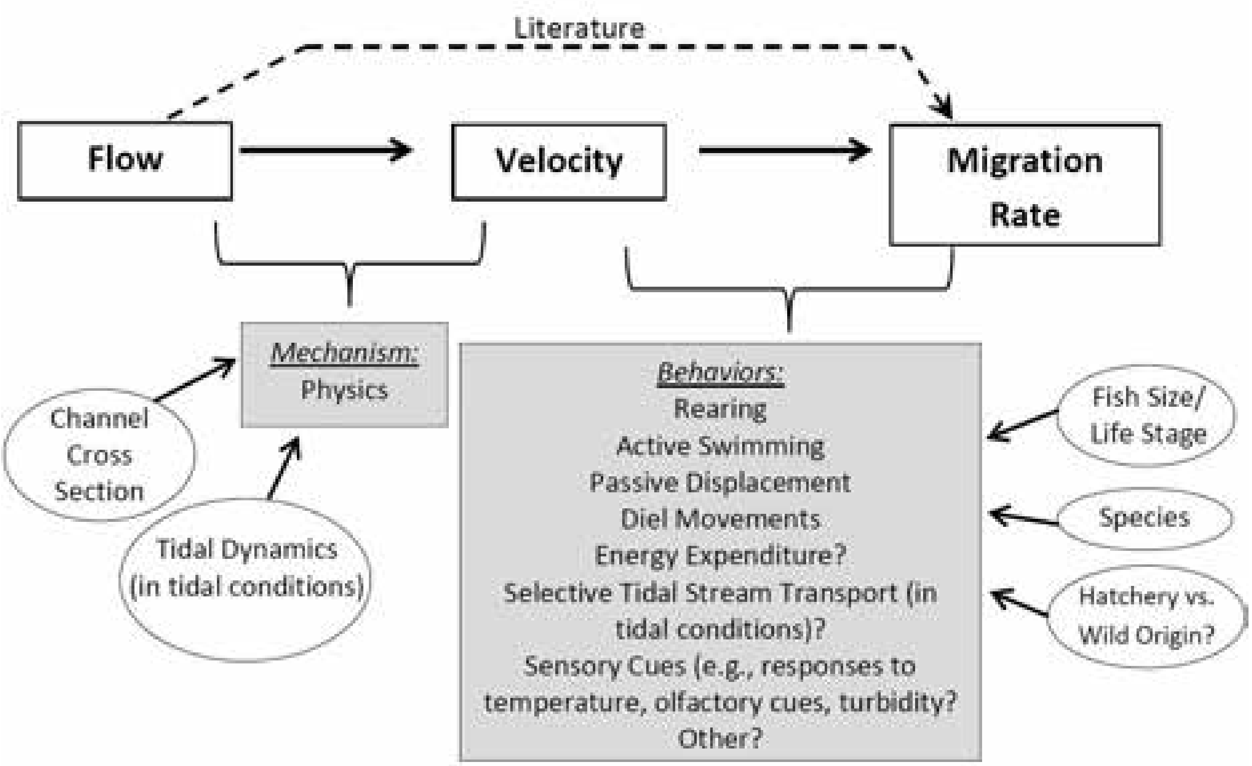

Figure D.2-1. Conceptual Model of the Effects of Channel Velocity on Juvenile Salmonid Migration Rate

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.

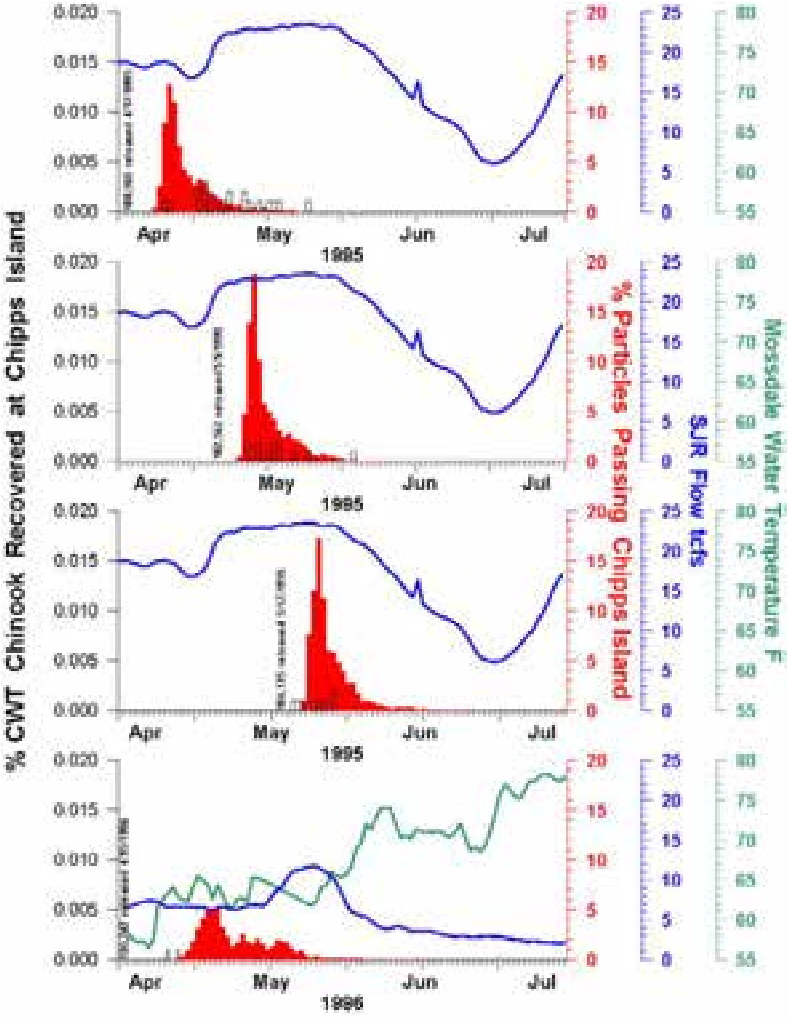

Figure D.6-1. Proportion of CWT-tagged Fish (hollow bars) Released into the San Joaquin River (SJR) During Two Relatively High-flow Years and Recovered in the Chipps Island Trawl, in Relation to Modeled Water Particle Travel Time (red bars), and SJR Flow (blue line) and Water Temperature (green line)

Source: DWR (2009)

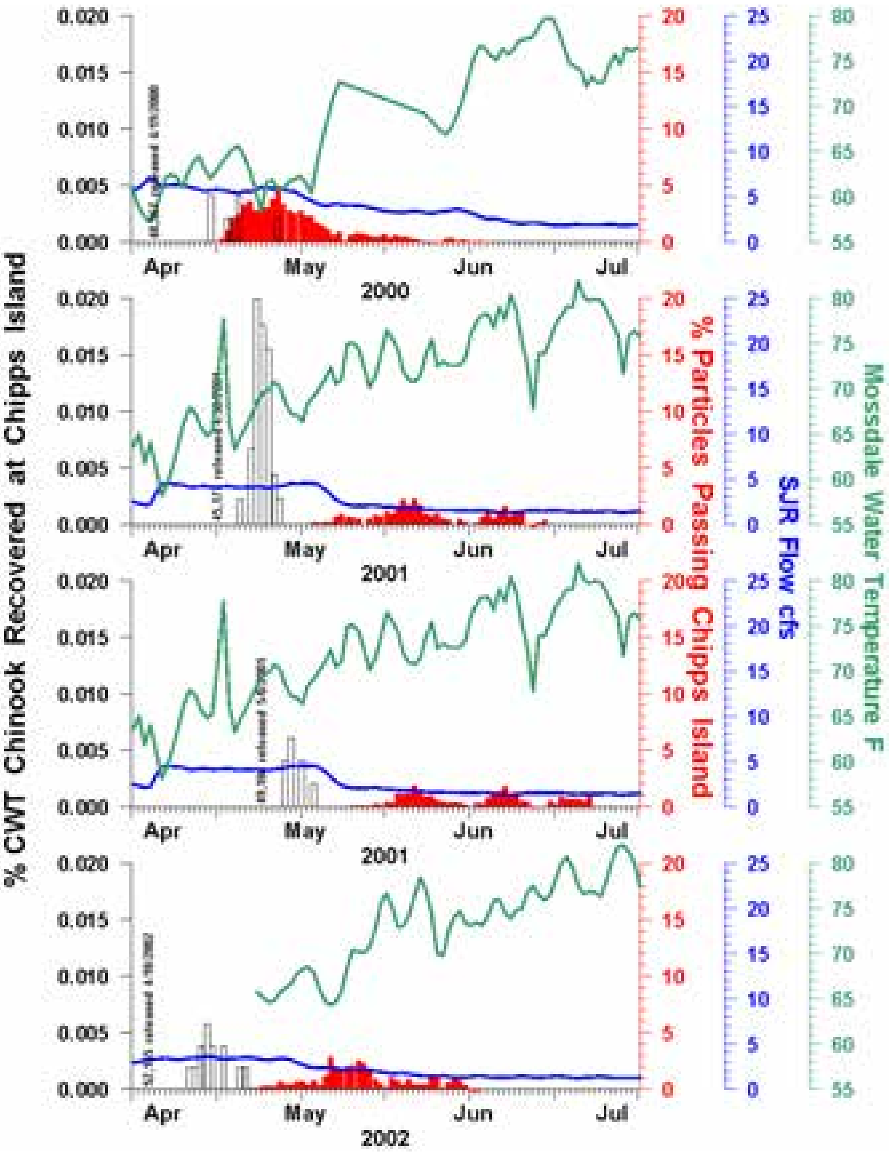

Figure D.6-2. Proportion of CWT-tagged Fish (hollow bars) Released into the San Joaquin River (SJR) During Three Low-flow Years and Recovered in the Chipps Island Trawl, in Relation to Modeled Water Particle Travel Time (red bars), and SJR Flow (blue line) and Water Temperature (green line)

Source: DWR (2009)

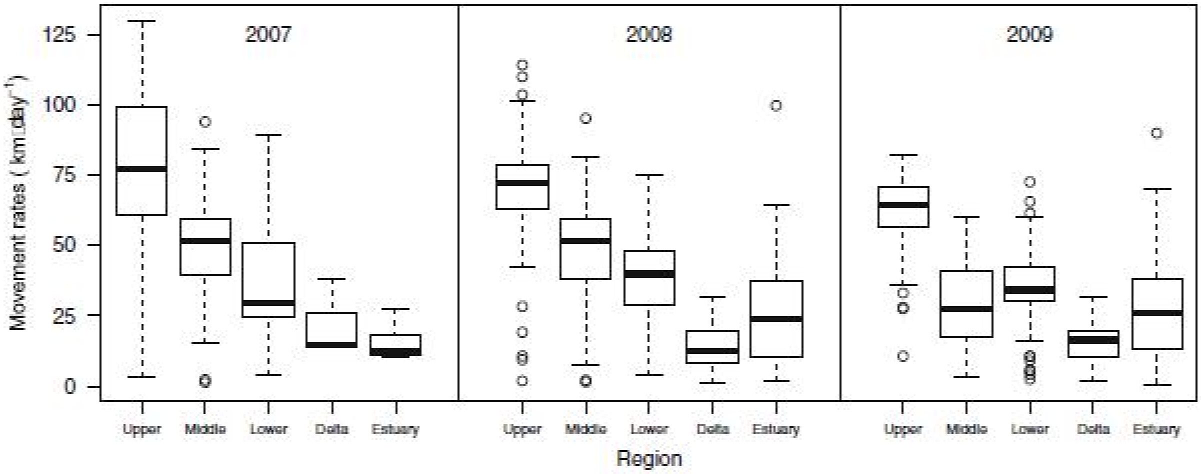

Figure D.6-3. Decreasing Migration Rates for Chinook Salmon in the Delta Compared to Migration Rates in Reaches Upstream of the Delta

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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Appendix E

Effects of Migration Behavior and Project Facilities on Juvenile Salmonid Survival

January 2017

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E.1 INTRODUCTION

The conceptual model relates water project operations to salmonid survival in the Delta in two primary ways: direct mortality caused by entrainment in or approach to the water export facilities, and an indirect effect of water project operations via influences on hydrodynamics in the Delta, which influences fish behavior, which in turn influences survival. The effect of water project operations on Delta hydrodynamics and the effect of changes in hydrodynamics on fish behavior are addressed in Appendices B and D, respectively. In this section, we address what is known about direct mortality from the water export facilities, how survival through the Delta may be related to fish behavior during migration, and how survival may be associated with water project operations overall.

For the purpose of this analysis, fish behavior is classified as the migration route selected and migration rate (Figure E.1-1). The conceptual model hypothesizes that fish that use the Interior Delta or pass through or near the water export facilities have lower survival than fish that remain in the mainstems of the San Joaquin River or Sacramento River. Migration route may influence survival by exposing migrating juvenile salmonids to regions that differ in factors such as predation pressure, entrainment risk into the State Water Project (SWP) or Central Valley Project (CVP) export facilities and other water diversions, water quality, and growth potential (Figure E.1-1). Regions of higher predation pressure or entrainment risk are hypothesized to decrease overall survival through the Delta, while using regions of higher growth potential may increase post-Delta survival if juvenile salmonids rear substantially during their migration through the Delta. Our scope of analysis was restricted to migration survival through the Delta, so the impact of using regions of higher growth potential on post-Delta survival is not investigated here. The conceptual model hypothesizes that migration rate may influence survival in one of two ways: a slow migration rate may lower survival by prolonging exposure to mortality risks such as predation or entrainment in the water export facilities, or it may increase survival by increasing exposure to favorable growing conditions (Figure E.1-1, Table E.1-1). The latter possibility is expected to affect primarily post-Delta survival, so this hypothesis is not investigated here. It is possible that other factors may link water export operations to survival in the Delta, in addition to migration route and migration rate (e.g., Table E.1-1). However, additional factors are either outside the scope of this gap analysis or there was insufficient time to evaluate them.

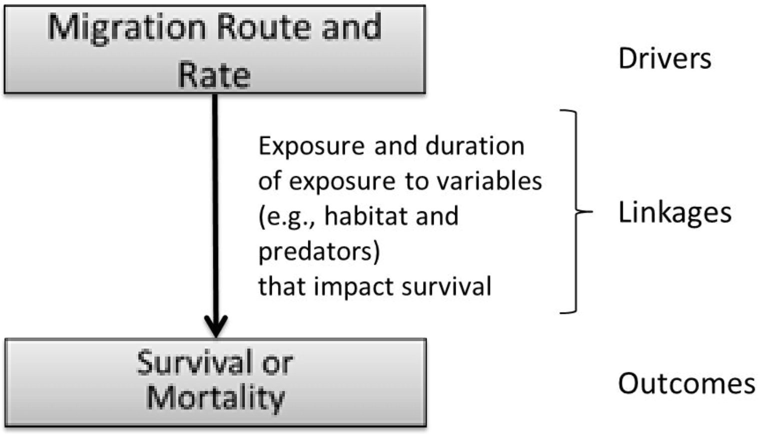

Figure E.1-1. Conceptual Model Depicting General Relationships Between Drivers, Linkages, and Outcomes Related to Survival That Were Evaluated By the Survival Sub-team

Table E.1-1. Drivers, Linkages, and Outcomes Considered Within Appendix E

Drivers	Linkages	Outcomes
• Juvenile migration route • Juvenile migration rate • *Migration timing* • *Timing of Delta entry* • *Delta residence time* • *Rearing location* • *Population scale outcomes depend on the spatial/temporal heterogeneity of individual outcomes*	• Exposure to variables (e.g., habitat and predators) that affect differential survival between routes or between years for the same route • Duration of exposure to route-specific conditions that affect survival • *Parr-smolt transformation* • *Juvenile condition and fitness* • *Spatial and temporal heterogeneity in size/timing of migration relationships*	• Mortality • *Survival at ocean entry* • *Survival while in ocean* • *Population fitness and resilience* • *Life history diversity*

Note: Black text identifies focal components analyzed in the report and red italicized text indicates components considered significant but not addressed or addressed only to a limited extent in this report because of time, resource, or scope constraints.

In this appendix, we present data and findings that pertain to the conceptual model components that relate Delta survival to migration route and rate and to direct mortality from the facilities. We address survival rate per kilometer in different regions of the South Delta (i.e., south and west of the San Joaquin River, including the San Joaquin River mainstem), the total through-Delta survival in different routes through the Delta, and survival in and around the water export facilities. We also examine findings that compare survival rate per kilometer to migration rate (i.e., travel time per kilometer), and compare findings from different regions throughout the Delta. We compare the findings to the predictions from the conceptual model.

In addition to focusing on how survival relates to migration route and rate in our conceptual model, we also address the larger question of how survival may relate directly to water export operations in terms of exports, inflow, the ratio of San Joaquin River inflow to exports (I:E), and the ratio of exports to total Delta inflow (E:I); barriers and flow in Old and Middle rivers (OMR) are addressed briefly but are not explored in depth. These analyses explore whether there is a relationship between these measures of water export operations and survival without limiting such a relationship to the conceptual model linkages of migration route, migration rate, and direct mortality, and accommodate the possibility that other linkages between water export operations and survival may exist. These analyses focus on survival in the South Delta on several spatial scales, under the realization that survival may respond to different factors in different regions of the Delta.

This appendix is organized as follows. We first describe the type of information that is available for assessing the survival components of the conceptual model, and both the potential and the limitations of the information available. We then provide an overview of the survival data available and the hydrological conditions (namely Delta exports and inflow) associated with the survival data. The bulk of this appendix consists of detailed discussions of what the available data show regarding survival relative to migration route and rate and measures of water export operations, and how these findings compare to the conceptual model. We end with a discussion of the findings and conclusions, including suggestions for future data and analyses that may fill gaps in our understandings of the system.

The types of information available for assessing the survival components of the conceptual model consist of published, peer-reviewed journal articles; publicly available but unpublished technical reports of survival analyses; and new compilations (produced by the Salmonid Scoping Team [SST] for this report) of survival and hydrological data. The survival data used for the new compilations come from previously published analyses and articles or reports of individual survival studies, of which some reports are publicly available and others are still in draft form or available only via personal communication. Although some of the data being compiled are taken from peer-reviewed publications, some are taken from agency reports of the studies underlying peer-reviewed publications because the publication focused on a different aspect of the study (e.g., different spatial scale). Analysis of these new data compilations is not peer-reviewed at this time because it has been performed directly for this report. Thus, while considerable attention is given to these new data compilations in this report to present the current support, or lack thereof, for the survival components of the conceptual model, we place more weight on the peer-reviewed results than on these new, non-peer-reviewed analyses. However, some members of the SST feel that some agency reports should receiver higher weight, despite not being peer-reviewed for journal publication.

There are several types of analysis that may be considered for the compiled survival data presented here, depending on the specific linkage or level of the conceptual model being assessed. Commonly used methods include regression and correlation analysis. Mean regression may be appropriate to explore a hypothesized relationship between the average survival and an independent variable or driver, such as export rates. In particular, regression assumes that the independent variable is set at known values without error, as is typical in experimental rather than observational studies. However, by conditioning on the observed values of the independent variable, regression techniques may be appropriate even in cases of observational rather than experimental data. Quantile regression and factor-ceiling analysis are similar to regression of the mean but model a specified quantile (e.g., maximum) of the response distribution as a function of the independent variable, rather than the mean response. For example, factor-ceiling analysis seeks a limiting relationship between the independent variable and the response (survival), such that the value of the independent variable imposes a limit on the range of the distribution of the response (typically the maximum), but not the mean of that distribution. Correlation analysis explores associations between two variables that are both varying, rather than assuming that one variable is observed at known levels and drives the distribution (e.g., mean or maximum) of the other variable; correlation analysis is often considered to be more appropriate than regression in ecological studies where most data are observational rather than experimental. Path analysis is a form of correlation analysis that can be helpful in identifying causal relationships, but it is most useful in relatively simple systems with few variables, rather than a complex ecosystem such as the Delta.

Both time constraints and data constraints limit our analysis of the newly compiled survival data presented in this section. The fact that these analytical methods have not previously been implemented with these data is a gap in assessment of our conceptual model; additionally, the effort needed to perform these analyses exceeds the time available for this report. Some of these analyses are in the process of being implemented outside of the SST process, as is analysis of more recent acoustic tag (AT) data (i.e., 2013, 2014, and 2015 data for both Chinook salmon and steelhead), but have not yet been completed. Perhaps more importantly, many of the data presentations included in this appendix demonstrate that there is too little variability in the observed value of the explanatory variable (e.g., export levels) to perform conclusive analysis using available data. Instead of providing quantitative analytical results, we provide qualitative discussion of the observed patterns in the data based on visual examination of scatterplots, using the various analytical concepts described above to focus discussion. We use these qualitative observations to provide preliminary support (or lack thereof) for various conceptual model components, and to suggest what additional data or analyses would be useful in making more definitive conclusions.

E.2 OVERVIEW OF THE DATA AVAILABLE

Several types of data are used in this appendix, including data on survival probability, migration route, and travel time through the Delta for juvenile Chinook salmon and steelhead, and data on water export operations. We also describe results of statistical models that relate ocean recovery rates and adult escapement to conditions during Delta outmigration (assumed to be two and a half years before adult return). We first present an overview of the data on migrating salmonids, and then an overview of the data used on water export operations. We also describe the data used to compare juvenile salmonid survival to water export operations directly.

E.2.1 DATA ON SALMONID SURVIVAL, ROUTE USE, AND MIGRATION RATE

Much of the information used to develop this section of the report is based on survival estimates derived from two different study methodologies. This subsection provides a summary of salmonid survival studies in the Delta. Most of the information on survival in the South Delta (west and south of the San Joaquin River, and including the San Joaquin River) is based on the results of coded wire tag (CWT) and AT studies of juvenile fall-run Chinook salmon from the San Joaquin River basin. Results of two years of AT studies for steelhead are also used. Survival in and through the Delta for smaller life stages (e.g., fry) of the late-fall, winter, spring, and fall runs of Chinook salmon has not been estimated using AT because the tags are still too large to implant in fry-sized fish (less than 70 millimeters [mm]). Spatially detailed survival and migration data within the South Delta are not available for populations from the northern Delta because of the relatively small numbers of acoustically tagged fish released upstream that survive to enter the South Delta. In addition, during previous AT studies, receiver arrays were not in place to estimate survival within certain areas of the interior and South Delta (Perry et al 2012; Michel et al. 2013).

All juvenile Chinook salmon and steelhead from the Central Valley must move through the Delta to reach the ocean (Figure E.2-1). Juvenile salmon of all runs occur throughout the Delta, although at slightly different times of the year, at different sizes, and with significant overlap (Fisher 1994; Yoshiyama et al. 1998; Pyper et al. 2013). The movement of Sacramento River water to the South Delta for supplying the export pumps, and the tidal mixing in the Delta, are expected to contribute to the mixing of juvenile salmon runs in the Delta. Table E.2-1 summarizes the availability of salmonid survival data for each of the salmonid runs in the Delta.

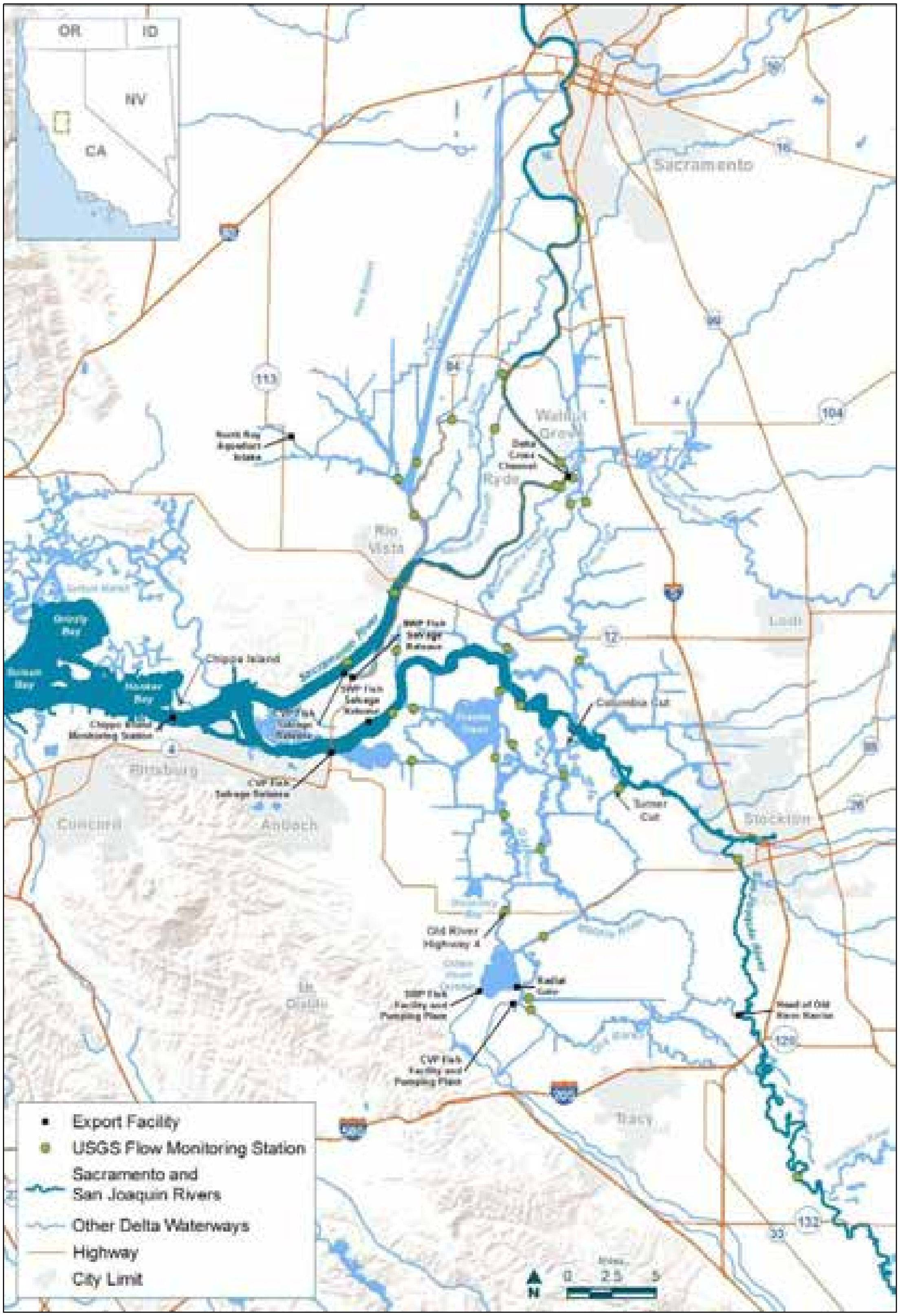

Figure E.2-1. Map of Sacramento-San Joaquin River Delta

Table E.2-1. Availability of Survival Study Information for Salmonids in the Delta

			Listed Populations			Non-listed Populations	
Life Stage	Tag	Region	Sac. R. Winter-run Chinook	CV Spring-run Chinook	CV Winter-run Steelhead (SR or SJ)	Fall-run Chinook (SR or SJ)	Late-fall-run Chinook
Fry (less than 70 mm)	CWT*	To and through Delta	Yes (H)	Yes (W)	Yes (H)	Yes (H, W)	No
		To Delta**	No	No	No	No	No
		Through Delta**	No	No	No	No	No
		Within Delta	No	No	No	Yes (H)	No
	AT	All	No	No	No	No	No
Smolt (≥ 70 mm)	CWT*	To and through Delta	Yes (H)	Yes (H, W)	Yes (H)	Yes (H)	Yes (H)
		To Delta**	No	No	No	No	No
		Through** Delta	No	No	No	Yes: North Delta (H) South Delta (H)	Yes: North Delta (H) Mokelumne (H)
		Within Delta	No	No	Yes (H)	Yes (H)	Yes (H)
	AT	To and through Delta	Yes (H)	Yes (H, W)	Yes: SR (H, W)	Yes: SR (H)	Yes: SR (H)
		To Delta	Yes (H)	Yes (H, W)	Yes: SR (H, W)	Yes: SR (H) SJR (H)	Yes: SR (H)
		Through Delta	Yes (H)	Yes (H, W)	Yes: SR (H, W) SJR (H)	Yes: SR (H) SJR (H)	Yes: SR (H)
		Within Delta	Yes	Yes	Yes: SR (H, W) SJR (H)	Yes: SR (H) SJR (H)	Yes (H)

*Notes: * = Survival indices are available from some of the CWT studies, while others provide absolute survival estimates. ** = It is possible to estimate survival indices or estimates to or through the Delta from existing data, but it has yet to been done. Better estimates of sampling efficiency at Sacramento and Chipps Island would yield improved survival estimates. H = hatchery; W = wild; SR = Sacramento River; SJR = San Joaquin River; To Delta = survival from river to Delta; Within Delta = survival and/or route selection in portion of Delta; Through Delta = total survival from Delta entry to Delta exit.*

Various statistical models have been fit to the CWT smolt survival data to identify the potential relative influence of several factors on survival through the Sacramento River Delta (Newman and Rice 2002; Newman 2003, 2008; K. Newman, personal communication). Factors identified as being important in the Delta for Sacramento River basin fall-run smolts included salinity, flow, Delta Cross Channel (DCC) gate position (both for Mokelumne and Sacramento River basin fish, although with opposite responses), release temperature, release location, and size of fish (Newman and Rice 2002; Newman 2003). Other factors increased or decreased in importance (i.e., exports or export/inflow ratio, tides) depending on which modeling framework was used (Newman and Rice 2002; Newman 2003). These results are discussed in more detail in the following sections.

Juvenile salmon and steelhead survival studies using ATs have been conducted throughout the Sacramento basin for fall-, spring-, and winter-run smolts or yearling-sized late-fall-run Chinook salmon and winter-run steelhead. Survival was estimated either to the Delta, to

Chipps Island or Benicia, or to the Golden Gate Bridge. Survival estimates for Sacramento River releases are summarized in Table E.2-2.

Table E.2-2. Estimates of Survival to the Delta, Through the Delta, and Through the Bay for Acoustic-tagged Winter-, Spring-, Fall-, and Late-fall-run Chinook Salmon and Steelhead from the Sacramento River Basin of the Central Valley[1]

Run	Origin	Year	Life-stage	Release Site/ Number Released	Total Survival to Delta	Survival through the Delta (Freeport to Benicia or Chipps Island) (SE)	Survival from Benicia to GG	Source
Winter	Livingston Stone Hatchery	2013	Smolt	Caldwell Park/148	0.15	0.32 (0.10)	1.00 (low confidence in estimate)	A. Ammann, personal communication
		2014	Smolt	Caldwell Park/358	0.36	0.35 (0.04)	0.32	A. Ammann, personal communication
Spring	Feather River	2013	Smolt	Feather River/300	0.08	0.30	1.00 (low confidence in estimate)	A. Ammann, personal communication
		2014	Smolt	Feather River/300	0.04	0.00		A. Ammann, personal communication
		2014	Smolt	Sacramento/200		0.00		A. Ammann, personal communication
Fall/Spring	Mill Creek-Wild	2013		Mill Creek/59	0.10	0.17	1.00 (Low confidence in estimate	A. Ammann, personal communication
		2014		Mill Creek/36	0.00			A. Ammann, personal communication
Spring/Fall	Battle Creek Wild	2014	Smolt	Battle Creek /76	0.00			A. Ammann, personal communication
Fall	Coleman NFH	2013	Smolt	Sacramento/200		0.00		A. Ammann, personal communication
Late-fall	Coleman NFH	Dec 2006	Yearlings	Sacramento/64		0.351		Perry et al. 2013
		Jan 2007	Yearlings	Sacramento/80		0.543		Perry et al. 2013
		Dec 2007	Yearlings	Sacramento/208		0.174		Perry et al. 2013
		Jan 2008	Yearlings	Sacramento/211		0.195		Perry et al. 2013
		Dec 2008	Yearlings	Sacramento/192; GS/100		0.368		Perry et al. 2013

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[1] Missing estimates reflect insufficient data to estimate survival or study design that did not provide survival estimate on given scale.

Run	Origin	Year	Life-stage	Release Site/ Number Released	Total Survival to Delta	Survival through the Delta (Freeport to Benicia or Chipps Island) (SE)	Survival from Benicia to GG	Source
		Jan 2009	Yearlings	Sacramento/192; GS/100		0.339		Perry et al. 2013
		Dec 2009	Yearlings	18 km upstream of Sac 167; GS 72		0.464		Perry et al. 2012
		Dec 2009	Yearlings	18 km upstream of Sac/168; GS 72		0.374		Perry et al. 2012
		Feb/Mar 2009	Yearlings	18 km upstream of Sac/ 249		0.64	0.35	G. Singer, personal communication
		Jan/Feb 2010	Yearlings	18 km upstream of Sac/ 248		0.52	0.58	G. Singer, personal communication
Steelhead	Coleman NFH	Feb/Mar 2009		18km upstream Sac/250		0.58	0.44	G. Singer, personal communication
		Jan/Feb 2010		18km upstream Sac/250		0.47	0.64	G. Singer, personal communication

E.2.1.1 San Joaquin River Releases

Survival of juvenile fall-run Chinook salmon migrating from the San Joaquin River has been measured for over two decades. From 1994 through 2006, CWTs were used with a paired release study design of hatchery juvenile Chinook salmon, from either Feather River or Merced River hatchery, to estimate survival from Durham Ferry, Mossdale, or Dos Reis to Jersey Point (Figure E.2-2). For each survival estimate, CWT fish were released at Durham Ferry, Mossdale, or Dos Reis, and a separate group of CWT fish was released at Jersey Point. The relative recovery rate in the Chipps Island trawl and/or ocean fishery was interpreted as the probability of survival between the upstream release site (Durham Ferry, Mossdale, or Dos Reis) and Jersey Point (Newman 2008). Recoveries in the Antioch trawl were also used when available (Brandes and McLain 2001; SJRGA 2013; Newman 2008).

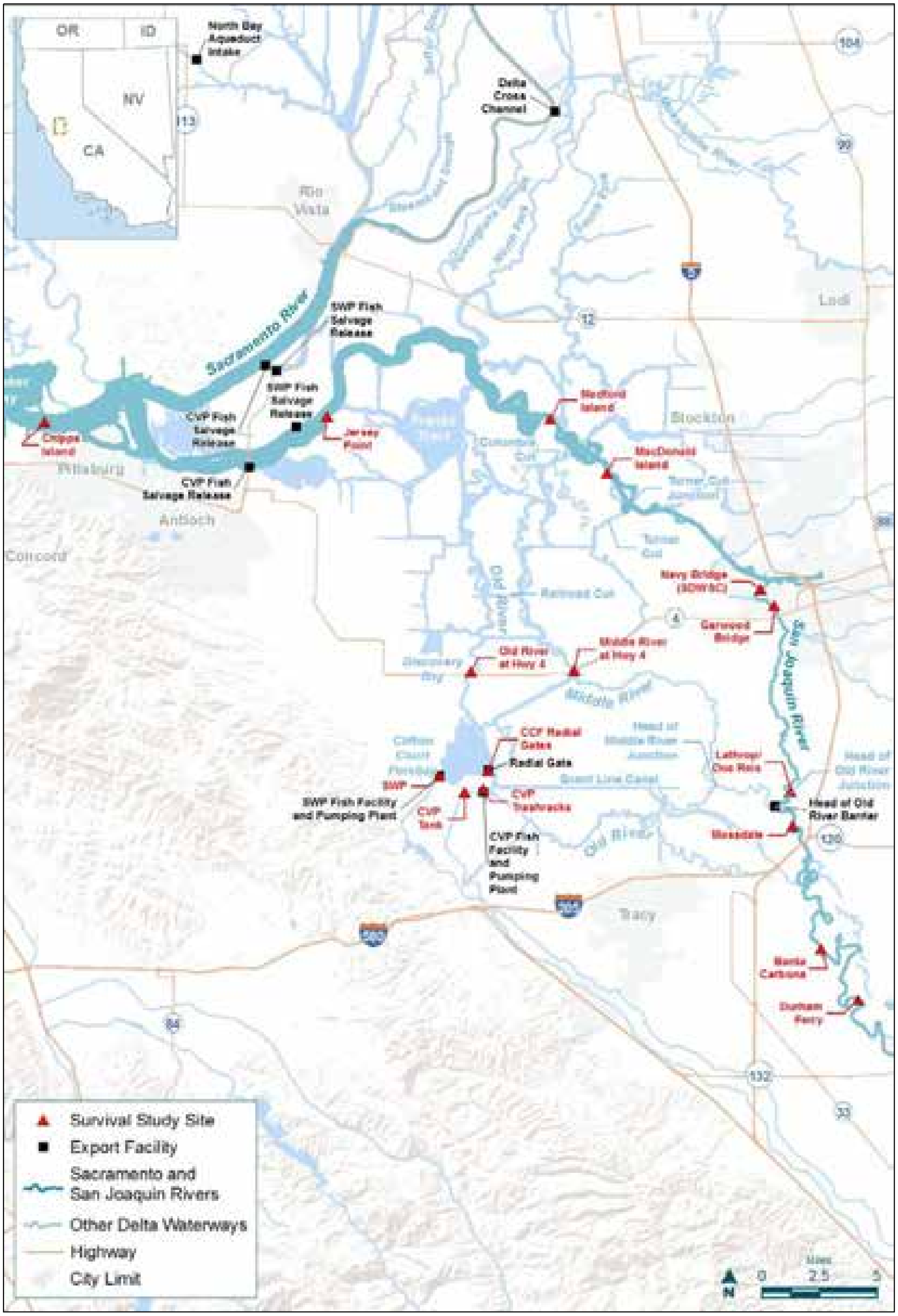

Figure E.2-2. South Delta Sites from CWT and AT Survival Studies

Starting in 2008, acoustic telemetry tags were used to estimate survival of Merced River hatchery fall-run Chinook salmon between Mossdale and Jersey Point or Chipps Island, or part way through the Delta as part of the Vernalis Adaptive Management Plan (VAMP) studies (SJRGA 2009, 2010, 2011, 2013; Holbrook et al. 2009, 2013; Buchanan et al. 2013). Since 2011, acoustic telemetry studies of fall-run Chinook salmon (SJRGA 2013; Buchanan et al. 2015) have been coordinated with concurrent studies of acoustic-tagged steelhead in the San Joaquin River Delta (i.e., 6-year study; Buchanan 2013, 2014). Acoustic telemetry also provided estimates of survival on smaller spatial scales (e.g., Mossdale to Stockton or Turner Cut) (Figure E.2-2).

Survival estimates from acoustic telemetry tags are not available for years when the full study was not performed (e.g., 2007 when a pilot study was performed) or when acoustic receivers were not located at either Jersey Point (2009 and 2010) or Chipps Island (e.g., 2009). The 2008 study was hampered by premature tag failure, and so survival estimates from 2008 reflect the joint probability of fish survival and tag survival, and are likely to represent the faster moving fish, which were more likely to be detected before their tags failed. Detections thought to have come from predators were removed in the 2009 to 2012 studies, but not from the 2008 study. In some years, a physical barrier was installed at the head of Old River. In other years, either no barrier was installed during the studies (i.e., 1995 to 1996, 1998 to 1999, 2005 to 2006, 2008, 2011) or an experimental non-physical barrier was installed for the entire study and was activated during passage of approximately half the study fish (i.e., 2009, 2010). The installation of the physical barrier is partially dependent on flows; flows greater than 5,000 cubic feet per second (cfs) prevent installation of the present configuration of the physical barrier, and flows greater than 7,000 cfs prevent operation of the barrier if it is installed. The number of culverts in the physical barrier has ranged from none (1994) to eight (2012); culverts allow some flow into Old River to supply irrigation water to the South Delta.

Over the years with survival estimates, survival of San Joaquin River fall-run Chinook salmon from Mossdale to either Jersey Point (CWT) or Chipps Island (AT) has ranged from a high of 0.79 to Jersey Point in 1995 (high flows and no barrier at the head of Old River; SJRGA 2013) to a low of 0.01 to Jersey Point in 2003 (low flows and a physical barrier; SJRGA 2013) and 0.00 to Chipps Island for the second release in 2012 (very low flows and a physical barrier; Buchanan et al. 2015) (Figure E.2-3). Survival to Chipps Island from AT fall-run Chinook salmon has been estimated at ≤ 0.1 for all years with estimates (Table E.2-3). Although the AT estimates represent survival all the way to Chipps Island, which is approximately 25 kilometers (km) downstream of Jersey Point, estimates to Chipps Island in 2010 to 2012 were comparable in value to estimates of survival to Jersey Point in 2002 to 2006 (Figure E.2-3). Survival from Dos Reis to Jersey Point was often slightly higher than from Mossdale. Survival from Durham Ferry to Jersey Point was similar in value to survival from Mossdale for most years (Figure E.2-3). It should be noted that test fish used for AT tagging were larger than those used in the CWT studies (105 mm versus 80 to 90 mm) to meet the recommended AT weight to body weight of no greater than 5%.

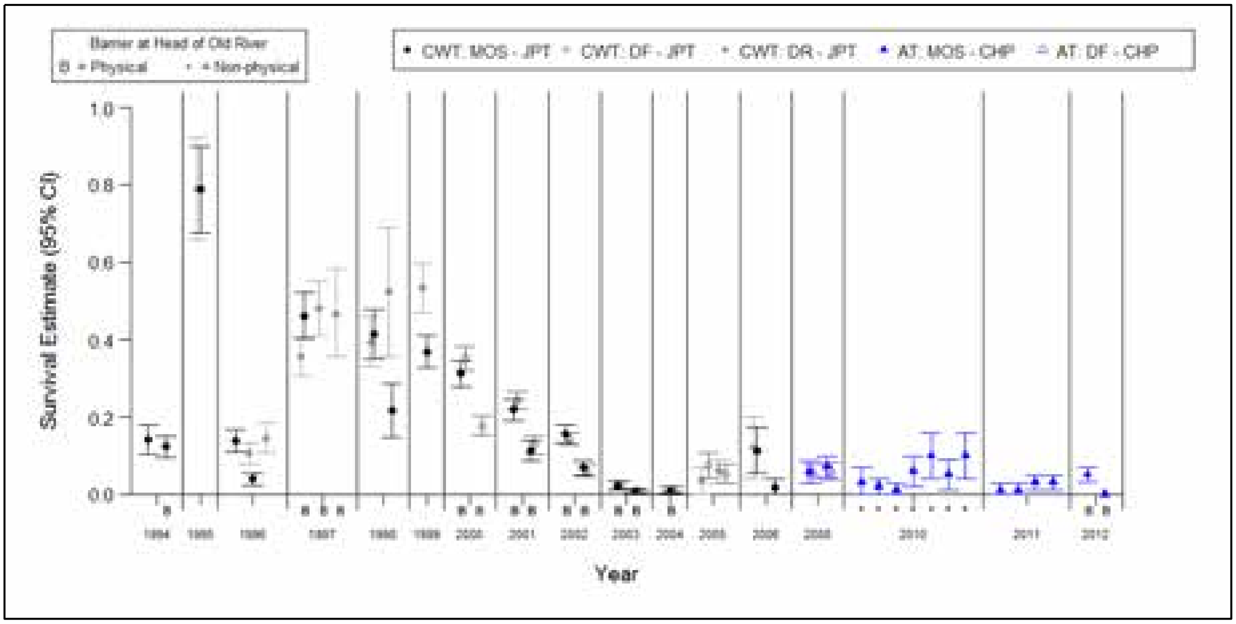

Figure E.2-3. Estimated Survival of Fall-run Juvenile Chinook Salmon from Mossdale (MOS), Durham Ferry (DF), or Dos Reis (DR) to Either Jersey Point (JPT; CWT) or Chipps Island (CHP; AT); Intervals are 95% Confidence Intervals, Truncated to 0 if Necessary

Sources: SJRGA 2013; Buchanan et al. 2015

Table E.2-3. Average Estimates of Survival Through the Delta (Mossdale to Chipps Island) for Acoustic-Tagged Chinook Salmon and Steelhead Released at Durham Ferry in the San Joaquin River

Species	Year	Number of Release Groups	Total Survival through Delta (SE)	Source
Chinook	2008[1]	2	0.06 (0.01)	Holbrook et al. 2009
	2009	(NA)	NA	SJRGA 2010
	2010	7	0.05 (0.01)	SJRGA 2011
	2011	4	0.02 (less than 0.01)	SJRGA 2013
	2012	2	0.03 (0.01)	Buchanan et al. 2015
Steelhead	2011	5	0.54 (0.01)	Buchanan 2013
	2012	3	0.32 (0.02)	Buchanan 2014

Notes: 1 = The survival estimates through the Delta for 2008 are minimum estimates, unadjusted for premature tag failure. No predator filter was used to remove likely predator detections in analysis of the 2008 data.

Survival of San Joaquin River Chinook salmon through the Delta is less than 0.2 for the majority (70%) of the estimates available since 1994 (Figure E.2-3). Even without the higher survival estimate of 0.79 to Jersey Point in 1995, there appears to have been a general trend of decreasing survival since 1998 (Figure E.2-3). Survival through the Delta tends to be lower than survival through comparable distances and environments for different populations (i.e., larger fish) or in different systems. Perry et al. (2010) estimated late-fall-run Chinook salmon survival from the Sacramento River through the Delta at 0.35 to 0.54 in winter 2007, for fish of about 140 mm fork length (FL), using similar study design, tagging, and analysis methods as the AT results reported here for the San Joaquin River in 2008 and 2010 to 2012. However, these individuals of the late-fall population move through a different part of the system and have the option of avoiding the South Delta entirely; additionally, they migrate during a different part of the year (i.e., they were released in December and January instead of April and May), and do not migrate during the striped bass spawning migration.

Chinook salmon smolts in other systems on the western coast of North America (e.g., Columbia River, Fraser River) also have higher survival rates through river estuaries, although they may be larger fish (Buchanan et al. 2013). For example, Chinook salmon smolts from the Thompson-Fraser River in 2004 had a survival rate of 0.989 per kilometer through more than 330 river kilometers (rkm) to the mouth of the Fraser River; this corresponds to a survival probability of 0.37 over a distance of 89 rkm, which is approximately the distance from Mossdale to Chipps Island (Welch et al. 2008; Buchanan et al. 2013). For comparison, estimated survival of fall-run Chinook from Mossdale to Jersey Point in 2004 was 0.011 (SE=0.0005) (Figure E.2-3).

Two years (2011 and 2012) of survival data have been analyzed for steelhead from the San Joaquin River Delta. Estimated survival from Mossdale to Chipps Island ranged from 0.26 for the first release in 2012 (lower flows and a physical barrier at head of Old River; Buchanan 2014) to 0.69 for the first release in 2011 (higher flows without a barrier; Buchanan 2013) (Figure E.2-4). Average survival estimates for these two years were 0.32 in 2012, and 0.54 in 2011 (Table E.2-3). Based on these two years of data, survival for steelhead appears to be greater than survival for fall-run Chinook salmon. The steelhead used in the tagging study are substantially older (yearlings) and larger than the fall-run Chinook salmon (subyearlings) used for the CWT or AT studies in the San Joaquin River and Delta.

E.2.2 DATA ON SURVIVAL VERSUS WATER EXPORT OPERATIONS

Formal analysis relating survival of fall-run San Joaquin River Chinook salmon through the Delta to inflow and exports is available for CWT data from release years 1994 to 2006 in Newman (2008), with additional analysis of CWT data from 1985 to 1991 to compare route-specific survival in the San Joaquin and Old rivers. Newman (2008) used hierarchical Bayesian analysis to explore the dependency of juvenile fall-run Chinook salmon survival on flow at Vernalis and exports, as well as the flow proportion at the head of Old River and flow both past Dos Reis and into upper Old River. Newman (2008) defined conditions using the two-day average (starting the day of release) of San Joaquin flows at Vernalis (from Dayflow), or an eight-day median flow at Stockton or Dos Reis (from DSM2 or equations from California Department of Water Resources [DWR], depending on the study year; see Table 6 of Newman [2008] for more details). To characterize exports, he used either the two-day average or the eight-day median of combined exports from CVP and SWP, depending on release site (Mossdale or Dos Reis, respectively). Regression analyses on the 1994 to 2006 data are available in SJRGA (2007).

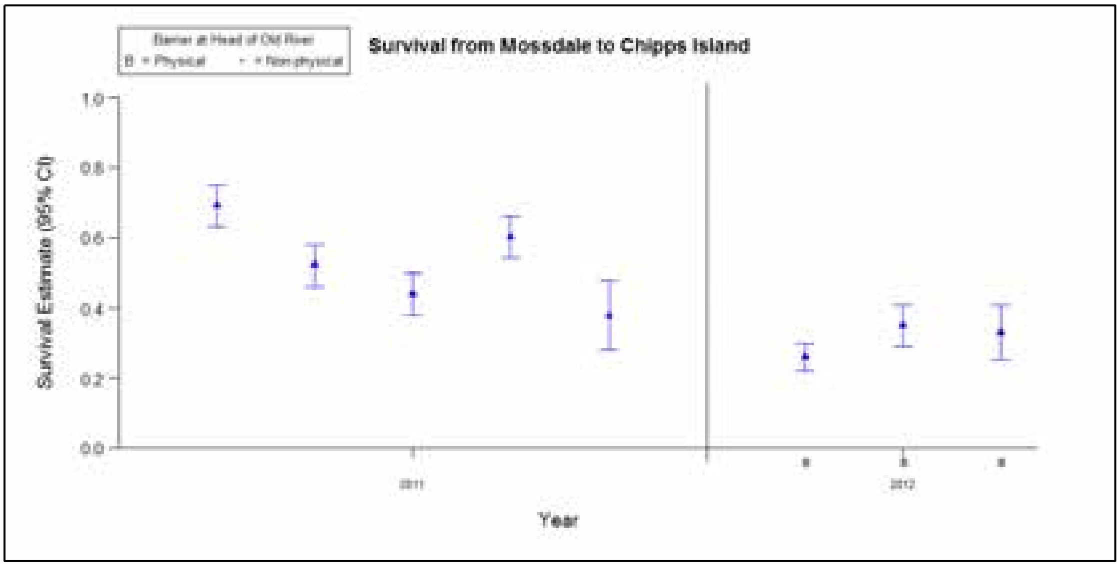

Figure E.2-4. Estimated Survival of Acoustic-tagged Juvenile Steelhead from Mossdale to Chipps Island; Intervals are 95% Confidence Intervals

Newman and Brandes (2010) used hierarchical models with CWT data to assess the effect of exports on survival of juvenile Sacramento River Chinook salmon (late-fall-run) migrating through the Delta as part of the Delta Action 8 study (winter releases 1993 to 2005). In particular, the relative survival of fish released in the Interior Delta to fish released in the Sacramento River mainstem was compared to exports (three-day average from SWP and CVP). Additionally, Newman and Rice (2002) modeled survival of fall-run juvenile Chinook salmon from the Sacramento River through the Delta as a function of various measures, including Sacramento River flow and the ratio of exports to inflow (E:I) (spring CWT releases 1979 to 1995). Newman (2003) further analyzed relative survival of upstream and downstream releases of juvenile fall-run Chinook salmon from the Sacramento River (including data analyzed by Newman and Rice [2002]), exploring the effects of multiple covariates including flow and exports.

Zeug and Cavallo (2013) also analyzed CWT data from fall-run Chinook salmon released in April and May in 1993 to 2003 in the San Joaquin River (Durham Ferry, Mossdale, or Dos Reis) and Sacramento River (near the tidal limit). Unlike the previous analyses of CWT data (Newman 2003), Zeug and Cavallo (2013) analyzed only ocean recovery rates, and thus did not isolate Delta survival from ocean survival; they also assumed similar ocean capture probabilities between years. Their analysis used an information theoretic approach to assess competing hypotheses regarding factors influencing ocean recovery rates, including Delta inflow (from either the San Joaquin River or the Sacramento River, depending on the release location) and export rates, water temperature and fish size at release, water quality, and ocean productivity. Although ocean recovery rates represent more than just juvenile survival through the Delta, this analysis offers an opportunity to asses a possible population-level effect of Delta conditions during juvenile outmigration.

AT data from the Sacramento River have been analyzed by Perry (2010). Perry (2010) used a release-recapture analysis to model survival through the Delta of acoustic-tagged late-fall-run Chinook salmon released in various locations in the Sacramento River and interior North Delta as a function of Sacramento River discharge, exports, and fish length.

No formal analysis has been completed relating survival estimates from San Joaquin River AT studies to measures of flow and exports for either fall-run Chinook salmon or steelhead. Such AT studies are ongoing; formal analysis relating survival to flow and exports is underway for fall-run Chinook salmon, and is planned to be completed for steelhead after survival results from more years have been analyzed. Preliminary, informal, and unpublished analysis using existing results from both CWT and AT data, as available, is presented here as an indication of the types of results and limitations that may be expected from more complete analysis. This type of visual inspection is only the first step in any analysis of the data, useful for observing obvious patterns but insufficient for accommodating multiple covariates with high correlation, accounting for unbalanced study designs, or objectively measuring the variability in the data. Furthermore, the simple scatterplots available here ignore other factors and do not provide insight into mechanisms that may relate survival to inflow or water exports; causal inference is not possible from observational, correlative analysis such as this. Thus, the preliminary graphical analysis provided by the SST is meant to suggest possible relationships based on existing data, but is not meant to provide final conclusions on the existence and type of relationships between survival and inflows or exports.

The data used in these graphical analyses include daily averages of observed inflow at Vernalis, exports at CVP and SWP, and the daily I:E, averaged over a multi-day period starting the final day of release of tagged study fish either at Mossdale (CWT releases) or at Durham Ferry (CWT and AT releases). For the I:E graphs, only tag releases from April and May were used, to address one of the management questions. The duration of the time period used to measure covariates was selected based on observed travel times through the Delta. Observed travel times from Durham Ferry to Chipps Island of acoustically tagged fish ranged from less than two days to over twelve days in 2010, 2011, and 2012; the median travel time was approximately four to five days in these years (Figure E.2-5). Travel times of acoustic-tagged salmon in 2007 from Durham Ferry to Route 16 on the San Joaquin River (just downstream of Columbia Cut) averaged six to seven days (SJRGA 2008). Travel times of

CWT salmon in 2006 from Mossdale to Antioch and Chipps Island ranged from six to twelve days (SJRGA 2007).

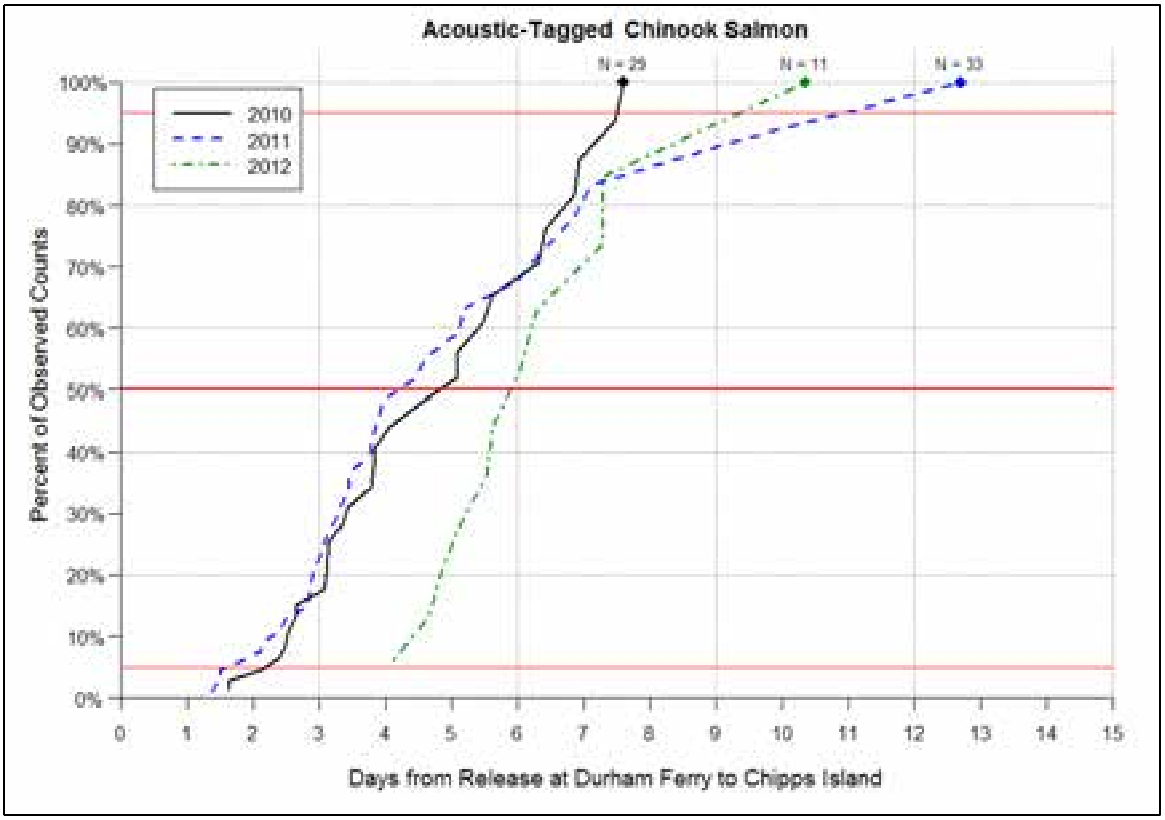

Figure E.2-5. Observed Travel Times from Release at Durham Ferry to Chipps Island for Acoustic-tagged Juvenile Fall-run Chinook Salmon

Note: Red lines indicate 5th, 50th, and 95th percentiles of arrival time distribution.

Baker and Morhardt (2001) report a median travel time through the San Joaquin Delta of eleven days (range = 5 to 26 days) from CWT Chinook salmon released in the Merced, Stanislaus, and Tuolumne rivers in 1986 to 1990. There was variation in travel time between fish within a release group and within each available study year. Thus, identifying the appropriate time period over which to measure inflow and exports for any particular release group is somewhat arbitrary. Periods of four days and ten days were considered. The linear correlation between the four-day measures and the ten-day measures were high for both inflow (0.998) and exports (0.970), so a ten-day average was used in the inflow, exports, and I:E plots in this appendix.

All inflow and export data were downloaded from the Dayflow database[2]. In addition to through-Delta survival (Durham Ferry or Mossdale to Jersey Point or Chipps Island), survival

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[2] Observed measures of Delta inflow from the San Joaquin River at Vernalis and export rates at the CVP and SWP are available from several databases. Daily averages are available from the Dayflow database

was also compared with inflow, exports, and the I:E ratio for the reach from Mossdale to Turner Cut (predominantly riverine) and for the reach from Turner Cut to Chipps Island (predominantly tidal) (Figure E.2-2). The informal results presented here have not been published and are merely preliminary, simple comparisons between survival and hydrological conditions.

Another way in which survival has been related to measures such as flow is to compare adult escapement to juvenile conditions 2.5 years earlier, when the returning adults were presumably outmigrating as juveniles (Kjelson and Brandes 1989). In the VAMP study, adult escapement of fall-run Chinook salmon to the San Joaquin River basin between 1951 and 2003 was compared to San Joaquin River flow and the ratio of flow to CVP and SWP exports two and a half years before adult return (SJRGA 2007). These analyses assume that adults return to freshwater at age 3. Although patterns of adult escapement represent more than just juvenile survival through the Delta, these comparisons provide an opportunity to assess a possible population-level effect of Delta conditions during juvenile outmigration using data other than tagging data. We briefly present the findings from these analyses in the pertinent sections below—both the original results from the 2006 VAMP report (SJRGA 2007) and those updated by the SST using adult return data through 2012.

E.2.3 INFLOW AND EXPORT CONDITIONS

A central issue confounding the ability to identify and isolate the influence of export and inflow as drivers of juvenile survival is the correlation of inflow and export rates across the range of conditions tested during acoustic telemetry and CWT survival studies. Mean values of San Joaquin River inflow at Vernalis during the VAMP management periods from 2000 to 2011 ranged from 2,280 cfs in 2009 to greater than 20,000 cfs in 2006; average observed export rates from the same periods ranged from 1,330 cfs to 5,750 cfs (Table E.2-4, Figure E.2-6). Correlation between inflow and exports was r=0.60 throughout the VAMP study; however, without the first observation from 2006, correlation was considerably higher (r=0.98) (Figure E.2-6, Table E.2-4). Correlation between inflow and exports was r=0.86 (r^2=0.74) for the CWT studies (pre-VAMP and VAMP) when the barrier was installed at the head of Old River (Figure E.2-7). Newman (2008) also reported that "exports and flows were highly positively correlated" (r=0.88) in an analysis of VAMP and pre-VAMP CWT data (Newman 2008). The overall correlation between the ten-day average values of inflows and

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(http://www.water.ca.gov/dayflow/) maintained by DWR. Both daily averages and 15-minute event data (for inflow) are available from the California Data Exchange Center (CDEC) (http://cdec.water.ca.gov/), but these are preliminary data that may include errors. The Dayflow data come from the same source as the CDEC data but have gone through some level of quality control. Exports rates from Dayflow are measured in cubic feet per second. The measure of the SWP export rate has changed over the years. Except in 2002, the SWP measure consisted of the Clifton Court Forebay inflow, but it omitted the Byron Bethany Irrigation District component before 2002 and included it after 2002. In 2002, the SWP exports metric measured the Banks Pumping Plant flow (as described at http://cdec.water.ca.gov/selectQuery.html).

exports used in the simple graphical analyses presented here, when all data points are included, is considerably lower (r=0.34) than the value presented in Newman (2008). However, when data are separated by tag type and barrier status, the observed correlation between inflow and exports is often higher (r≤0.89; Figures E.2-8 through E.2-10). Inflow is also partially confounded with the status of the barrier at the head of Old River because the barrier cannot be installed when flows are greater than 5,000 cfs or operated when flows are greater than 7,000 cfs.

Table E.2-4. Summary of Observed Flows at Vernalis and Observed Delta Exports During VAMP Periods, 2000 – 2011

Year	VAMP Target Flow Period	Observed Flow at Vernalis – VAMP period mean (cfs)	Observed Delta Exports – VAMP period mean (cfs)
2000	4/15 – 5/15	5,870	2,160
2001	4/20 – 5/20	4,220	1,420
2002	4/15 – 5/15	3,300	1,430
2003	4/15 – 5/15	3,240	1,450
2004	4/15 – 5/15	3,160	1,330
2005	5/1 – 5/31	10,390	2,990[a]
2006	5/1 – 5/31	27,900/24,260[b]	1,560/5,750[b]
2007	4/22 – 5/22	3,260	1,490
2008	4/22 – 5/22	3,160	1,520
2009	4/19 – 5/19	2,280	1,990
2010	4/25 – 5/25	5,140	1,520
2011	5/1 – 5/31	12,650	3,360

Notes: Reproduced from SJRGA 2013, Chapter 2, p. 25, Table 2-8. a = May 1 – 25 average was 2,260 cfs; exports increased starting May 26 in conjunction with increasing existing flow; May 26 – 31 average was 6,012 cfs.
b = First fish release-recapture period (May 1 – 15 for flow at Vernalis, May 3 – 17 for Delta exports)/Second fish release-recapture period (May 16 – 31 for flow at Vernalis, May 18 – June 2 for Delta exports).

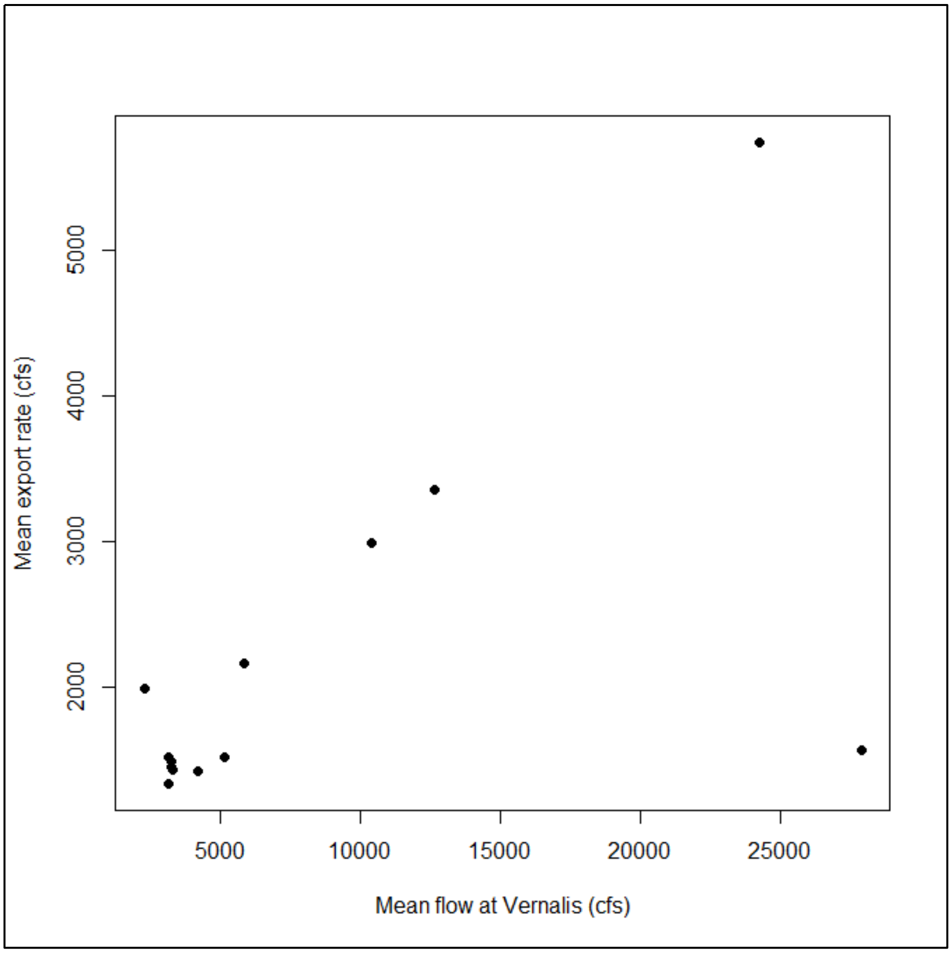


Figure E.2-6. Observed Mean Inflow and Exports During VAMP Period, 2000 – 2011

Note: Reproduced from SJRGA 2013, Chapter 2, pg. 25, Table 2-8. The observation with mean flow = 27,900 cfs and mean export rate = 1,560 cfs (in lower right corner of plot) is from 2006.

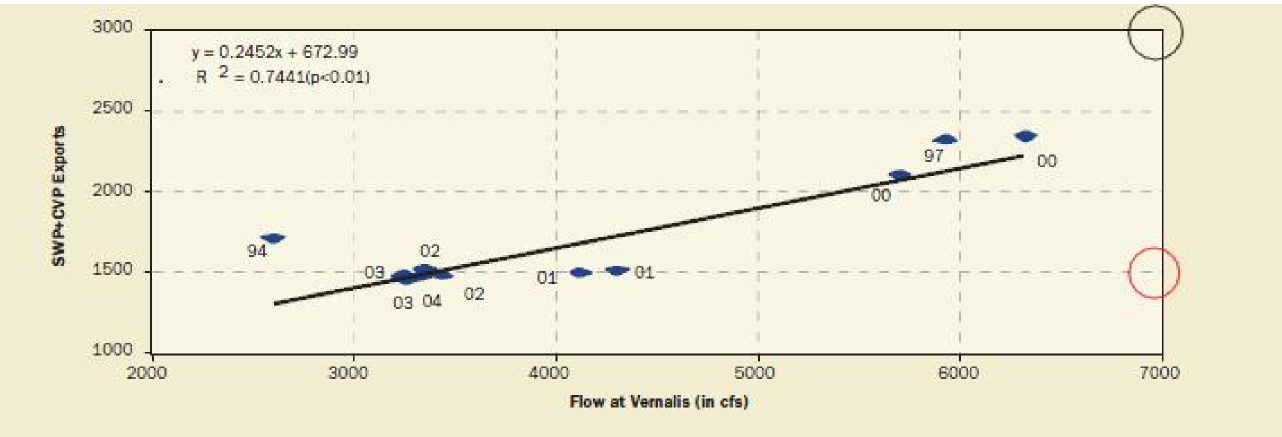


Figure E.2-7. Inflow and Exports During CWT Studies in the San Joaquin River with the Head of Old River (physical) Barrier in Place for 1994, 1997, and 2000 – 2004

Note: Reproduced from SJRGA 2007, Chapter 5, pg. 61, Figure 5-16.

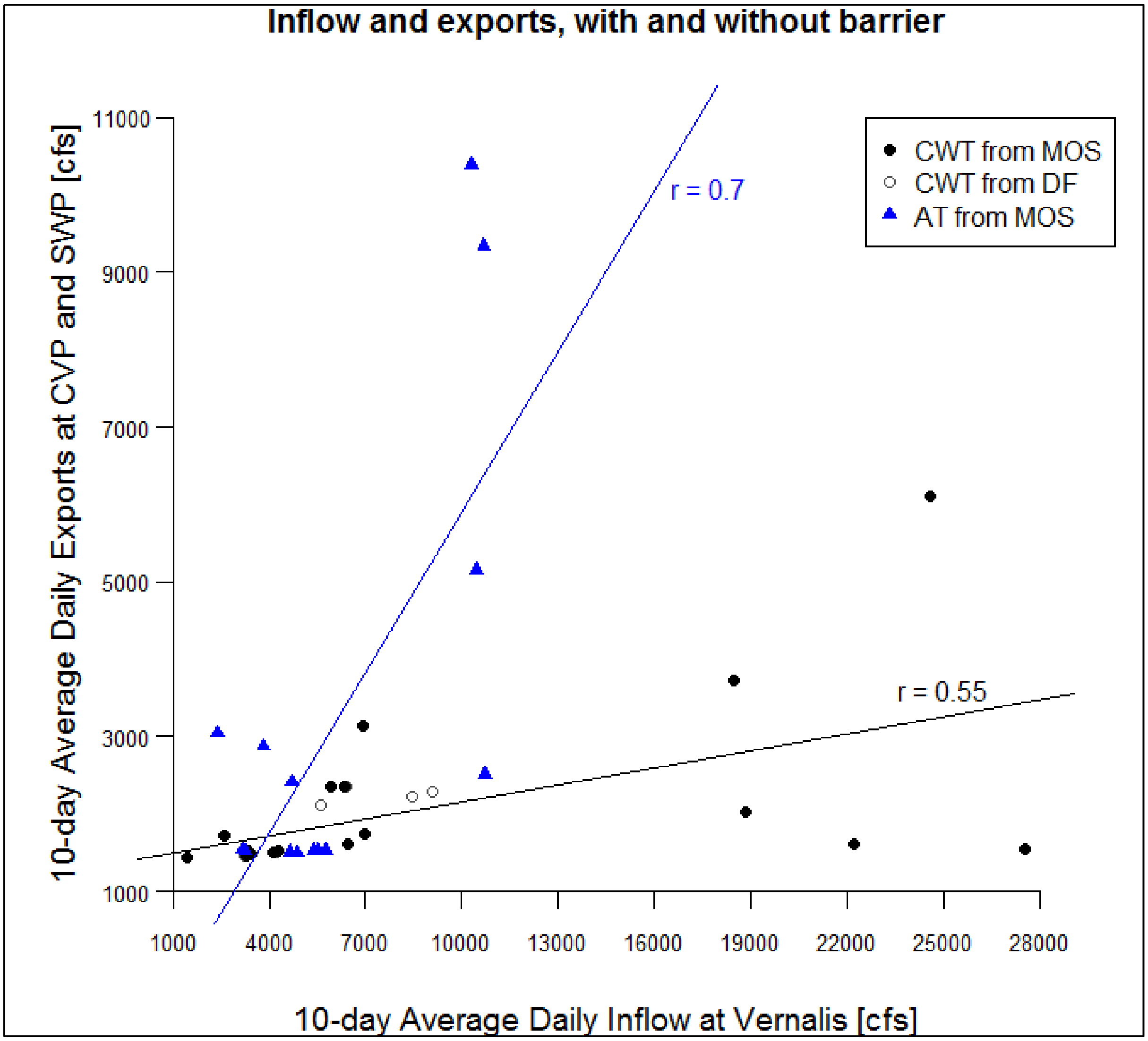


Figure E.2-8. Observed Average Inflow and Export Rates for the Release Groups of CWT and Acoustic-tagged Fall-run Chinook Salmon Presented in this Section, Regardless of Barrier Status at the Head of Old River, with Pearson Correlation Coefficient (r) for Each Tag Type; Fish Were Released at Either Durham Ferry (DF) or Mossdale (MOS)

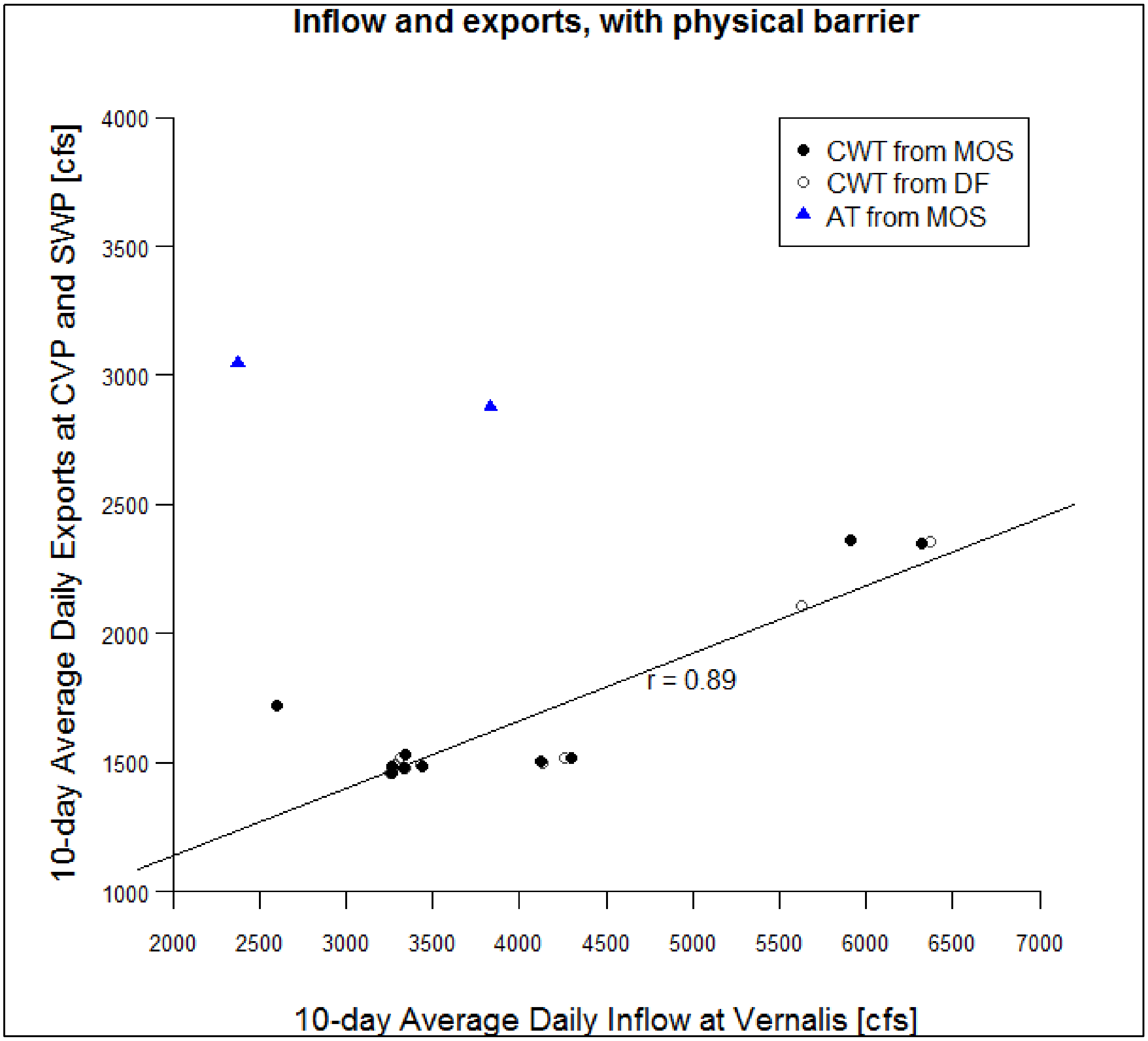


Figure E.2-9. Observed Average Inflow and Export Rates for the Release Groups of CWT and Acoustic-tagged Fall-run Chinook Salmon Presented in this Section, with Physical Barrier Installed at the Head of Old River, with Pearson Correlation Coefficient (r) for CWT Releases; Fish Were Released at Either DF or MOS

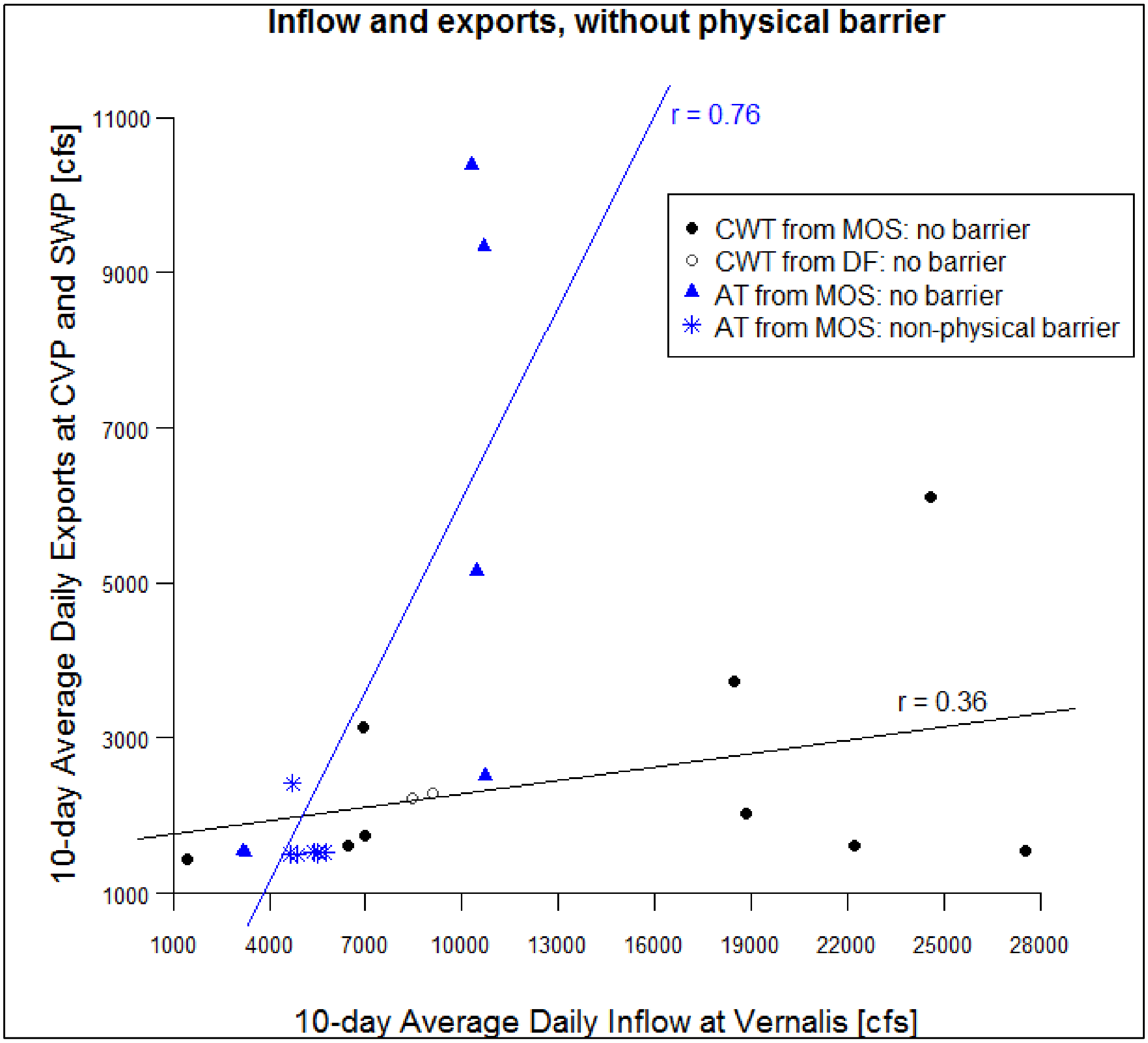


Figure E.2-10. Observed Average Inflow and Export Rates for the Release Groups of CWT and Acoustic-tagged Fall-run Chinook Salmon Presented in this Section, without Physical Barrier at the Head of Old River, with Pearson Correlation Coefficient (r) for each Tag Type; Fish Were Released at Either DF or MOS

High correlation between covariates confounds estimation of the effects of the individual covariates. Single-variable analyses can identify observed relationships between individual covariates and survival, but will not be able to determine which covariates actually drive survival or to account for multicollinearity. A multi-covariate analysis may be more appropriate to determine the relative effects of inflow, exports, and the barrier on survival, but will still be hindered by the degree of correlation among the covariates. Additional data that include observations for previously unobserved or uncommon combinations of inflow and exports (e.g., low exports combined with high flows or a range of exports for a given inflow level) is likely necessary to properly identify the relative effects of inflow and exports on survival. Separating the effects of inflow and exports on survival is further complicated by the practice of increasing upstream reservoir releases to provide water for export and irrigation supply.

Existing analysis found in the literature has focused on modeling the mean survival probability as a function of covariates (e.g., exports, inflow, barrier status). An alternative approach is to model a quantile of the survival response, such as the maximum, as a function of covariates (e.g., quantile regression). This approach may be more appropriate than modeling the mean response if the covariate is a limiting factor in the survival distribution. For example, the covariate (e.g., exports) may determine the range of possible survival values, while other factors determine the mean survival within the possible range. This hypothetical situation is an example of a factor-ceiling relationship (Thomson et al. 1996). We have not found analyses of these data in the literature that assess potential factor-ceiling relationships or attempt to model quantiles of the survival distribution. It is outside the scope of this report to perform new, formal analysis here, but we take the opportunity to visually examine scatterplots and address the possibility of a factor-ceiling relationship in the results that follow.

It is important to note that limitations on inference exist regardless of the analysis method used, whether it is regression of the mean, quantile regression, factor-ceiling analysis, or correlation analysis. In particular, inference is valid only over the range of the explanatory variable (e.g., exports or inflow) that is observed in the data, and the quality of the inference may be poor in regions with few observations (e.g., high export levels in the results that follow). Additionally, problems of correlation among covariates and confounding of effects still apply.

E.3 DIRECT MORTALITY FROM THE FISH FACILITIES

The conceptual model frames direct mortality from the fish facilities as a function of both route selection, resulting from tidal and water project operation influences on migration cues, and stressors within the facilities after the fish has selected a facility route. The export rate affects both route selection and factors such as pre-screen mortality and louver efficiency, and thus the possibility of salvage, within-facility mortality, and the opportunity for effects of handling and transport (Figure E.3-1). We consider salvage facility operations separately from other questions of migration route because the mechanisms of mortality are potentially different in the facilities than in other regions of the Delta. Fish collection and transport, in particular, are unique to the salvage facilities apart from other Delta habitats. Additionally, focused studies have examined the mechanistic linkages between salvage facility operations and survival. We consider those mechanistic linkages in detail here, and address other effects of route selection in Section E.4.

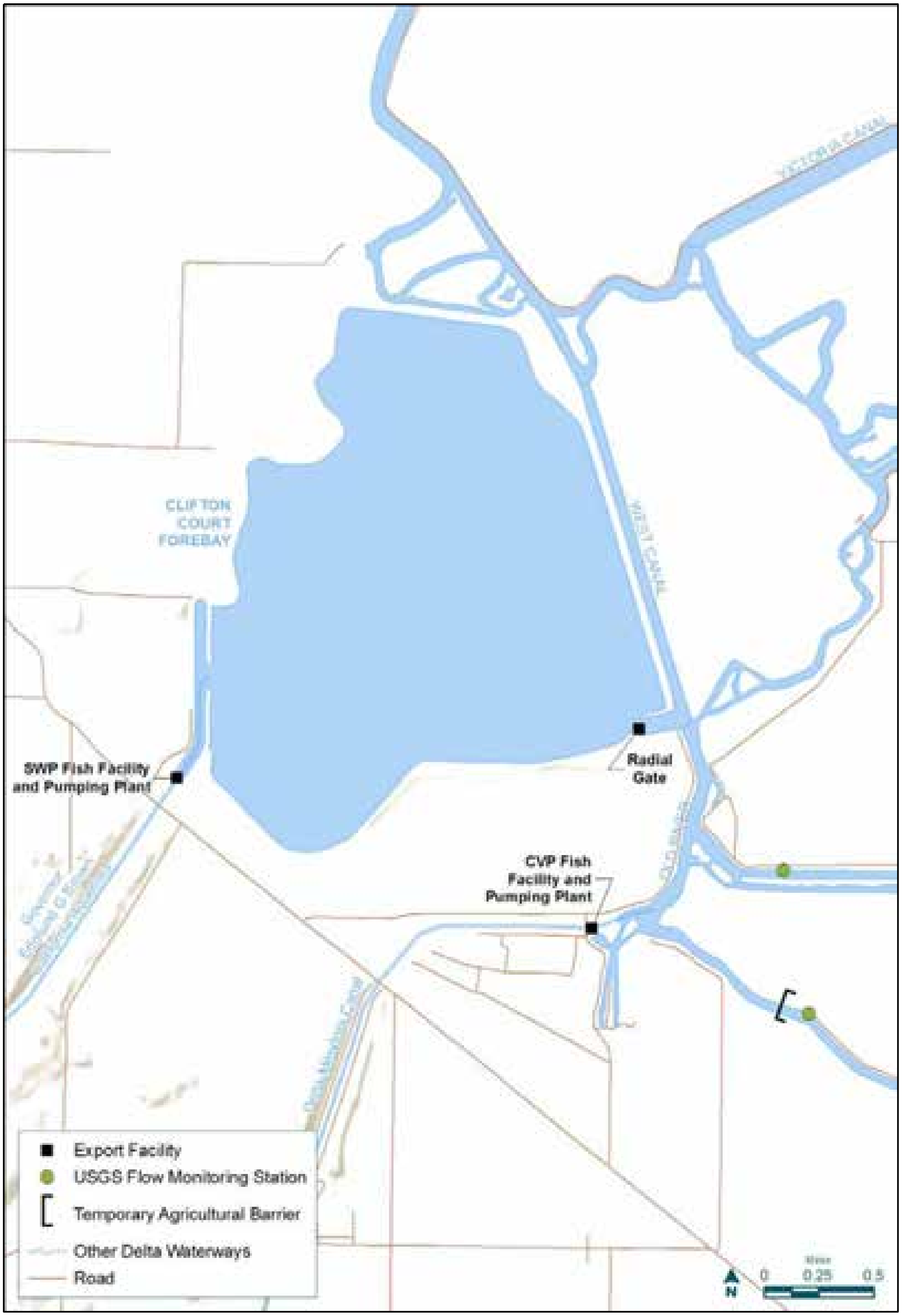


Figure E.3-1. Location of CVP and SWP Fish Salvage Facilities Relative to Clifton Court Forebay

The geographic extent of the facility operations includes the Clifton Court Forebay (CCF), louver and salvage facilities, and intake canals leading to the facilities (Figure E.3-1). Salvage facilities are located on the intake canals for the South Delta pumping plants—Tracy Fish Collection Facility (CVP) and John F. Skinner Delta Fish Protection Facility (Skinner Facility; SWP).

These facilities are similar in design, using a primary louver system to direct fish out of the intake canals (primary channel) and into secondary channels. A secondary louver system (or fish screen system, at SWP) on the secondary channels directs fish into holding tanks, where fish are concentrated. As needed, fish in holding tanks are transferred to transport trucks, moved to release sites on the lower Sacramento and San Joaquin rivers (Figure E.2-2), and released back into Delta waters through a pipe. The SWP and CVP salvage facilities differ in that the SWP facility is preceded by a large forebay (i.e., CCF) where water is collected and stored during high tides to maintain adequate water elevations for pumping. Although this forebay allows more flexibility for the timing of pumping relative to tidal stage, Chinook salmon and steelhead juveniles suffer high mortality rates in the forebay compared to the salvage facilities (i.e., from the trash racks at the entrance of the facilities through release after salvage) at the SWP (Gingras 1997; Clark et al. 2009). On the other hand, a multi-channel primary intake at the SWP salvage facility allows greater control over intake velocities and, therefore, more effective fish salvage than available at the CVP; nevertheless, the cumulative survival rate for juvenile salmonids routed through the CCF and SWP salvage facility is lower than through the CVP facility.

The conceptual model predicts the following:

- Direct mortality is a function of export rates.
- Pre-screen mortality is higher at the SWP than at the CVP because fish must navigate the CCF outside the SWP.
- Pre-screen mortality is higher for Chinook salmon than for steelhead because Chinook salmon are smaller.
- Louver efficiency is higher at higher export levels.
- Salvage can be used as an index for rates of direct entrainment mortality through the louvers and into the intake canals, and also total mortality at the facilities.

E.3.1 SUMMARY: CONCEPTUAL MODEL PREDICTIONS ON DIRECT MORTALITY FROM THE FISH FACILITIES

The conceptual model predicts that direct mortality is a function of exports rates. This prediction is supported indirectly, but the relationship is complicated.

- Direct mortality (loss) is estimated from salvage counts, which have been found to increase with increasing export rates (Kimmerer 2008; Zeug and Cavallo 2014).

- Mortality due to louver inefficiency has been found to decrease at the CVP for higher secondary channel velocities, which are controlled by export rates (Bowen et al. 2004; Karp et al. 1995).

The conceptual model predicts that pre-screen mortality is higher at the SWP than at the CVP. Evidence for this prediction is indirect.

- A large population of striped bass large enough to eat juvenile salmon has been observed in the CCF (Brown et al. 1996; Gingras and McGee 1997).
- Pre-screen mortality at the SWP was estimated at 0.63 to 0.99 for Chinook salmon between 1976 and 1993 (Gingras 1997); no comparable estimates of pre-screen mortality have been made for the CVP.
- Detections of AT Chinook salmon show a higher probability of moving to Chipps Island via the CVP than via the SWP (Holbrook et al. 2009; SJRGA 2011, 2013).

The conceptual model predicts that pre-screen mortality is higher for Chinook salmon than for steelhead. This prediction has moderate direct and indirect support.

- Pre-screen mortality estimates at the SWP have ranged from 0.63 to 0.99 for Chinook salmon between 1976 and 1993 (Gingras 1997), and from 0.78 to 0.82 for steelhead (Clark et al. 2009).
- No estimates of pre-screen mortality have been made for the CVP; the assumed value is 15%, but it unknown how representative that value is (Anonymous 2013).
- AT data have resulted in higher estimates of survival for steelhead than for Chinook salmon from CVP trash racks to Chipps Island via salvage, and from the CCF radial gates to Chipps Island (presumably via the SWP) (VAMP study, 6-year steelhead study; also shown in Figures E.4-5 and E.4-6 of this appendix; Holbrook et al. 2009; SJRGA 2010, 2011, 2013; Buchanan 2013, 2014; Buchanan et al. 2015).

The conceptual model predicts that louver efficiency is higher at higher export levels. This prediction has been supported by studies at the CVP.

- Bowen et al. (2004) reported a positive association between secondary louver efficiency and average channel velocity, although the authors state the relationship is weak.
- Sutphin and Bridges (2008) report higher efficiency of the secondary louvers for higher bypass water velocities.
- Channel velocity at the CVP is controlled by the export rate.

The conceptual model predicts that salvage can be used as an index for direct entrainment mortality through the louvers into the intake canals, and also total mortality at the facilities.

- Both intake canal entrainment mortality and total facility mortality (“loss”) are currently estimated as functions of salvage counts.

- However, no studies have been found that directly test the relationship between salvage and total mortality at the facilities.

E.3.2 FINDINGS ON CONCEPTUAL MODEL LINKAGES AND PREDICTIONS: DIRECT MORTALITY FROM THE FISH FACILITIES

E.3.2.1 Understanding Loss Calculations

Before considering the basis of knowledge that supports our conclusions regarding exports and mortality at the facilities, it is helpful to understand the components that comprise facility loss and how they are estimated, and how salvage is incorporated into loss estimates. Direct mortality of juvenile salmon at federal and state water projects is typically attributed to three general components: pre-screen mortality, entrainment into the water project intakes, and within-facility or salvage mortality, which includes mortality due to predation and handling within the facility, during trucking and release, and potentially after release. Pre-screen mortality is defined as mortality occurring on the facility side of the trash racks at the federal facility, and on the facility-side of the radial gates at the entrance to CCF at the SWP, and is assumed to be due to predation.

Loss at the SWP and CVP salvage facilities is estimated from a formula that uses salvage counts as the primary biological input variable (CDFW 2013). From salvage counts, the number of juveniles encountering the fish screens (encounter rate) on the intake canals is estimated based on water-velocity-modulated louver efficiency; from encounter rate, pre-screen mortality (assumed due to predation) is estimated using a formula agreed upon by resource and regulatory agencies. Total loss is equivalent to the number of juveniles encountering the screens, plus the pre-screen predation mortality, minus the number of fish salvaged, plus salvaged juveniles that die during trucking and handling.

Here, we consider three forms of mortality (pre-screen mortality, intake canal entrainment mortality, and within-facility mortality), as well as salvage as linkages between water export operations and survival. We examine what is known about contributions to direct mortality and survival from each component separately, and briefly consider the larger effects of each component on individual-level and population-level survival through the Delta.

One of the challenges of evaluating impacts to or apportioning mortality among different stocks at the salvage facilities is correctly identifying fish (e.g., race, tributary of origin) that enter the facilities relative to those that enter and leave the Delta. Genetic tissue sampling for the winter run has occurred at the fish facilities for many years, and has occurred for some spring-run stocks more recently (Banks et al. 2014; Harvey et al. 2014) but not consistently in monitoring for juvenile salmon entering, within, and leaving the Delta. Genetic sampling of winter and some spring-run stocks of Chinook has also occurred for three years for fish entering the Delta at Sacramento (2009, 2010, and 2011); additional genetic testing is planned for 2016. Additional analyses of these samples could provide an opportunity to better enumerate the proportional mortality of winter-run and spring-run fish entering the fish facilities. Tissue sampling for salmon that enter and leave the Delta would help put the genetic information obtained at the fish facilities into a population context.

Pre-screen Mortality

Our basis of knowledge related to pre-screen mortality of Chinook salmon and steelhead is medium at the SWP fish facility, and low at the CVP fish facility. Multiple non-peer-reviewed agency studies have attempted to directly monitor pre-screen mortality or factors assumed to contribute to pre-screen mortality, for both Chinook salmon and steelhead. Our understanding is lower at the CVP than at the SWP because studies have not been able to successfully partition pre-screen mortality as a part of whole facility loss at the CVP.

Pre-screen mortality is mortality that occurs on the facility side of the trash racks at the CVP and of the radial gates at the entrance to the CCF. It is assumed to result from predation by a large predator population adjacent to the facilities, and from physical structures and altered hydrodynamics that increase predator efficiency. The magnitude and variability of the pre-screen mortality contribution to estimates of overall facility survival and through-Delta survival is unknown, and has been identified as a key uncertainty in attempts to estimate population mortality to direct effects of exports (Kimmerer 2008).

The evidence of mortality due to predation adjacent to the facilities comes from a variety of sources. Indirect evidence from outside of the Delta illustrates that salmonid predators aggregate at areas where migrating smolts are concentrated (Rieman et al. 1991; Ward et al. 1995; Sabal 2014). Within the Delta, Brown et al. (1996) observed that predators are abundant near intakes, screens, and louvers at the CVP and SWP facilities. Furthermore, during a one-month beach seining effort in 1992, more than 80% of the fish sampled from the CCF were striped bass that were large enough to prey on juvenile Chinook salmon (Brown et al. 1996). Gingras and McGee (1997) observed large numbers of predator-sized striped bass move back and forth through the CCF radial gates on very short timescales.

Structures provide conditions that improve predator effectiveness by providing sites used for ambush, and prey may be confused as they pass into or through pipes (Tucker et al. 1998 as cited in Sutphin et al. 2014). Additionally, both the SWP and the CVP have structures that create conditions considered to make juveniles more vulnerable to predators, such as sudden drop in elevation, flow concentration, and changes in light levels in bypass canals that serve to disorient juvenile salmonids and affect their ability to evade predators (Rieman et al. 1991; Larinier 2001 as cited in Sutphin et al. 2014). Clark et al. (2009) reported that 65% (29 of 44) of the tagged steelhead remaining in CCF until the end of an acoustic telemetry study were last detected at the radial gates; several of the tags were stationary, and were assumed to have been consumed and defecated by striped bass; in addition, several steelhead were observed within the intake canal, but never salvaged (Clark et al. 2009). Clark et al. (2009) hypothesized that steelhead may perceive the trash rack at the intake canal as a barrier and congregate there without moving into the salvage facility, which may make them more vulnerable to predation.

Estimates of pre-screen mortality at the Skinner Facility (SWP) ranged from 63 to 99% for a series of tagged Chinook salmon releases between 1976 and 1993 (summarized in Gingras [1997]). Studies conducted with tagged steelhead reported estimated mortality between 78% (+/- 4%, 95% CI) and 82% (+/- 3%, 95% CI) (Clark et al. 2009). These pre-screen mortality rates were considerably higher than those estimated for steelhead once they had entered the Skinner Facility (26%, +/- 7%, 95% CI) (Clark et al. 2009).

In the 2010 VAMP study, a large number of detections at the CCF radial gates of ATs originally inserted into juvenile fall-run Chinook salmon were classified as predator detections based on assumed behavioral differences between Chinook salmon and predators such as striped bass. When detections classified as coming from predators were included in survival analysis, the estimated probability of passing through the CCF entrance channel to the interior CCF was 0.74 (SE=0.04); without those “predator-type detections,” the estimated probability of entering the CCF was reduced to approximately 0.28 to 0.36 (SE=0.05), depending on the status of the gate upon arrival in the entrance channel. In both cases, estimated survival from the radial gates to Chipps Island was very low: 0 without the predator-type detections, and 0.01 with the predator-type detections (SJRGA 2011).

Tracy salvage facilities (CVP) provide favorable habitat for piscivorous fish, primarily striped bass. Striped bass reside around and inside the bypass channels of the salvage facility in higher densities than typically observed in natural settings. These predatory fish take advantage of low velocity holding areas provided by facility structures to prey on smaller fish drawn into the facility, including juvenile salmonids (Liston et al. 1994; Vogel 2010; Sutphin et al. 2014). Mobile monitoring in 2010 suggested predation may still be an issue in front of the CVP trash racks, with a total of 37 ATs detected near this location (SJRGA 2011).

Since 2008, DWR has not allowed installation of AT receivers at the SWP inlet or in the holding tanks; instead, DWR evaluates facility mortality at the CCF and SWP based on passive integrated transponder (PIT)-tagged fish. Allowing the installation of acoustic receivers throughout the SWP would provide additional information on the areas of mortality within the SWP that are of greatest concern to salmon and steelhead. Interrogation of ATs in salvage at the SWP to verify that tags are still in salmonids would inform the various predator data filters that are used in estimating salmonid survival throughout the Delta.

Entrainment into Intakes

Our basis of knowledge for entrainment mortality into the canals at the CVP and SWP fish facilities is high. Early published engineering studies and multiple non-peer-reviewed agency studies have measured intake canal entrainment mortality by monitoring louver efficiency at both fish facilities. The predictability of the relationship is largely constrained by variability in operations or other management actions, but also depends on external factors including fish size.

Entrainment into canal intakes depends on the efficiency of the louver system that is designed to guide fish away from intakes and into the salvage facilities. Louver efficiency varies for size of fish, and between species and facilities, and may be influenced by operational parameters (e.g., day or night operation, water velocity approaching louvers) (Anonymous 2013). Variability in louver efficiency contributes to uncertainty about how salvage and loss rates affect the proportional loss of the population of salmonids by direct entrainment through the louvers at the fish collection facilities and into the pump canals (Kimmerer 2008).

Some early louver efficiency experiments at the Skinner Facility (SWP) and the Tracy Fish Collection Facility (CVP) reported overall efficiency estimates ranging from 50 to 90%, where the lower efficiencies were observed for the smaller fish (less than 38 mm) passing through the system (Skinner 1974; Heubach and Skinner 1978 as summarized in Odenweller and Brown 1982). However, for Chinook salmon ranging in size from approximately 50 mm to 125 mm, smaller fish have been observed to have higher louver efficiency at the SWP (CDWR/CDFG 1973 as cited in Brown et al. 1996; Anonymous 2013). Estimates of overall louver efficiency at CVP from a 1993 study ranged from 12 to 72% (average = 47%) for Chinook salmon; however, these estimates include mortality due to predation within the facility as well as entrainment into the intakes (Karp et al. 1995).

The efficiency of the louver system depends on the efficiency of both the primary and secondary louvers. In 1993, daytime releases of juvenile Chinook at the CVP found the secondary louvers individually were 70 to 87% efficient at recovering Chinook salmon released directly upstream of louvers; as a pair they were 98 to 100% efficient (Karp et al. 1995). The primary louvers recovered only 13 to 25% of fish, but this estimate does not factor out predation mortality between the release site and the holding tanks where fish were recovered, nor fish that exited the facility, which were not identifiable in the study (Karp et al. 1995). Nighttime releases had similar recovery rates for the secondary louvers, but much higher recovery rates for the primary louvers (75 to 77%; Karp et al. 1995). Even greater recovery rates of 81 to 84% occurred for releases upstream of the trash rack at nighttime, suggesting that release strategy above the primary louvers may have accounted for some of the poor performance (Karp et al. 1995). Compared to secondary louvers, primary louvers are also exposed to greater variability in tidal and export driven water velocity and debris load, all of which may have affected louver efficiency measurements. Efficiency of the primary louver system is also related to the behavior of salmonids entering the primary channel. Haefner and Bowen (2002) identified both the cross-channel position of fish as it enters and the energy reserves of those fish as important variables that influence entrainment into the intakes.

Variability has been observed between salmonid species in efficiency estimates for the secondary louver at CVP. In a study of the secondary CVP louver system from March 1996 to November 1997, Bowen et al. (2004) reported average secondary louver efficiency estimates of 85% for Chinook salmon and 100% for steelhead. Bowen et al. (2004) also reported a statistically significant positive association between secondary louver efficiency and average channel velocity, although the authors state that the relationship is too weak to use average channel velocity as a predictor for secondary louver efficiency. More recent fish insertion experiments conducted in May 2005, across a broad range of bypass velocities at the CVP, including lower velocities resulting from export restrictions related to the Biological Opinion (NMFS 2009), suggested a positive effect of bypass water velocity on secondary louver efficiency; efficiency estimates for Chinook salmon ranged from less than 40% at low velocities (less than 1 foot per second [ft/s]) to over 80% at high velocities (greater than 4 ft/s) (Sutphin and Bridges 2008).

Within Facility Mortality

Our basis of knowledge for within-facility mortality is medium at both the CVP and SWP facilities. Multiple agency studies have measured and reported within-facility mortality at the CVP, but there have been fewer studies at the SWP; handling and transport effects have been evaluated in peer-reviewed literature from other systems. The predictability of the relationship is largely constrained by variability in operations or other management actions.

During and after the salvage process, salmonids may be exposed to additional mortality caused by predation within the facility, stressors during handling or trucking, or post release predation. At the CVP, juvenile Chinook salmon survival estimates from just downstream of the secondary louvers to the holding tanks ranged from 91 to 100% in a 1993 study, indicating within-facility predation mortality of up to 9% (Karp et al. 1995). Karp et al. (1995) also reported that the overall survival probability from the primary louvers to the holding tank was estimated at 12 to 24% for daytime releases and 66 to 72% for nighttime releases, although these values represent both canal entrainment mortality (i.e., passing through the louvers) and predation after passing either the primary or secondary louvers and within the holding tank. Predators (e.g., striped bass large enough to eat juvenile Chinook salmon) have been observed in the holding tanks at the CVP (Karp et al. 1995). Comparisons of predator avoidance in laboratory tests indicated that the shape of holding tanks may influence predation rates, but holding time had no significant effect on those tests (Portz 2007).

Sutphin et al. (2014) concluded that the Tracy Fish Collection Facility (CVP) supports a higher density of predators than the natural environment. The secondary channel allows natural light into the water and may explain why more striped bass, which are visual predators, are present relative to tactile predators such as catfish (Sutphin et al. 2014; Stevens 1966 as cited in Sutphin et al. 2014). Furthermore, using a bioenergetics model and salvage estimates, Sutphin et al. (2014) estimated that 6% of the Chinook salmon salvaged in 2005 at the CVP (total of 25,637) were eaten in the secondary channel by predators, with most of the Chinook salmon consumed by striped bass greater than 200 mm FL.

Within-facility mortality at the SWP (i.e., between the trashracks and release from salvage) was estimated for steelhead using PIT tags in 2007, and reported to be between 26% (95% confidence interval = 19 to 33%) and 18% (11 to 25%); estimates ranged from 0 to 83% (Clark et al. 2009). Only pre-screen mortality estimates (i.e., no within-facility mortality estimates) were found for Chinook salmon at the SWP (Gingras 1997).

Salvage handling and trucking may have a variable impact on collected fish. Early studies noted “substantial” trucking and handling mortality for Chinook collected at the CVP (Menchen 1980 as cited in Raquel 1989). Studies of juvenile fishes undertaken to develop an estimate of handling and trucking mortality found that for Chinook salmon at the SWP, mortality during holding and trucking was estimated at 2% for fish less than 100 mm and 0% for larger fish; most mortality was attributed to handling during transfer (Raquel 1989). Karp and Lyons (2008) found 100% survival for 11 steelhead monitored for 24 hours following salvage handling. In general, handling and trucking procedures are not believed to directly cause significant reductions in survival compared to other sources of mortality around the CVP/SWP export facilities (NMFS 1997 as cited in Kimmerer 2008).

It is possible that handling and trucking procedures may contribute to mortality indirectly, however. The stress of handling and transporting salmonids may decrease predator avoidance capability (Olla et al. 1995) and increase susceptibility to predation after release from trucking. In general, handling and transporting salmonids increases physiological indices of stress (Maule et al. 1988; Congleton et al. 2000), and predator avoidance response time may be increased for fish that are exposed to acute handling stress (Sigismondi and Weber 1988). Predators have been found to disproportionately capture stressed salmon compared to unstressed salmon, although salvaged Sacramento Chinook salmon were observed to more closely resemble the stress level of the control group than experimentally stressed groups (Portz 2007).

In addition to the possibility of reduced predator avoidance ability following salvage and trucking, hydroacoustic and DIDSON camera observations have documented aggregations of predatory species at salvage release sites following large releases of transported salmonids (Miranda et al. 2010). Also, hydroacoustics monitoring at the salvage release sites was able to document predator abundance changing between seasons and related to the number of fish being salvaged, with higher abundances in the early spring, summer, fall, and late fall (Miranda et al. 2010). Thus, the release of salvaged fish from single point locations may attract predators and result in higher mortality than if release sites were moved frequently (e.g., Collis et al. 1995).

Salvage

Our basis of knowledge regarding salvage at the fish facilities as an index for mortality at the facilities is minimal. Also, our basis of knowledge regarding population-level effects (e.g., benefits) of salvage is minimal. Multiple studies have measured salvage rates of tagged fish releases at both fish facilities; indirect evidence of salvage is also found via acoustic telemetry studies that are available in agency reports. The relationship between salvage counts and total facility mortality is not well understood, nor is the extent to which operations constrain that relationship.

Despite the risks associated with within-facility mortality and the salvage process, salvage has the potential to improve survival because it moves fish away from the Interior Delta. On the other hand, Muir et al. (2006) observed that transported fish may have increased vulnerability to predation in the estuary or ocean because they are potentially smaller and may have different ocean entry timing than non-transported fish. This mechanism may increase mortality of salvaged rearing salmonids compared to migrants, which spend more time growing within the Delta, by lowering post-release survival. However, travel time differences between transported and non-transported salmonids in the Delta are likely to be small compared to the differences observed by Muir et al. (2006) for Columbia River Basin fish because the travel distance truncated by salvage is much shorter in the Delta.

Salvage rates and the survival of salvaged fish have been estimated but there is considerable uncertainty about the proportion of salmonid migrants that are salvaged annually, and the population-level effect of salvage operations. From recent AT studies in the South Delta, it appears that most of the mortality within the Old River migration route occurred after the fish entered CCF or the CVP or migrated past Highway 4 on Old River, for juvenile Chinook salmon in 2010 and 2011, and for juvenile steelhead in 2011 and 2012 (SJRGA 2011, 2013; Buchanan 2013, 2014; Buchanan et al. 2015). In each of these cases, survival from Mossdale to the facilities (CVP trash rack or CCF radial gates) or Highway 4 (annual average = 0.66 to 0.77 for Chinook salmon, 0.55 to 0.78 for steelhead) was considerably higher than total survival from Mossdale to Chipps Island for fish migrating through the Delta via the Old River route from the head of Old River (annual average = 0.04 to 0.07 for Chinook salmon, 0.07 to 0.52 for steelhead). Furthermore, approximately three times as many Chinook salmon and three to nine times as many steelhead, entered the facilities as arrived at Highway 4 (annual averages). This observation, combined with low survival from the facility entrances or Highway 4 to Chipps Island, suggests that the greatest proportion of mortality in the Old River route in these studies occurred after juvenile salmonids either passed through the CVP trash racks or entered the CCF. In 2012, too few salmon were observed passing the physical barrier at the head of Old River and entering Old River to provide spatially detailed estimates of survival probabilities within the Old River route (Buchanan et al. 2015).

Among the fish that entered the facilities in these acoustic telemetry studies, similar proportions of Chinook passed through the CVP trash racks as entered the CCF in 2010 and 2011 (SJRGA 2011, 2013; Buchanan 2013, 2014). Nevertheless, for Chinook salmon in 2010 and 2011, estimated survival probabilities from the CVP trash rack to Chipps Island (0.20 to 1.00) were higher than from the CCF to Chipps Island (0 to 0.03), indicating higher mortality due to some combination of pre-screen mortality, canal entrainment mortality, and facility mortality at CCF and SWP than at the CVP in those years (SJRGA 2011, 2013). In 2012, very few Chinook salmon were observed entering the Old River route, none were detected at CCF, and only one was detected at the CVP (which was later detected at Chipps Island) (Buchanan et al. 2015). In contrast to Chinook salmon, more steelhead entered the CCF than the CVP in both 2011 and 2012, and no more than 10% of the tagged steelhead detected at Chipps Island came via the CVP in these years (Buchanan 2013, 2014).

Despite the high mortality observed through the facilities in these studies, the route through the CVP salvage, holding tank, and truck transport sometimes provided the majority of the tagged Chinook salmon observed at Chipps Island from all possible migration routes through the South Delta. In 2010 and 2011, over 60% of the acoustic-tagged Chinook salmon detected at Chipps Island came through the salvage facilities and truck transport at CVP (SJRGA 2011, 2013). In 2010, 19 of the 20 acoustic-tagged juvenile Chinook salmon that survived to Chipps Island via the head of Old River route, and of the 29 tagged salmon that survived to Chipps Island via all routes combined, came by way of salvage at the CVP (Buchanan et al. 2013), suggesting that survival through the CVP was higher than through all alternative South Delta routes. However, the estimated transition probability from the CVP trash racks to the holding tanks in 2011 was only 0.23 (SE=0.03), implying that there is considerable mortality in the CVP migration route. Additionally, based on acoustic data, the per-kilometer survival rate from the radial gates at CCF to Chipps Island was the lowest of all Interior Delta routes for Chinook salmon and steelhead (Figures E.4-5 and E.4-6, Table E.4-3).

The proportion of various salmon populations that are salvaged or lost to the facilities is not well understood. Overall, low survival prior to the facilities will result in low salvage rates because few fish are available, and vice versa. Zeug and Cavallo (2014) reported that 0.2% of CWT late-fall-run Chinook salmon released in the Sacramento River basin from 1993 to 2007 were salvaged. This result suggests that a small proportion of the population of juvenile Chinook salmon enter the facilities. However, this estimate includes mortality experienced from the release site to the Delta, selection of the facilities route among all routes through the Delta, and mortality during migration through the Delta to the fish facilities, in addition to salvage and facility mortality. For example, from 64 to 100% of acoustic-tagged fish that were released in the Sacramento River died before arriving at the Delta (fifth column in Table E.2-2). Also, release site and export conditions may affect the proportion lost to the facilities. For example, Zeug and Cavallo (2014) reported that relative loss (i.e., combined loss at the diversions [CVP + SWP] compared to total migration mortality) ranged from less than 1 to 17.5% for San Joaquin River fall-run Chinook salmon depending on diversion rate and release location. Newman and Brandes (2010) examined CWT data from late-fall-run Chinook salmon released from 1993 to 2005, and found that the proportion of fish released into Georgiana Slough that were subsequently recovered in salvage varied between 0 and 2.5%, and was higher as exports increased.

For juvenile winter-run Chinook salmon, estimates of combined facility loss as a proportion of the juvenile population are based on Delta length-at-date race assignments from fish observed during salvage sampling at the facilities (Harvey et al. 2014); juvenile population abundance is taken from the juvenile production estimate (JPE), an estimate of the number of juvenile winter-run salmon from each brood year that enter the Delta (Pyper et al. 2013). It should be noted that the false positive error rate for the Delta length-at-date race assignment of winter run varies among years, depending on the relative numbers of Chinook juveniles from all races that are encountered at the fish facility and fall into the winter-run length-at-date category (Harvey et al. 2014). This fact is addressed in the Endangered Species Act (ESA) take limits for winter run, which allow half of all winter-run-length fish to be considered non-winter-run. However, genetic testing has shown the false positive error rate to vary widely both inter- and intra-annually, with incidents of both positive and negative bias occurring in annual take estimates over the years (Harvey et al. 2014). A program of rapid genetic testing of salvaged winter-run length fish has been implemented in recent years to provide more accurate take estimates.

E.3.2.2 Summary: Direct Mortality

There is evidence of direct mortality at the facilities in several components: pre-screen mortality after passing the trash racks at CVP or entering the CCF radial gates; entrainment mortality in the intake canals due to variable louver efficiency; and within-facility mortality due to predation after passing the louvers or stressors during salvage. Survival of Chinook salmon is low in both facilities, and especially in the CCF. Survival of steelhead appears to be higher, but there is considerable uncertainty because only a few years of data are available for steelhead. However, although there is evidence of direct facility mortality of juvenile salmonids, the available data suggest that direct facility mortality is not the primary cause of low salmonid survival in the Delta. The population-level effect of direct mortality due to the facilities is difficult to estimate and varies with run and diversion rates; available estimates of combined mortality at the facilities as a proportion of total migration mortality have ranged from less than 1 to 5.5% for winter-run Chinook salmon, and from less than 1 to 17.5% for San Joaquin River fall-run Chinook salmon (Zeug and Cavallo 2014). Additionally, in some recent acoustic telemetry studies of Chinook salmon released in the San Joaquin River, salvage at the CVP provided the most surviving fish to Chipps Island of all routes through the Delta, possibly because survival has been very low in all routes.

In conclusion, there has been considerable attention devoted to the components of direct mortality at the CVP and SWP/CCF. However, estimates of mortality (pre-screen mortality and louver efficiency) have shown high variability between years and species. The estimation of total loss depends on relationships between export rates and pre-screen mortality and entrainment. At very low regional survival rates, migration to the Delta exit at Chipps Island has been shown to be more successful through the CVP than through Delta waters, reflecting the complicated effect of export operations on the migration population.

Suggestions for actions to reduce direct facility mortality include:

- Control predator populations in the CCF and behind the CVP trash racks.
- Control secondary louver efficiency by control of bypass water velocities.
- Keep primary and secondary louvers free from debris, but also reduce time when they are inoperable for cleaning.
- Improve salmon passage within the CVP, and decrease predator passage within the CVP.
- Consider alternate truck release locations of salvaged fish to prevent large predator assemblages.

E.3.3 SUMMARY: KNOWLEDGE GAPS ON DIRECT MORTALITY

There is a need for improved understanding of the factors affecting direct mortality at the facilities and the population-level effect of this type of mortality, including:

- Improved identification of run among salvaged fish at the fish facilities
- Improved estimates of juvenile abundance for population-level loss estimates
- Improved identification of mortality hot spots within the facilities, including within the CCF
- Additional and/or improved estimates of pre-screen mortality and predation pressure within the CCF for both Chinook salmon and steelhead
- Better understanding of salmonid and predator behavior in and around the facilities
- Estimates of pre-screen mortality at the CVP separate from whole facility mortality
- Improved estimates of primary louver efficiency at the CVP, separated from within-facility predation
- Variability in the relationship between salvage counts and total facility mortality within and between different populations of salmonids
- Magnitude and variability of the pre-screen mortality contribution to estimates of overall facility survival and through-Delta survival
- Improved understanding of mortality during salvage handling and trucking, and the extent to which moving release locations often may reduce post-release mortality

Several of these data gaps may be addressed by tagging studies. However, the potential of detecting tags from predated salmonids complicates interpretation of acoustic telemetry data in predator-rich environments. Development and use of an effective predation tag, or other method to precisely indicate when a tagged study fish has been predated, would be useful. Such tags are in testing or are newly available.

E.4 SURVIVAL AS A FUNCTION OF ROUTE SELECTION

The conceptual model assumes that route selection is a major factor in determining the probability of survival, as migrating fish enter or avoid habitats that vary in predation pressure, entrainment risk in the water export facilities or other pump intakes, and water quality (e.g., temperature). The underlying hypothesis of this component of the conceptual model is that different routes through the Delta have probabilities of survival that vary in a predictable way. For example, because the water export facilities are located on or near Old River in the Interior Delta, it is reasonable to expect that the migration route through the South Delta that uses Old River at its distribution point from the San Joaquin River is likely to have lower probability of survival through the Delta than the route that uses the San Joaquin River at that river junction. Fish that enter the Interior Delta from distribution points farther downstream on the San Joaquin River (e.g., Turner Cut or Columbia Cut) or via Georgiana Slough are expected to have lower survival through the Delta than fish that remain on the mainstem river, whether they are migrating from the San Joaquin River or from the Sacramento River. In addition, survival rates (per kilometer) are expected to vary among regions within the Delta because of differences in habitat and predation pressure.

In this section, predictions from the conceptual model regarding migration route and survival are identified and reviewed considering findings from both Chinook salmon and steelhead. Our primary focus in this section is on survival of fish migrating from the San Joaquin River through the Delta (Figure E.2-2).

E.4.1 SUMMARY: CONCEPTUAL MODEL PREDICTIONS ON SURVIVAL AS A FUNCTION OF ROUTE SELECTION

The conceptual model predicted that survival through the South Delta is higher in the San Joaquin River route than in the Old River route, from the head of Old River to Chipps Island.

- Results from CWT studies from 1985 to 1990 are consistent with that hypothesis, but acoustic telemetry data from 2010 to 2012 have generally not been consistent with that hypothesis. In most years, there was no significant difference between survival in the two routes, based on AT data, and survival has been very low in both routes. Survival from AT data was higher in the San Joaquin River route for one release group

(in 2010), and higher in the Old River route for four release groups (in 2010 and 2011).
- The routes that include the water export facilities tend to have the lowest survival through the Delta, including the route from Turner Cut through the Interior Delta.
- However, estimated survival from the CVP to Chipps Island was sometimes higher than survival estimates through the lower San Joaquin River reaches. Approaching the CVP appears to have high risk of predation, but successful passage to and through the salvage system enables the fish to avoid migrating through the rest of the Interior Delta.

The conceptual model predicts that survival to Chipps Island from downstream entry points to the Interior Delta is higher for fish that remain in the San Joaquin River mainstem than for fish that enter the Interior Delta. This finding has partial support from data.
- Survival from the Turner Cut junction to Chipps Island has consistently been higher for fish that remain in the San Joaquin River at that junction than for fish that enter Turner Cut, for both Chinook salmon and steelhead. This is despite the possibility that fish that stay in the San Joaquin River at Turner Cut may enter the Interior Delta further downstream.
- No data are available for other junctions on the San Joaquin River, including Columbia Cut, Old River mouth, and Middle River mouth.

The conceptual model predicts that survival rates per kilometer will vary in different reaches of the Delta because of differences in habitat and predation pressure. This finding has partial support from data.
- Survival rate per kilometer tends to be higher in the upstream reaches and in the San Joaquin River mainstem compared to the Interior Delta, although survival rate through the lower San Joaquin River reaches appears comparable to survival through Interior Delta reaches.
- The linkages relating survival rate to migration route are not well understood. Predation is hypothesized to be a major factor in mortality, but there is little direct information on predation rates, predator communities, and habitat characteristics that might affect predation rates throughout the South Delta.
- Entrainment is also hypothesized to be a major factor in mortality; because it is pertinent only to fish passing the fish facilities, it may contribute to differences in survival rate in different regions of the Delta. Survival of acoustic-tagged salmonids tends to be low in the reaches that include the SWP and CVP facilities, but mortality due to entrainment into the canals is not estimated separately from predation mortality in the available studies. Additionally, survival from the CVP to Chipps Island was sometimes higher than survival through the lower San Joaquin River reaches. Entrainment is addressed further in Section E.3.

The interannual variability observed among the Chinook salmon data suggest that more survival data are necessary to draw firm conclusions about many of the reaches, for Chinook salmon and especially steelhead. However, the following conclusions can be made even with the observed variability:

- Entering the Interior Delta at Turner Cut is not a successful migration route for Chinook salmon, and has low (but greater than 0) survival compared to other routes for steelhead.
- For Chinook salmon that approach the water export facilities, the route through the CVP has higher survival than the route through the CCF and SWP.
- For Chinook salmon, the survival rate per kilometer tends to be lower through the city of Stockton than from Lathrop to Stockton.

E.4.2 FINDINGS ON CONCEPTUAL MODEL LINKAGES AND PREDICTIONS: EFFECTS OF ROUTE SELECTION ON SURVIVAL

We first describe the major routes through the Delta and examine findings on their relative survival. We then examine survival in different reaches of the various routes to explain any differences in route selection observed or the lack of anticipated differences. We then consider possible mechanisms linking migration route and survival.

Two primary migration routes through the Delta were examined for salmonids migrating from the San Joaquin River: the “San Joaquin River route” (Figure E.4-1) and the “Old River route” (Figure E.4-2), classified by route selection at the head of Old River. Migration through the CVP and SWP fish facilities is a component of both the Old River route and the San Joaquin River route (for fish that enter the Interior Delta at Turner Cut or downstream); the analysis of migration through the fish facilities is described separately in Section E.3 because of the unique operational and facility attributes that exist at those facilities. Within the San Joaquin River route, we also examined the use of Turner Cut, which diverts fish from the San Joaquin River to the Interior Delta. Because the San Joaquin River route includes the Interior Delta, the Old River and San Joaquin River migration routes encompass potentially overlapping migration regions. The primary differences in the routes are the upstream reaches, the proportion of fish actually entering the Interior Delta from the two routes, and the entry points to the Interior Delta.

It should be noted that migrating salmonids can also enter the Interior Delta through other junctions on the San Joaquin River downstream of Turner Cut (Columbia Cut, OMR, and False River; Figure E.2-2). We do not examine these other junctions here because there are no data on their use, but we recognize that they may be important entrances to the Interior Delta.

We first examined broad scale route-specific survival from the head of Old River junction through the Old River and San Joaquin River routes, then focused on reach-specific information to better understand patterns of survival at a smaller spatial scale. Finally, we looked at the evidence to link route and reach survival to specific mechanisms.

For all routes, the outcome evaluated is survival, and conversely mortality. The linkages between migration route and survival are exposure to variables (e.g., habitat and predators) that affect survival between routes or between years for the same route (Figure E.1-1, Table E.1-1).

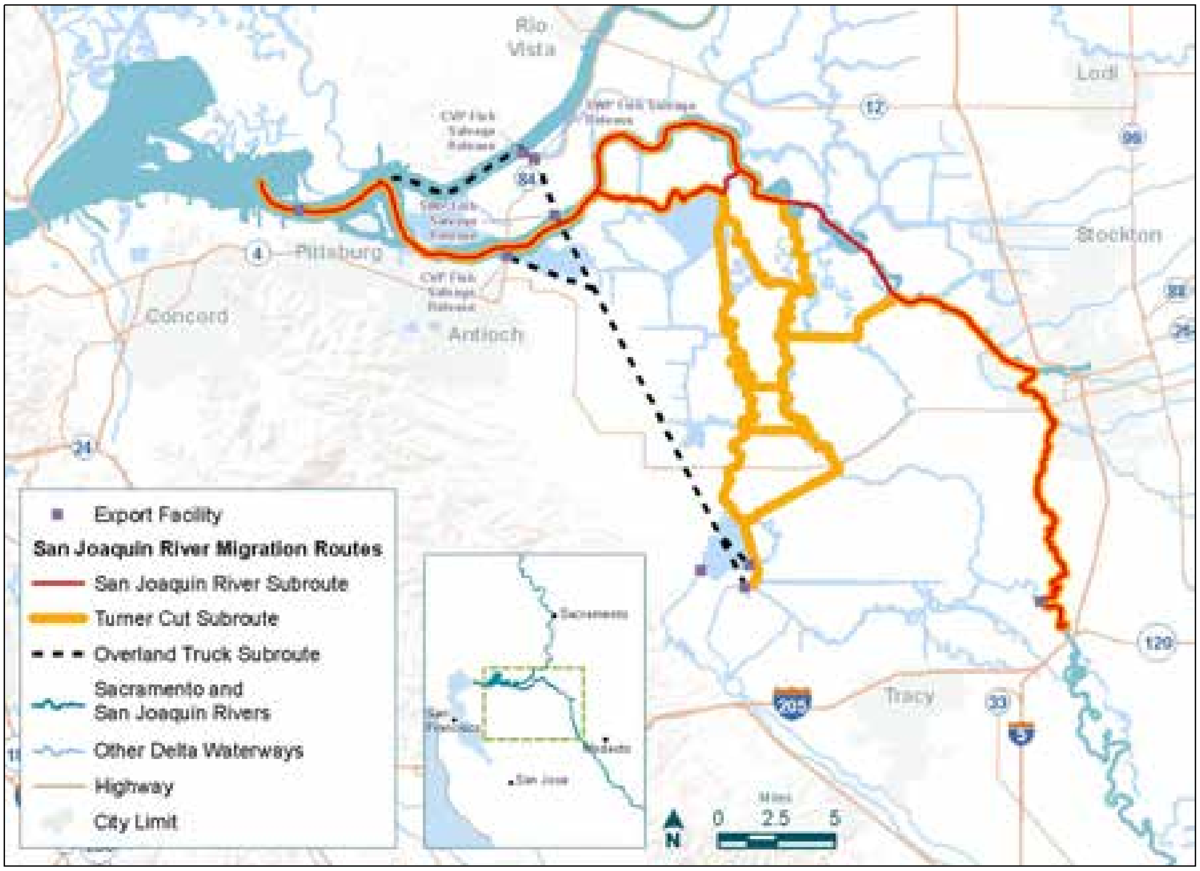


Figure E.4-1. Migration Routes to Chipps Island for Fish that Remain in the San Joaquin River at the Head of Old River ("San Joaquin River Route")

Note: Migration route of salvaged fish is shown as dashed line. The San Joaquin River mainstem sub-route is shaded in red, and the Turner Cut sub-route through the Interior Delta is shaded in orange.

E.4.2.1 Route Survival from Head of Old River Junction

Our basis of knowledge regarding how migration route selection at the head of Old River affects juvenile Chinook salmon through-Delta survival is low. Multiple field studies have collected Chinook salmon data on this question, and results have been presented in peer-reviewed publications, agency reports, and this report. However, the route from the head of Old River that produced the highest through-Delta survival has varied across and within years. Our basis of knowledge regarding migration route selection at the head of

Old River and juvenile steelhead through-Delta survival is low. A single multi-year field study has collected steelhead data on this question, and results are available in technical reports and in this report. The extent to which operations constrain the relationship between route selection at the head of Old River and through-Delta survival is not well understood.

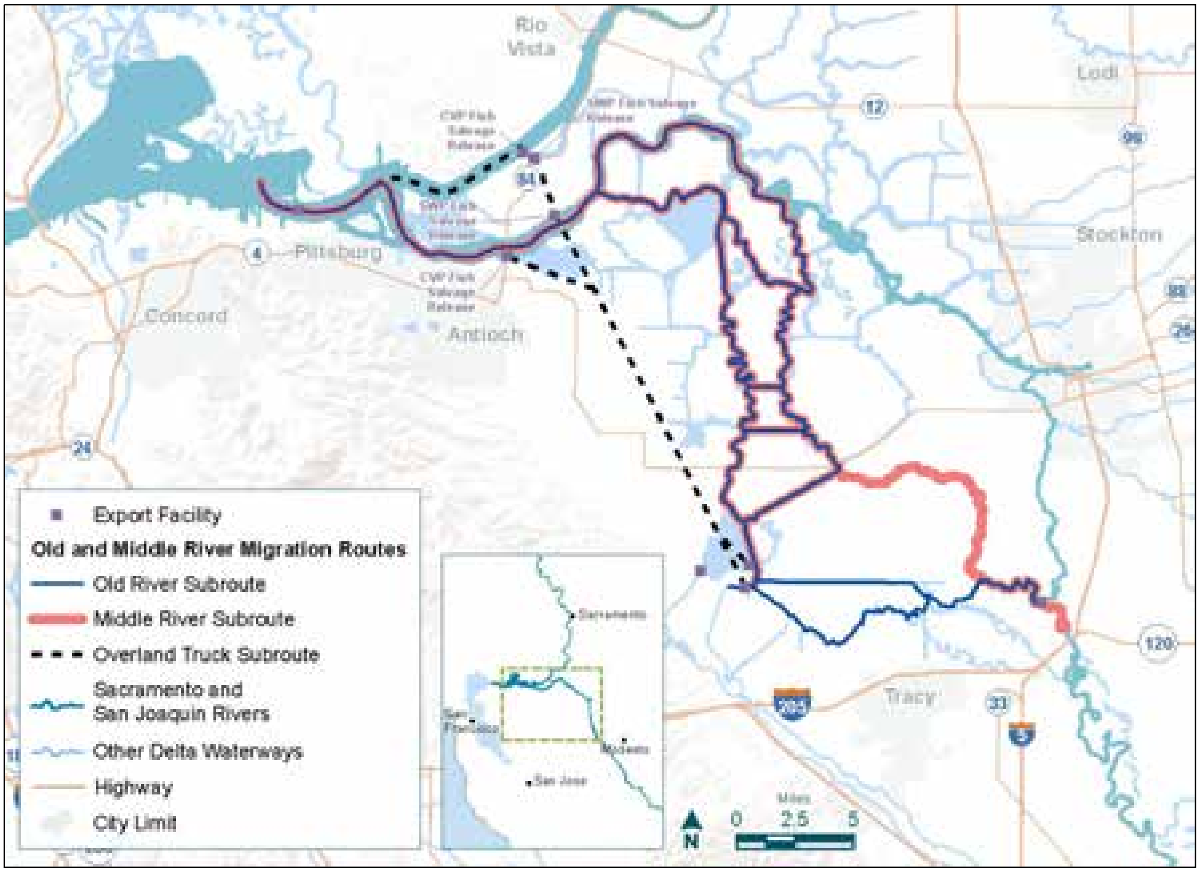


Figure E.4-2. Migration Routes to Chipps Island for Fish that Enter Old River at the Head of Old River ("Old River Route")

Note: Migration route of salvaged fish is shown as dashed line. The Old River sub-route is shaded blue, and the Middle River sub-route is shaded pink.

At the head of Old River, fish enter one of two routes. Fish may enter Old River and move into the Interior Delta or fish may remain in the San Joaquin River (Figure E.4-1, Figure E.4-2). Fish that remain in the San Joaquin River, however, may enter the Interior Delta further downstream (e.g., through Turner Cut, Columbia Cut and OMR, and False River; Figure E.2-1). In many years, a temporary physical barrier has been installed at the head of Old River to reduce the number of migrating salmon entering the Interior Delta at that river junction. In 2009 and 2010, an experimental non-physical barrier (bioacoustic fish fence) was tested in place of the physical barrier. In 2012, the physical barrier was installed (DWR 2015).

Measures of survival for fall-run Chinook salmon are available from CWT releases into Old River and at Dos Reis in 1985 to 1990 (Brandes and McLain 2001), and from acoustic-tagging studies in 2008 and 2010 to 2012 (Holbrook et al. 2009; SJRGA 2011, 2013; Buchanan et al. 2015). The relative survival to Chipps Island of Chinook salmon that entered Old River versus those that remained in the San Joaquin River route at the head of Old River has varied in these years. Survival indices (i.e., recovery rates expanded by sampling effort) to the Chipps Island trawl of CWT fish in 1985 to 1990 were generally greater for fish released at Dos Reis in the San Joaquin River compared to those released into upper Old River (Figure E.4-3; Brandes and McLain 2001; Newman 2008). There has been no consistent pattern among the AT data, and survival estimates have been similar (≤0.16) in both routes (Figure E.4-3, Table E.4-1).

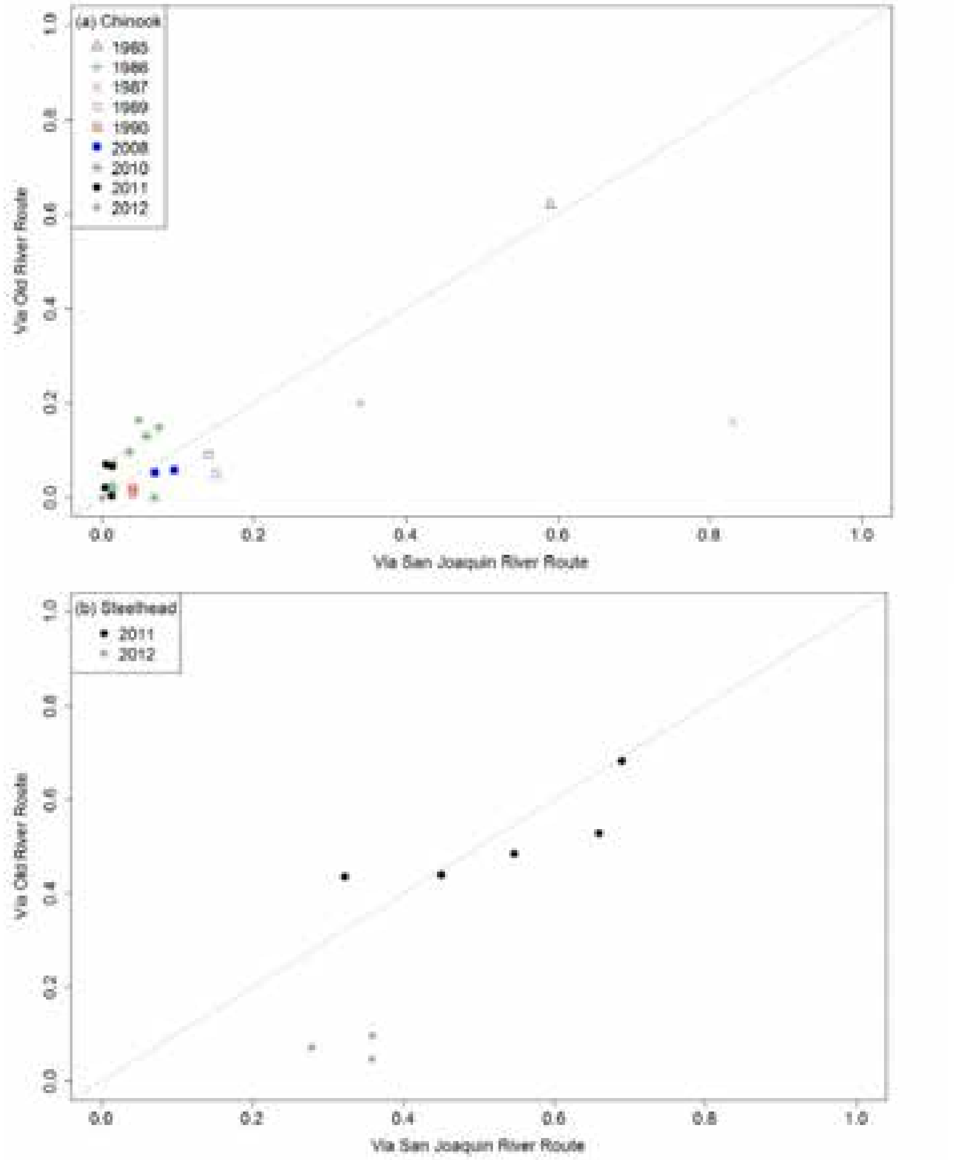


Figure E.4-3. Estimates of Route-specific Survival to Chipps Island via the Old River Route Versus the San Joaquin River Route, from CWT Salmon and AT Salmon (a) and Steelhead (b) Studies

Note: Chinook: Years 1985 – 1990 are CWT survival indices (recoveries expanded by sampling effort) to Chipps Island from release in upper Old River or Dos Reis in the San Joaquin River; years 2008 – 2012 are AT survival estimates from Mossdale. Dashed line indicates equal survival between routes. Sources: Brandes and McLain 2001; Holbrook et al. 2009; SJRGA 2011, 2013; Buchanan et al. 2015; Buchanan 2013, 2014.

Table E.4-1. Entrainment Rates and Route Specific Survival to Chipps Island for Acoustic-tagged Fall-run Chinook and Steelhead Released in the San Joaquin River

Species	Year	Number of Release Groups	Entrainment into Old River (SE)	Survival through South Delta[2] (SE)	Route-Specific Survival to Chipps: San Joaquin	Route-Specific Survival to Chipps: Old River
Fall-run Chinook	2008[1]	2	0.66 (0.03)	NA	0.08 (0.01)	0.06 (0.01)
	2009	3	0.53 (0.03)	0.06 (0.01)	NA	NA
	2010	7	0.53 (0.02)	0.56 (0.03)	0.04 (0.01)	0.07 (0.01)
	2011	4	0.42 (0.01)	0.56 (0.01)	0.01 (less than0.01)	0.04 (0.01)
	2012	2	0.02 (0.01)	0.23 (0.02) (SJR route)	0.03 (0.01)	0.11 (0.10)
Steelhead	2011	5	0.49 (0.02)	0.81 (0.01)	0.55 (0.02)	0.52 (0.02)
	2012	3	0.06 (0.01)	0.81 (0.02)	0.33 (0.02)	0.07 (0.03)

Notes: 1 = Minimum estimates of survival due to high tag failure. 2 = "South Delta" = from Mossdale to either the Turner Cut junction in the San Joaquin River or the water export facilities, or Highway 4 on OMR. Sources: Holbrook et al. 2009; SJRGA 2010, 2011, 2013; Buchanan et al. 2015; Buchanan 2013, 2014.

In 1985 to 1990 (CWT survival indices), the Chinook salmon survival index to Chipps Island was greater for the San Joaquin River release than for the Old River release for all but one release group (Figure E.4-3); no barrier was installed in these years (Brandes and McLain 2001). In 2008 (no barrier), acoustic-tagged Chinook salmon that remained in the San Joaquin River at the head of Old River had higher apparent survival than fish that entered Old River, although fish mortality was confounded with a high rate of premature tag failure (Holbrook et al. 2009) and there was no predator filter applied that year. In 2010 (non-physical barrier), the relative survival of Chinook salmon in the San Joaquin River route versus those that took the Old River route varied throughout the study: only the first release group had significant differences between routes, with higher survival in the San Joaquin River, but when pooled across all releases, fish that took the Old River route had higher survival (SJRGA 2011). In 2011 (no barrier), survival to Chipps Island was consistently low, but was higher (less than 0.05) for the Old River route than for the San Joaquin River route for the two groups released during higher export levels. There were no significant differences between routes for the other individual release groups in 2010 or 2011 (SJRGA 2013). In 2012 (physical barrier), survival was not significantly different for fish that remained in Old River, but very few (ten) fish migrated through that route, increasing the uncertainty in the estimate (Buchanan et al. 2015).

Acoustic telemetry studies using juvenile steelhead began in 2011 as part of the six-year study, and results are available from the 2011 and 2012 studies (Buchanan 2013, 2014). In 2011 (no barrier), route-specific survival to Chipps Island varied throughout the study, and survival depended significantly on route for only one of five release groups; for this group, survival was higher in the San Joaquin River route. Averaged over all release groups, there was no statistical difference in survival between routes. In 2012 (physical barrier), survival was consistently higher in the San Joaquin River route than in the Old River route (Figure E.4-3, Table E.4-1; Buchanan 2013, 2014).

A comprehensive analysis of the existing acoustic telemetry data from fall Chinook salmon and steelhead that combines data from multiple years has not been performed. However, work to examine multiple years of AT data from fall Chinook salmon is underway (R. Buchanan, personal communication). Similar work is planned for steelhead as part of the six-year study, but requires more individual years of acoustic telemetry data than are currently available (J. Israel, USBR, personal communication).

E.4.2.2 Route Survival from Turner Cut Junction

Our basis of knowledge regarding migration route selection at the Turner Cut junction and survival to Chipps Island is low. Several years of field studies have collected data relevant to this question for both Chinook salmon and steelhead, and results are presented in this report. The extent to which operations constrain the relationship between migration route selection at the Turner Cut junction and through-Delta survival is not well understood.

Turner Cut connects the Interior Delta with the San Joaquin River from approximately 10 km downstream of the city of Stockton, California (Figures E.2-1 and E.2-2). Fish entering the Interior Delta at Turner Cut may either eventually turn north and navigate out of the Delta through the Delta channels, or they may turn south and enter the water export facilities, where they may be salvaged and trucked to a release point just upstream of the Delta exit at Chipps Island (Figure E.4-1). Mortality occurs along all portions of all routes. Fish that remain in the San Joaquin River at Turner Cut may either continue to Chipps Island via the San Joaquin River, or they may enter the Interior Delta from downstream entrance points (Columbia Cut, OMR, or False River). Estimates of survival from the Turner Cut junction to Chipps Island via these two major routes are available from acoustic-tagged studies in 2008 and 2010 to 2012 for Chinook salmon (Holbrook et al. 2009; SJRGA 2011, 2013; Buchanan et al. 2015) and 2011 to 2012 for steelhead (Buchanan 2013, 2014).

For Chinook salmon, estimated survival to Chipps Island in the Turner Cut route was 0 for all but one release group; the only fish observed successfully moving from Turner Cut to Chipps Island passed through the CVP holding tank in 2008 (Holbrook et al. 2009). Survival from the Turner Cut junction to Chipps Island in the San Joaquin River route was consistently higher except for one release group from 2012, when survival was 0 in both routes (Figure E.4-4a); however, survival to the Turner Cut junction was very low for that release group, and there were very few fish available for estimating survival downstream of that junction. For steelhead, estimated survival to Chipps Island was positive in both routes for all release groups, but survival was consistently higher for fish that stayed in the San Joaquin River at the Turner Cut junction (Figure E.4-4b).

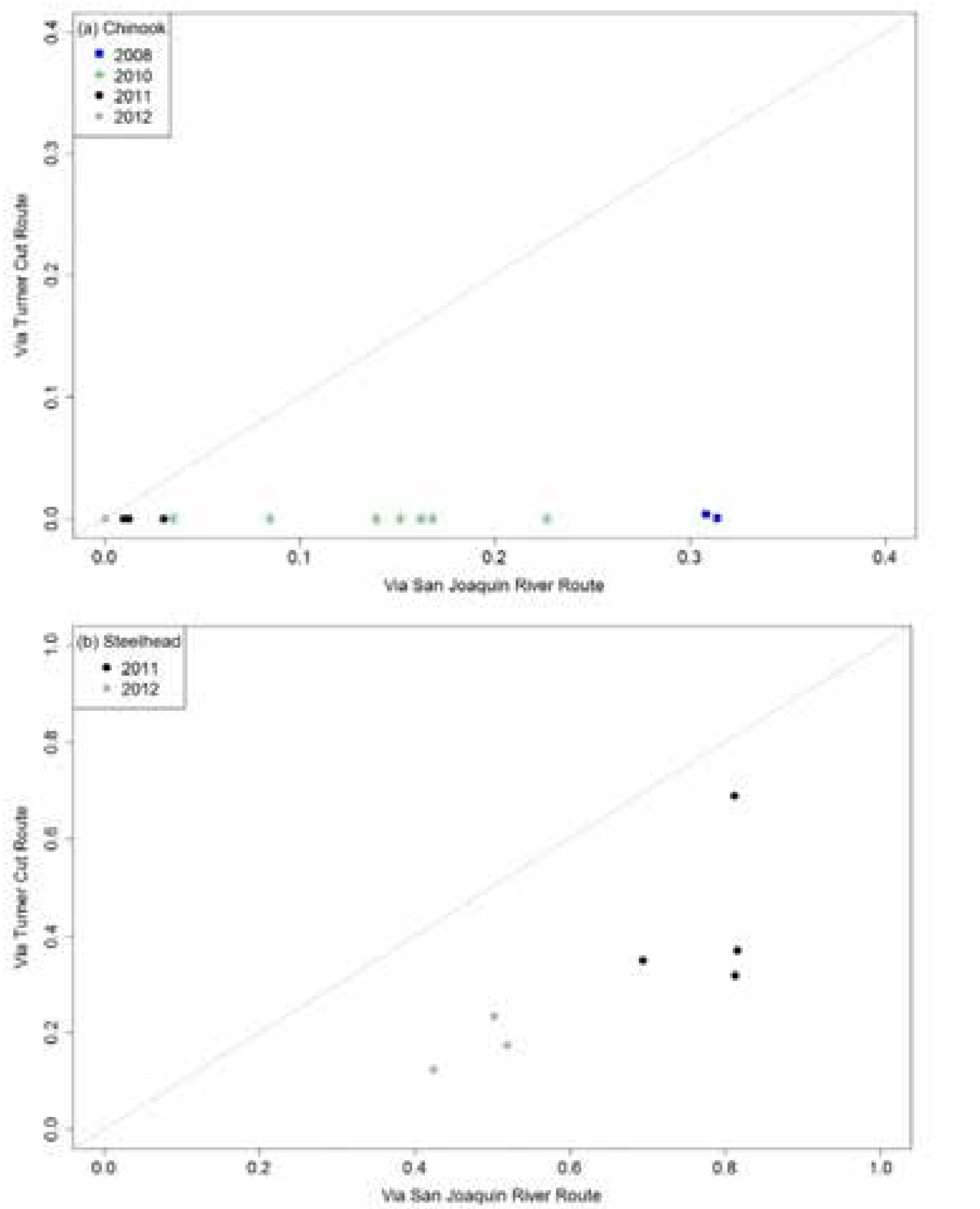


Figure E.4-4. Estimates of Route-specific Survival from Turner Cut Junction to Chipps Island via the Turner Cut Route Versus the San Joaquin River Route, from AT Salmon (a) and Steelhead (b) Studies

Sources: Holbrook et al. 2009; SJRGA 2011, 2013; Buchanan et al. 2015; Buchanan 2013, 2014.
Notes: Dashed line indicates equal survival between routes.

The impact on through-Delta survival of the typically low probability of survival to Chipps Island for fish that enter the Turner Cut route depends on the proportion of migrating fish that enter Turner Cut. For AT fall-run Chinook salmon that survived to the Turner Cut junction in the 2008 to 2012 San Joaquin River tagging studies, the estimated probability of entering Turner Cut ranged from 0 for two release groups in 2009 and one group in 2010, to 0.32 (SE=0.05) for one release group in 2008 (mean = 0.12, SE=0.02) (Holbrook et al. 2009; SJRGA 2011, 2013; Buchanan et al. 2015). Thus, for Chinook salmon that remain in the San Joaquin River past the head of Old River, the expected impact of the very low survival expected in the Turner Cut route is variable but expected to be fairly low. For acoustic-tagged steelhead from the first two years of the six-year study, the probability of entering Turner Cut (for fish that survived to the Turner Cut junction) ranged from 0.09 (SE=0.02) for one release group in 2011, to 0.37 (SE=0.04) for a single release group in 2012 (mean = 0.26, SE=0.03) (Buchanan 2013, 2014). Overall, it appears that steelhead are more likely than Chinook salmon to enter Turner Cut, and that they are more likely to successfully reach Chipps Island after entering Turner Cut (no formal testing has been done).

The full impact of low survival in the Turner Cut route depends not only on route selection probabilities at the Turner Cut junction, but also on route selection probabilities at all other river junctions along the San Joaquin River migration route: head of Old River, Columbia Cut, and the downstream confluence of the San Joaquin River with OMR. The effectiveness of blocking the Turner Cut route will depend on how that action changes route selection probabilities at downstream junctions (e.g., Columbia Cut). Also pertinent are the relative survival probabilities in those alternative routes; if survival is very low in all routes, then improvements to survival in the Turner Cut route will have minimal effect on overall survival through the Delta. A formal sensitivity analysis of through-Delta survival to either the probability of entering Turner Cut or the low survival once in Turner Cut has not yet been performed for either Chinook salmon or steelhead, although such analysis is planned (R. Buchanan, personal communication). Nevertheless, despite the uncertainty, a tentative conclusion is that the increase in overall Delta survival resulting from either improving survival in the Turner Cut route or else blocking salmon from entering Turner Cut is expected to be small, and will likely be insufficient to raise Delta survival rates to desired levels without additional improvements in survival elsewhere in the Delta.

E.4.2.3 Route Survival within Interior Delta

Our basis of knowledge regarding route selection and route-specific survival within the Interior Delta is minimal. Few studies have attempted to measure route selection or route-specific survival within the Interior Delta; the single study found was published in an agency report. The extent to which operations constrain the relationship between route selection in the Interior Delta and survival in the Interior Delta is not well understood.

The complexity of the channels in the Interior Delta and the strong tidal influence in this region has prevented robust estimation of route selection and route-specific survival in the Interior Delta. The AT Chinook salmon studies and the six-year steelhead study estimate the probability of successfully moving from one location in the Interior Delta to another (e.g., from Turner Cut to the CCF), but do not attempt to separate the probability of dying along a particular route from the probability of selecting an alternative route (SJRGA 2010, 2011, 2013; Buchanan 2013, 2014; Buchanan et al. 2015). Survival estimates are available from some locations in the Interior Delta to Chipps Island from these AT studies (see "Reach Survival" below). The 2012 steelhead stipulation study measured route selection at the junction of Railroad Cut with Old River but did not measure route-specific survival from that junction to Chipps Island (Delaney et al. 2014).

E.4.2.4 Reach Survival

Our basis of knowledge regarding differential survival in various river reaches and regions of the South Delta is medium. Several years of field studies have collected data relevant to this question for both Chinook salmon and steelhead; individual year results are presented in technical reports and peer-reviewed literature, and data compilations across multiple years are presented in this report. The extent to which operations constrain differential survival in various river reaches and regions of the Delta is not well understood.

We next examined survival rates at the reach scale for Chinook salmon and steelhead in the San Joaquin River and Old River to see how specific reaches contribute to route-specific survival. The examination used reaches and subreaches that generally corresponded with landmarks from previous studies and important junction locations within the Interior Delta, including the head of Old River, Lathrop, and the Turner Cut junction (Figure E.2-2). For the San Joaquin River route, these reaches were: 1) Lathrop to Stockton Deep Water Ship Channel (SDWSC); 2) SDWSC to Turner Cut; and 3) Turner Cut to Chipps Island. The breakdown of estimated survival rate per kilometer within reaches and subreaches is presented in Table E.4-2, Figure E.4-5, and Figure E.4-6 for years with data available. The Old River reaches included parts of Old River, Middle River, Grant Line Canal, and the fish facilities, as described in Section 4.2.2.2.

Table E.4-2. Heat Map Depicting Survival Rates ($S^{(1/km)}$) Through San Joaquin River Reaches to Chipps Island

	Survival estimate per km ($S^{(1/km)}$)						
	Chinook					Steelhead	
Reach Name (km)	2008	2009	2010	2011	2012	2011	2012
Durham Ferry (Release) to Banta Carbona (11)			0.999	0.994	0.975	0.962	0.967
Banta Carbona to Mossdale (10/9)			0.995	0.993	0.953	0.982	0.978
Mossdale to Head of Old River (4/5)	0.967	0.954	0.981	0.997	0.987	0.985	0.995
Lathrop to SJR at Garwood Bridge (18/15)	0.986	0.971	0.989	0.993	0.980	0.995	0.997

Reach Name (km)	Survival estimate per km ($S^{(1/km)}$)						
	Chinook					Steelhead	
	2008	2009	2010	2011	2012	2011	2012
Garwood Bridge to SDWSC (3)	0.955	0.921	0.983	0.980	0.936	0.993	0.990
SDWSC to Turner Cut junction (15)	0.958	0.852	0.942	0.965	0.947	0.997	0.994
MacDonald Island to Medford Island (5)			0.863	0.833	0.852	0.942	0.923
Turner Cut to Jersey Point (includes Interior Delta route but not SJR) (28)	0			0	0	0.958	0.934
Medford Island to Jersey Point (21)				0.881	0.964	0.992	0.987
Jersey Point to Chipps Island (22)	0.981			0.983	0.971	0.997	0.989

Notes: Red boxes indicate lowest survival rate (less than 0.90 per km) and lighter boxes indicate higher survival rate (white: ≥ 0.99 per km). Missing values reflect too few fish present in the reach to estimate survival, or the study was not designed to estimate parameter.

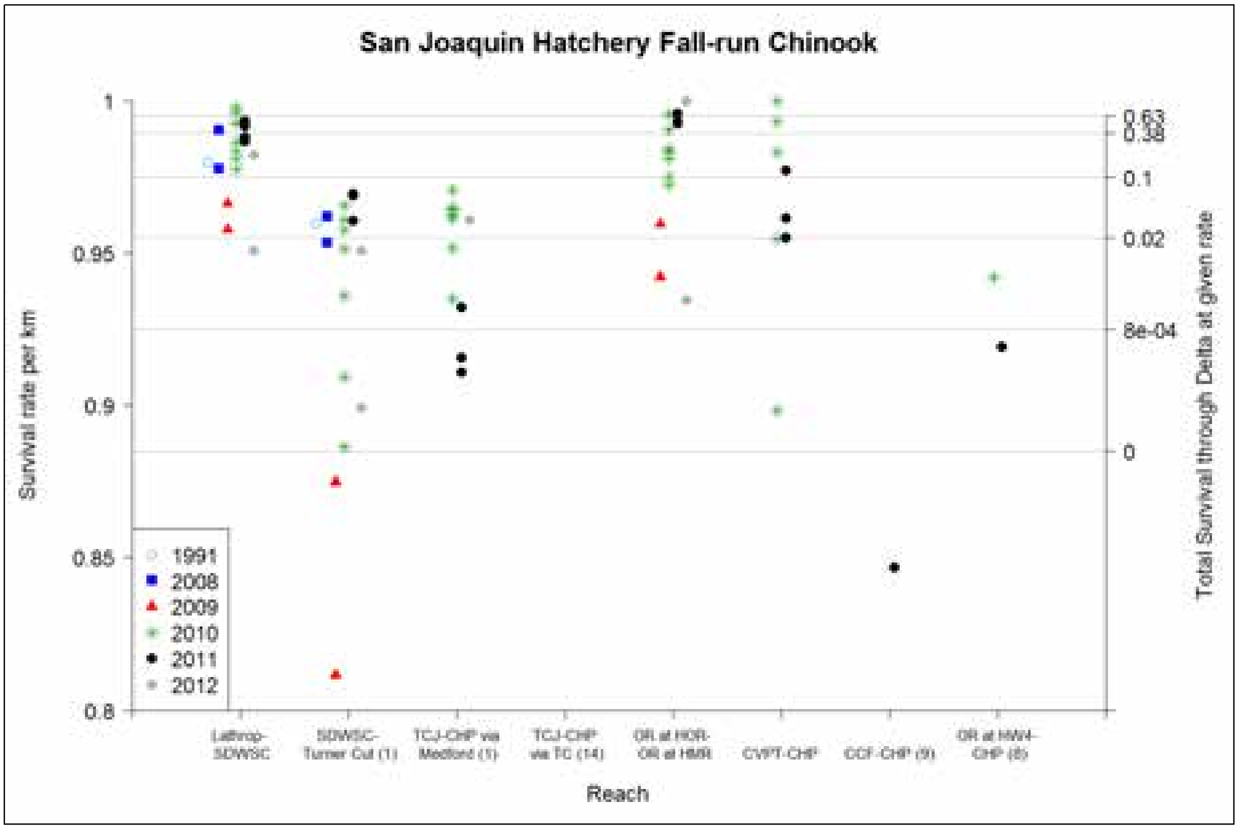


Figure E.4-5. Estimated Survival Rate ($S^{(1/km)}$) by Reach for Acoustic-tagged Fall-run Chinook Salmon in the VAMP Studies, and CWT fall-run Chinook Salmon in 1991

Sources: Brandes and McLain 2001; Holbrook et al. 2009; SJRGA 2010, 2011, 2013; Buchanan et al. 2015.
Notes: Total Survival through Delta assumes a travel distance of 91 rkm. Reach labels: Numbers in parentheses = number of releases with survival estimate of 0. SDWSC = Stockton Deep Water Ship Channel; TCJ = Turner Cut junction; CHP = Chipps Island; OR = Old River; HOR = Head of Old River; HMR = Head of Middle River; CVPT = Central Valley Project Tank; CCF = Clifton Court Forebay (just inside entrance gates), HW4 = Highway 4.

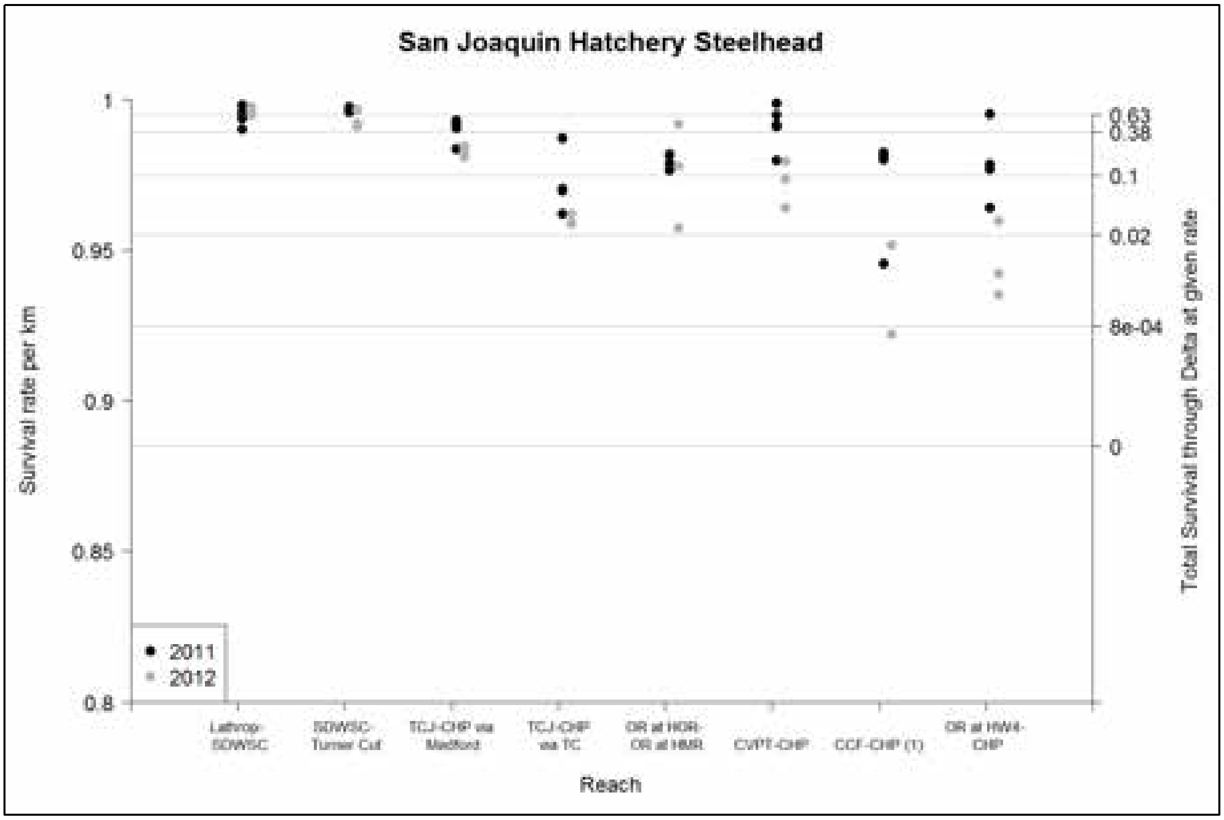


Figure E.4-6. Estimated Survival Rate ($S^{(1/km)}$) by Reach for Acoustic-tagged Steelhead in the 2011 and 2012 6-year Study

Notes: Total Survival through Delta assumes a travel distance of 91 rkm. Reach labels: Numbers in parentheses = number of releases with survival estimate of 0. SDWSC = Stockton Deep Water Ship Channel; TCJ = Turner Cut junction; CHP = Chipps Island; OR = Old River; HOR = Head of Old River; HMR = Head of Middle River; CVPT= Central Valley Project Tank; CCF = Clifton Court Forebay (just inside entrance gates), HW4 = Highway 4. Source: Buchanan 2013, 2014.

San Joaquin River Reaches

Survival rates per kilometer in San Joaquin River reaches tended to be higher in the upstream reaches, although there was considerable variability between years and species (Table E.4-2). Figure E.4-7 shows an illustration of survival rate estimates for Chinook salmon in 2011, in which survival rate tended to decrease as the population of tagged fish moved downriver. Survival from the Turner Cut junction through both the Interior Delta and the San Joaquin River mainstem was very low in 2011 (Figure E.4-7). Over all common reaches and study years, survival rates tended to be higher for steelhead than for Chinook salmon, although Chinook salmon had higher survival rates in some upstream reaches (Table E.4-2).

Lathrop to SDWSC: The reach of the San Joaquin River between Lathrop, located just downstream of the head of Old River, and the upstream entrance of the SDWSC just past the Navy Bridge toward the downstream end of Stockton, typically includes the transition zone between riverine (unidirectional flow) habitat and tidal (bidirectional flow) habitat (Figure E.2-2). In low flow years, the transition point between riverine and tidal habitat occurs in the upstream region of this reach, near the head of Old River. In high flow years, the transition point occurs toward the downstream end, close to the SDWSC.

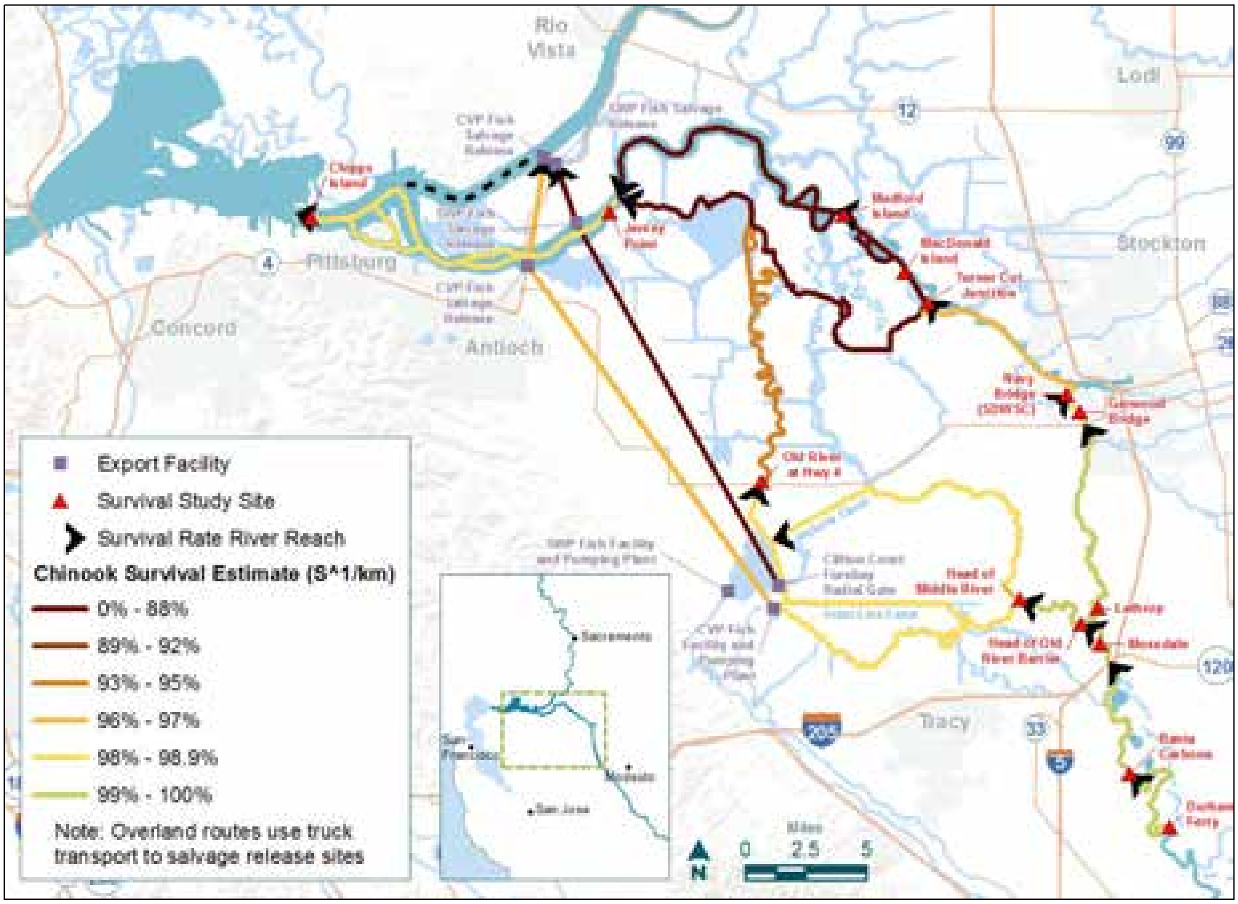


Figure E.4-7. Geographical Illustration of Heat Map Survival Rate (per kilometer) Estimates for 2011 Chinook Salmon

Note: See Table E.4-2 and Table E.4-3 for complete results from all years and species.

Salmonid survival in this reach (Lathrop to SDWSC) has been estimated directly using ATs for Merced River hatchery fall-run Chinook salmon in four years (2008 and 2010 to 2012) and for Mokelumne River hatchery steelhead in two years (2011 and 2012) (Holbrook et al. 2009; SJRGA2011, 2013; Buchanan 2013, 2014; Buchanan et al. 2015). Estimates are available from 2009 for acoustic-tagged fall/spring-run hybrid Chinook salmon from the Feather River hatchery (SJRGA 2010). Data from additional years of study have yet to be completely analyzed. An indirect estimate of survival is available for 1991 from CWT data using hatchery fish from Feather River hatchery. These six years of data show that survival tends to be higher in this reach than in reaches farther downstream, on a per-kilometer basis, but that it varies considerably within and between years (Figure E.4-5 and Figure E.4-6).

SDWSC to Turner Cut: The reach of the San Joaquin River from the upstream end of the SDWSC to the Turner Cut junction is tidal, and considerably wider and deeper than the reach from Lathrop to the SDWSC. The reach is 15 km long, and at the downstream end of the reach is an entrance to the Interior Delta (Turner Cut) (Figure E.2-2).

AT studies of fall-run Chinook salmon (Holbrook et al. 2009; SJRGA 2010, 2011, 2013; Buchanan et al. 2015) and steelhead (Buchanan 2013, 2014) have measured survival through this reach during the spring outmigration. One year of CWT data (1991) also provided a survival estimate through this approximate reach, using a paired release in Stockton and at Empire Cut, approximately 20 km downstream of Turner Cut.

Survival probability estimates for fall-run Chinook salmon for this reach were consistently lower than survival estimates for the same release groups in the preceding reach (Lathrop to SDWSC; Figure E.4-5). The average survival probability estimated for fall-run Chinook salmon between 2009 and 2011 ranged from 0.06 (2009) to approximately 0.60 (2011). The two years (2011, 2012) of steelhead data available, however, show comparable survival estimates between this reach and the upstream reach (Figure E.4-6). Steelhead survival probability estimates in this reach averaged 0.96 in 2011 (Buchanan 2013) and 0.91 in 2012 (Buchanan 2014).

Turner Cut junction to Chipps Island: Survival of fish on the San Joaquin River mainstem between the Turner Cut junction and Chipps Island (Figure E.2-2) is among the lowest for both Chinook salmon and steelhead (Turner Cut junction to Chipps Island via Medford in Figures E.4-5 and E.4-6), but it appears better than migrating into Turner Cut (Turner Cut junction to Chipps Island via Turner Cut in Figures E.4-5 and E.4-6). Chinook salmon acoustic telemetry data strongly suggest that migrating into Turner Cut results in poorer survival to Chipps Island, compared to remaining in the San Joaquin River at Turner Cut. Results in 2010, 2011, and 2012 indicate that none of the 13%, 21%, or 11% of the Chinook salmon estimated to have migrated into Turner Cut in those three years, respectively, survived to Chipps Island (although some tags identified as predators were detected at Chipps Island) (SJRGA 2011, 2013; Buchanan et al. 2015). In contrast, the probability of surviving from the Turner Cut junction to Chipps Island for fish that remained in the San Joaquin River at Turner Cut was estimated at 0.14, 0.02, and 0.14 (SE≤0.04) for these three years, respectively (SJRGA 2011, 2013; Buchanan et al. 2015).

The acoustic telemetry study of juvenile steelhead that was part of the 2012 stipulation study found that survival to Chipps Island was lower for steelhead that entered Turner Cut than for steelhead that remained in the San Joaquin River. Specifically, the study reported the route-specific survival probability to Chipps Island via Turner Cut was 0.270 (SE=0.03), and was 0.567 (SE=0.024) to Chipps Island for fish that did not use Turner Cut (Delaney et al. 2014). A similar pattern was observed in the first two years of the six-year study of acoustic-tagged steelhead: in 2011 and 2012, respectively, the estimated probability of surviving from the Turner Cut junction to Chipps Island was 0.43 and 0.18 (SE≤0.05) for fish that entered Turner Cut, compared to 0.78 and 0.49 (SE≤0.03) for fish that remained in the San Joaquin River (Buchanan 2013, 2014). This suggested that staying in the San Joaquin River at Turner Cut was beneficial for steelhead, as well as Chinook salmon. Some of the steelhead that entered Turner Cut and survived to Chipps Island were observed passing through the salvage facility at CVP or entering the CCF after leaving Turner Cut in both 2011 and 2012; however, these were a minority (44% and 28% in 2011 and 2012, respectively) of those that survived to Chipps Island from Turner Cut (Buchanan 2013, 2014).

Old River Reaches

Reaches within the Old River route are typically narrower and shallower than the San Joaquin River reaches, and in some cases completely lack sinuosity (e.g., Grant Line Canal) (Figure E.2-2). The higher water temperatures typical of shallower water and the lack of channel complexity that may accompany a lack of sinuosity suggest that reaches in the Old River would have lower survival than reaches in the San Joaquin River. It may also be expected that the reaches without sinuosity (Grant Line Canal) will have lower survival among the Old River reaches than those with a more natural construction (e.g., Old River north of the water export facilities).

Reaches evaluated in the Old River migration route are identified in Table E.4-3, and include the head of Old River to the head of Middle River, the head of Middle River to the entrances to the water facilities or Highway 4, Old River near Highway 4 to Jersey Point or Chipps Island, and the CVP holding tank or CCF radial gates to Chipps Island (Figure E.2-2). Survival rates per kilometer were often higher in the most upstream reach (Old River from its head to the head of Middle River), but there is considerable variability between years (Table E.4-3). Survival rates for reaches leading to or bypassing the fish facilities (i.e., not passing through the facilities) were generally comparable to those observed in the San Joaquin River (Tables E.4-2 and E.4-3) for both Chinook and steelhead for years in which estimates were available. However, survival estimates are missing for some reaches and Chinook salmon release groups, either because the study design did not allow for survival estimation in the reach (e.g., survival to Jersey Point or Chipps Island in 2009; Table E.4-3) or because too few fish were observed in the region to estimate survival (i.e., from the Highway 4 sites in 2012, when a physical barrier was installed at the head of Old River; Table E.4-3). The survival rates for fish passing the radial gates into the CCF were consistently low compared to other reaches for Chinook and steelhead (Table E.4-3). The lowest observed survival rates for Chinook salmon, among all reaches in both the Old River route and the San Joaquin River route, occurred in reaches that included the SWP and CVP fish facilities (including the Turner Cut route). Nevertheless, survival from the CVP to Chipps Island was sometimes higher than survival through the lower San Joaquin River reaches (Tables E.4-2 and E.4-3). Figure E.4-7 shows an illustration of survival rate estimates for Chinook salmon in 2011, in which it is apparent that the survival rate from the salvage tank at the CVP was considerably higher than in many downstream reaches, while the survival rate through the CCF and SWP salvage was the lowest of all Old River reaches for Chinook salmon in that year.

Table E.4-3. Heat Map Depicting Survival Rates ($S^{(1/km)}$) through Old River Reaches to Chipps Island

	Survival Estimate per km ($S^{(1/km)}$)						
	Chinook					Steelhead	
Reach Name/(km)	2008	2009	2010	2011	2012	2011	2012
Old River (head) to Middle River Head; (6)		0.953	0.983	0.997	0.981	0.990	0.977
Middle River Head to CVP/CCF/HWY 4; (20/21)		0.912	0.997	0.981		0.994	0.977
Old River near HWY 4 to Jersey Point; (60)			0.926	0.936		0.992	0.958
CVP tank to Chipps Island; (15/19)	0.845		0.972	0.969		0.988	0.973
CCF Radial Gates (interior) to Chipps Island; (21/24)	0.904		0	0.83		0.979	0.924

Note: Red boxes indicate lowest survival rate (less than 0.90 per km) and lighter boxes indicate higher survival rate (white: ≥ 0.99 per km). Missing values reflect too few fish present in the reach to estimate survival, or the study was not designed to estimate parameter.

Old River at its Head to Head of Middle River: The reach of the Old River from its head to the head of Middle River is approximately 6 km long, and tended to have survival rates that were similar for the upstream San Joaquin River reach for Chinook salmon (Figures E.2-2 and E.4-5). For steelhead, survival rates in this Old River reach tended to be lower than for the upstream San Joaquin River reaches (Figure E.4-6). Annual survival estimates in this reach ranged from 0.67 to 1.00 for Chinook salmon, and 0.77 to 0.95 for steelhead (SJRGA 2010, 2011, 2013; Buchanan 2013, 2014; Buchanan et al. 2015).

Old River at Highway 4 to Chipps Island: The reach from Old River at Highway 4 to Chipps Island includes the lower Old River and the lower San Joaquin River between Jersey Point and Chipps Island, and potentially the lower Middle River, Frank's Tract, and False River (Figure E.2-2). Although fish may also move from Highway 4 to Chipps Island via the facilities, the estimates shown in Figures E.4-5 and E.4-6 represent only the in-river migration route, and exclude the facility routes.

In the Chinook salmon AT studies, survival from Old River at Highway 4 to Chipps Island was estimated at 0 for eight of ten release groups. The two positive survival rate estimates were comparable to survival estimates in the San Joaquin River from Turner Cut junction to Chipps Island (Figure E.4-5). For steelhead, survival rates in this reach were generally higher than for Chinook, but demonstrated considerable variability between years and among release groups within years (Figure E.4-6).

E.4.2.5 Linkages Between Migration Route and Survival

Although data for migration route and survival both exist, the specific mechanisms linking migration route to survival are poorly understood for these routes, apart from the fish facilities. The primary mechanisms linking route with survival in the conceptual model are predation and entrainment in the fish facilities. Entrainment is considered in Section E.3. Predation and the possible migration route characteristics associated with predation are considered here.

Our basis of knowledge regarding migration route characteristics and route-specific survival is minimal. The extent to which operations constrain the relationship between migration route characteristics and route-specific survival is not well understood.

In general, predation is hypothesized to represent a potentially high risk for salmonids within the South Delta (Grossman et al. 2013; Hayes et al. 2015; Demetras et al. 2016) and is identified as a threat to ESA-listed winter-run Chinook salmon, spring-run Chinook salmon, and steelhead (NMFS 2014). However, most evidence for the magnitude of predation and specific habitat factors influencing interactions among predators and salmonids is circumstantial or indirect. Predators are clearly abundant throughout the Delta (e.g., Moyle 2002; Nobriga and Feyrer 2007; Hayes et al. 2015); nevertheless, many of the reaches in which salmonid survival is measured (and ostensibly linked to predation) lack site-specific data for predation pressure specifically on salmonids, predator abundance, predator community composition, and evaluations of habitat conditions that might influence predator effectiveness. Thus, the supporting evidence for the influence of predation on route-specific survival is mostly indirect, using ecological principles and relationships observed in general or for salmonids in particular, but from elsewhere in the Delta or in other river systems.

A recent predation study by the National Marine Fisheries Service (NMFS) explored the community of predatory fishes, predator movements, and salmonid predation pressure in the San Joaquin River between Mossdale Bridge and the SDWSC; preliminary results found differences in predator density and site fidelity in different reaches of the river, and more predators in the reach that includes the head of Old River than further downstream (Hayes et al. 2015). Striped bass and largemouth bass were most prevalent, although genetic testing of stomach contents suggested more targeted predation of salmonids by channel catfish than by either of the bass species; analysis is ongoing (Hayes et al. 2015).

Aside from the new NMFS study of predation, much of the evidence of assumed predation is based on interpretation of data from ATs implanted in migrating salmonids in specific reaches of the San Joaquin River and Old River. In particular, the observation of motionless tags or tags that exhibit unusual tracking patterns may indicate that a predation event has occurred (Table E.4-4); however, predator behavior and smolt behavior can overlap

(C. Karp, personal communication) and motionless tags indicate only mortality, not that the mortality occurred from predation.

Table E.4-4. Results of Mobile AT Monitoring Showing Locations of Stationary Tags, Which May Be the Result of Predation Mortality

Year	Mobile Tracking Region in SJR*	Hot Spots from VAMP
2007	Head of Old River to SDWSC	Railroad bridge, just upstream from Stockton Waste Water Treatment Plant
2009	Head of Old River to SDWSC	Throughout Lathrop to Stockton, especially toward upstream end; channel bends, scour holes, pump stations
2010	Head of Old River to Turner Cut	Primarily in Stockton DWSC; of those between HOR and SDWSC, about 56% between HOR and Stockton, and 44% between Stockton and DWSC (shorter reach, so higher concentrations in Stockton than upstream)
2011	Head of Old River to Turner Cut	SDWSC near Turner Cut, and close to Stockton; evenly distributed through reach between HOR and SDWSC

** = mobile tracking typically included regions upstream of the Head of Old River and regions in Old River and near the export facilities, as well. See Figure E.2-2 for site locations.*
Source: SJRGA 2011.

Within the Delta, habitat that has been hypothesized to attract predators includes scour holes and structures such as bridges (Vogel 2010). The Mossdale Bridge crosses the San Joaquin River upstream of the head of Old River; there are five bridges that cross the San Joaquin River in or near Stockton, California, including Highway 4 and a railroad bridge just upstream of the Stockton Waste Water Treatment Plant. Scour holes are often found at river bends, in particular if the shoreline is covered with riprap. Vogel (2010) found immobile ATs from juvenile Chinook salmon deposited in channel bends and scour holes, and near pumping stations in the reach from Lathrop to the SDWSC in 2009. This stretch of river has several bends compared to regions downstream, especially toward the upstream portion of the reach. Additionally, there is a large scour hole just upstream of Lathrop, at the head of Old River, thought to be a predator hot spot (Vogel 2010).

The Stockton area appears to be a region where concentrations of non-moving tags are found, and may be an area of high predation, based on the mobile acoustic telemetry surveys. The Stockton Waste Water Treatment Plant has an outfall toward the southern end of the city. It has been hypothesized that the changes in water chemistry or temperature in this region either attract predators or else affect smolt ability to evade predation, or result in death of smolts due to exposure to toxics or high ammonia levels. In 2007, when many salmon ATs were detected in this region, a subsequent investigation determined that the waste water treatment plant had higher levels of certain constituents downstream of the waste water discharge than upstream when measured the following spring (SJRGA 2009), but had been in compliance with discharge permit requirements during the 2007 VAMP study (SJRGA 2008). In 2010, a predator-tagging study tagged several striped bass and largemouth bass caught in the Stockton area with ATs and monitored their movements using fixed site receivers (Vogel 2011). Individuals of both species that were tagged in Stockton were observed to either remain there or return there after moving elsewhere, suggesting that this region provides favorable habitat for some predators. However, other individuals (striped bass) left and did not return during the duration of the study (Vogel 2011). Preliminary results from acoustic tagging of predatory fish in 2014 and 2015 also showed variable site fidelity among striped bass, largemouth bass, channel catfish, and white catfish (Hayes et al. 2015).

Mobile telemetry surveys as part of the 2010 and 2011 VAMP studies covered the SDWSC to Turner Cut reach, and found a considerable number of immobile ATs (Table E.4-4). In 2010, mobile tracking found that the majority of immobile tags observed in the San Joaquin River between the head of Old River and Turner Cut were located in the SDWSC, but identified no hot spots (SJRGA 2011). In 2011, mobile tracking found a large number of immobile tags from Chinook salmon in the SDWSC within 2 miles of Turner Cut, and also toward the upstream portion of the reach near Stockton (SJRGA 2013; Table E.4-4). The large number of immobile tags from Chinook salmon found in the SDWSC in both 2010 and 2011, relative to the numbers found upstream of SDWSC in those years, is consistent with the observed pattern of estimated survival rates in those reaches: the estimated survival rate was lower from the entrance of the SDWSC to Turner Cut than from Lathrop to SDWSC in both years (Figure E.4-5, Table E.4-2). However, the higher concentration of immobile tags observed near Lathrop than in Stockton in 2009 is inconsistent with the lower survival rate observed between Garwood Bridge and SDWSC in 2009 (Tables E.4-2 and E.4-4).

Within the Interior Delta, mobile monitoring in 2011 identified a total of 162 Chinook salmon tags detected in Old River and Grant Line Canal between the head of Old River and the state and federal pumping facilities (SJRGA 2013). The highest concentration of the tags detected by mobile monitoring in this reach were detected in Grant Line Canal at 54%, while 29% were found in the vicinity of the state and federal pumping facilities, and the remaining 17% were detected in Old River upstream of Grant Line Canal. The number of tags detected in Grant Line Canal in 2011 was much higher than in previous years (SJRGA 2013) suggesting high numbers of predators in Grant Line Canal, or an increase in predator effectiveness possibly due to the lack of cover habitat in Grant Line Canal that year. Nevertheless, the 2011 survival rate estimate in the reach that includes Grant Line Canal was intermediate compared to 2009 and 2010 (Table E.4-3).

Additional understanding of how predation may influence survival in various reaches of the South Delta is based mostly on more general ecological principles or observations from elsewhere in the Delta. For instance, Cavallo et al. (2012) and Sabal (2014) both performed predator removal studies from elsewhere in the Delta, and observed that predator removal was followed by increased salmonid survival. However, Cavallo et al. (2012) also observed that salmonid survival quickly reverted to pre-manipulation levels. The 2014-2015 NMFS predation study included a BACI (Before-After Control-Impact) predator removal experiment to assess the effect of moving predators from one reach to another on survival of juvenile salmonids; results are not yet available (Hayes et al. 2015).

The distribution and effectiveness of predators in the Delta depend on habitat features and water quality factors. For instance, invasive ambush predators such as largemouth bass have been observed favoring regions with high densities of submerged aquatic vegetation (SAV; Miranda et al. 2010), whereas poor water quality reflected by high concentrations of dissolved solids may block adult striped bass from migration further upstream (Radke 1966). Predation rate and predator effectiveness also depend on water quality. Metabolic rate is known to increase with warmer water temperatures (e.g., Brown et al. 2004); thus, channels with higher water temperatures, such as those with little riparian vegetation, may be expected to have higher predation rates and lower salmonid survival. Higher water temperatures may also lower salmonid survival by impairing their swimming ability (Hayes et al. 2015); water velocity and swimming depth are also associated with predation events (Hayes et al. 2015; Demetras et al. 2016). Lower survival is also expected in years with lower flows and higher temperatures, as anticipated during drought years and as a consequence of climate change. Riparian vegetation also provides protective cover for juvenile salmonids, so predation effectiveness is expected to be lower in regions with higher riparian vegetation (Tabor and Wurtsbaugh 1991). Turbidity may affect salmonid survival by limiting predator effectiveness; salmonid predators that rely on visual prey acquisition are more efficient in less turbid water (Gregory and Levings 1998). Finally, the rate of piscivory among the predator community has been observed to depend on both predator size and season. In particular, a study by Nobriga and Feyrer (2007) found that although striped bass, largemouth bass, and Sacramento pikeminnow were consistently collected from Medford Island, downstream of the Turner Cut junction, largemouth bass and Sacramento pikeminnow piscivory was mostly a function of predator size, whereas striped bass piscivory was a function of season and was most intense in summer and fall.

These findings suggest that salmon mortality due to predation may be strongly influenced by reach- or route-specific habitat conditions within the Delta. However, other linkages may exist between migration route and survival, reflecting the variability in habitat and water quality through the Delta; clear mechanistic relationships have not been evaluated in this analysis. Without additional survival studies that are specifically designed to address habitat and predator interactions on small and large spatial scales, the baseline of existing survival data has limited utility for identifying causal relationships between migration route and survival.

E.4.3 SUMMARY: KNOWLEDGE GAPS ON MIGRATION ROUTE

A variety of knowledge gaps exist regarding both the spatial use of the Delta by migrating juvenile salmonids and their survival in general, and how their survival in different regions is affected by exports in particular. Additional information is needed about the following issues:

- Conditions that correlate with higher survival in the San Joaquin River route over the Old River route, or vice versa (e.g., head of Old River barrier [HORB], flow, export rate, temperature).
- Survival and route selection on various spatial and temporal scales
  - Survival on the scale of reaches and subreaches throughout the Delta, including the Interior Delta, on the same spatial and temporal scale as measures of habitat characteristics.
  - Survival in the lower reaches of the San Joaquin River, especially between Medford Island and Jersey Point, including through Frank's Tract.
  - Route selection at river junctions in San Joaquin River downstream of Turner Cut (i.e., Columbia Cut, the mouths of OMR, and False River).
  - Route use within the Interior Delta.
- Habitat characteristics and water quality on the reach-scale throughout the Delta
  - Predator communities and predator-friendly habitat structures in various regions of the Delta.
  - Water quality in various regions of the Delta.
  - Reach-specific habitat characteristics, and how these relate to juvenile salmonid and predator use of habitat (e.g., distribution of SAV, riparian vegetation, water quality measures).
- Nature of the relationship between salmonids and predators
  - Reach-specific and temporal characterizations of predator pressure on juvenile salmonids during the time period when juvenile salmon and steelhead are migrating through the reach.
  - Direct evidence of predation as a cause of mortality on a reach-specific level, including evidence of predation by either predatory fish or avian predators.
  - Potential of predator removal to affect juvenile salmonid survival in various reaches and on various spatial and temporal scales.
  - Effect of fish condition and species on predation risk.
- Extent to which water project operations drive changes in physical habitat, water quality, and species assemblages, and the extent to which these changes influence salmonid growth and survival
  - The potential of water project operations to affect the spatial and temporal composition of the ecological community in various reaches of the Delta, including SAV, predatory fish and avian predators, invertebrates, phytoplankton, and zooplankton.
  - The potential of water project operations to affect river channel geometry and riparian vegetation.
  - The potential of water project operations to affect water temperature and water quality gradients in various regions of the Delta.

- The potential of actions that support water project operations (e.g., levee maintenance, riprap installation on shorelines) to affect the Delta ecosystem.

A further knowledge gap has been identified regarding the incremental role of water project operations on juvenile salmonid survival in the Delta in relation to other factors, and the management actions needed to significantly increase juvenile survival from current levels. The SST believes that management actions beyond the current water project and related management actions are required to increase survival, including actions that address non-project-related stressors, but has not identified the specific mix of actions required. The necessary management actions are expected to involve water project exports as well as an integrated set of actions addressing flow, habitat, juvenile migration conditions, and other stressors such as predation and climate change, some of which are outside the scope of this analysis.

E.5 SURVIVAL AS A FUNCTION OF MIGRATION RATE

The conceptual model views migration rates as a driver of survival by varying the exposure of the migrating salmonid to either positive or negative conditions. Extended exposure to higher water temperatures may reduce fitness because of increased disease, or increase predation rate because of heightened metabolic rate of the predators. Independent of temperature, prolonged exposure to regions with higher predation risk is expected to increase the probability of mortality. It is also possible that a faster migration rate reduces growth opportunities of migrating salmonids in the Delta, resulting in smaller smolts that experience higher predation risks upon entry to estuarine and ocean environments after exiting the Delta (Muir et al. 2006). Although ocean survival is outside the scope of this report, the SST acknowledges it as an important element of assessing population-level effects of any management actions.

This section focuses on the hypothesis that a slower migration rate (longer travel time) through a reach results in increased mortality through the reach by increasing exposure to predation or poor habitat. The specific mechanism may be exposure to either a higher abundance of predators or to habitat that augments the efficiency of predators that are present, or a combination of both. Habitat that lowers the vitality of migrating salmonids is included in the latter. A further prediction is that the relationship between migration rate and survival varies with reach or region of the Delta.

E.5.1 SUMMARY: CONCEPTUAL MODEL PREDICTIONS ON SURVIVAL AS A FUNCTION OF MIGRATION RATE

The conceptual model predicts that fish with slower migration rates will have lower survival probabilities through the Delta. Evidence for this prediction is mixed.

- Research in the North Delta and lower Mokelumne River has observed this pattern (Perry et al. 2010; Cavallo et al. 2012).
- CWT Chinook salmon data from 1996 to 2006 showed no such pattern for survival from Mossdale to Chipps Island (data from Newman 2008; analysis by SST).
- Preliminary analysis by the SST of survival and travel time estimates from AT Chinook salmon in the South Delta observed this pattern for some reaches (Lathrop to SDWSC, Old River between the heads of Old and Middle rivers) but not for other reaches (e.g., Turner Cut junction to Chipps Island); conclusions could not be made for some reaches because of insufficient data (SJRGA 2010, 2011, 2013; Buchanan et al. 2015).
- Preliminary analysis by the SST of survival and travel time estimates from AT steelhead in the South Delta observed this pattern between Lathrop and SDWSC, SDWSC and the Turner Cut junction, and Turner Cut junction and Chipps Island, but not in Old River between the heads of Old and Middle rivers or between Highway 4 and Chipps Island (Buchanan 2013, 2014).

The conceptual model predicts that the relationship between migration rate and survival will vary for different reaches, and be stronger in more tidal reaches. Evidence for this prediction is mixed.

- Preliminary analysis of AT data by the SST found that the relationship between migration rate and survival varies between reaches (see above).
- There was little or no evidence that the relationship is stronger in more tidal reaches.

The conceptual model predicts that the relationship between migration rate and survival is due to increased exposure to predation.

- The XT predator-prey model predicts that survival of prey (salmonids) will be proportional to migration rate in tidal reaches, as prey slow down relative to predators (Anderson et al. 2005).
- Mechanisms (e.g., predation) relating mortality to migration rate have not been explored directly.

E.5.2 FINDINGS ON CONCEPTUAL MODEL LINKAGES AND PREDICTIONS: EFFECTS OF MIGRATION RATE ON SURVIVAL

Our basis of knowledge of the linkages between migration rate and survival is high for Chinook salmon in the North Delta, low for Chinook salmon in the South Delta, and low for steelhead in the South Delta. Multiple field studies have collected data relevant to this question, and results have been published in peer-reviewed literature, agency reports, and this report. Low understanding is due to mixed results from these studies, and sparse data in some cases. Additional support comes from the ecological theory literature or other river systems. The extent to which operations constrain the effect of migration rates on survival is not well understood.

Several publications are available on the relationship between migration rate and survival in the Delta. It has been observed in the North Delta that slower migration rates are correlated with increased mortality of juvenile Chinook salmon; however, no effort was made to relate this finding directly to predator density (e.g., Perry et al. 2010). Cavallo et al. (2012) observed in an experimental study that large increases in flow were followed by increased migration rates and higher survival for juvenile Chinook salmon in the lower Mokelumne River, but the survival effect was not consistent across reaches. Finally, the XT predator-prey model predicts that survival of prey (salmonids) will be proportional to migration rate in tidal reaches, as prey slow down relative to predators (Anderson et al. 2005).

The majority of information pertaining to the South Delta comes from CWT and AT tagging studies, compiled and analyzed by the SST. We examined migration rates and survival in the San Joaquin River and Old River for the same reaches used in the examination of migration route on the reach scale (Section E.4.2.4) to better understand potential relationships. Reaches in the San Joaquin River examined include: 1) from Lathrop to the upstream entrance of the SDWSC; 2) from SDWSC to the Turner Cut junction; and 3) from Turner Cut junction to Chipps Island. Reaches in the Old River examined include: 1) between the heads of Old and Middle rivers; and 2) between Highway 4 and Chipps Island. Data come from acoustic telemetry studies of Chinook salmon and steelhead in the South Delta (Holbrook et al. 2009; SJRGA 2010, 2011, 2013; Buchanan 2013, 2014; Buchanan et al. 2015). We also explored observed patterns in travel time and survival from Mossdale to Chipps Island and Jersey Point, using data from CWT studies from 1996 to 2006 (Newman 2008).

Migration rate (kilometers per day) tended to be faster for both Chinook salmon and steelhead in the upstream reaches (Lathrop to SDWSC and Old River to the head of Middle River) compared to downstream reaches (Figure E.5-1; see Figure E.2-2 for site locations). The predominantly tidal reach between the upstream entrance of the SDWSC and the Turner Cut junction tended to have slower rates of travel. The reach from the CCF gates to Chipps Island (via salvage at SWP) had the slowest travel rates for steelhead, although too few Chinook salmon estimates were available for this reach to make comparisons (Figure E.5-1).

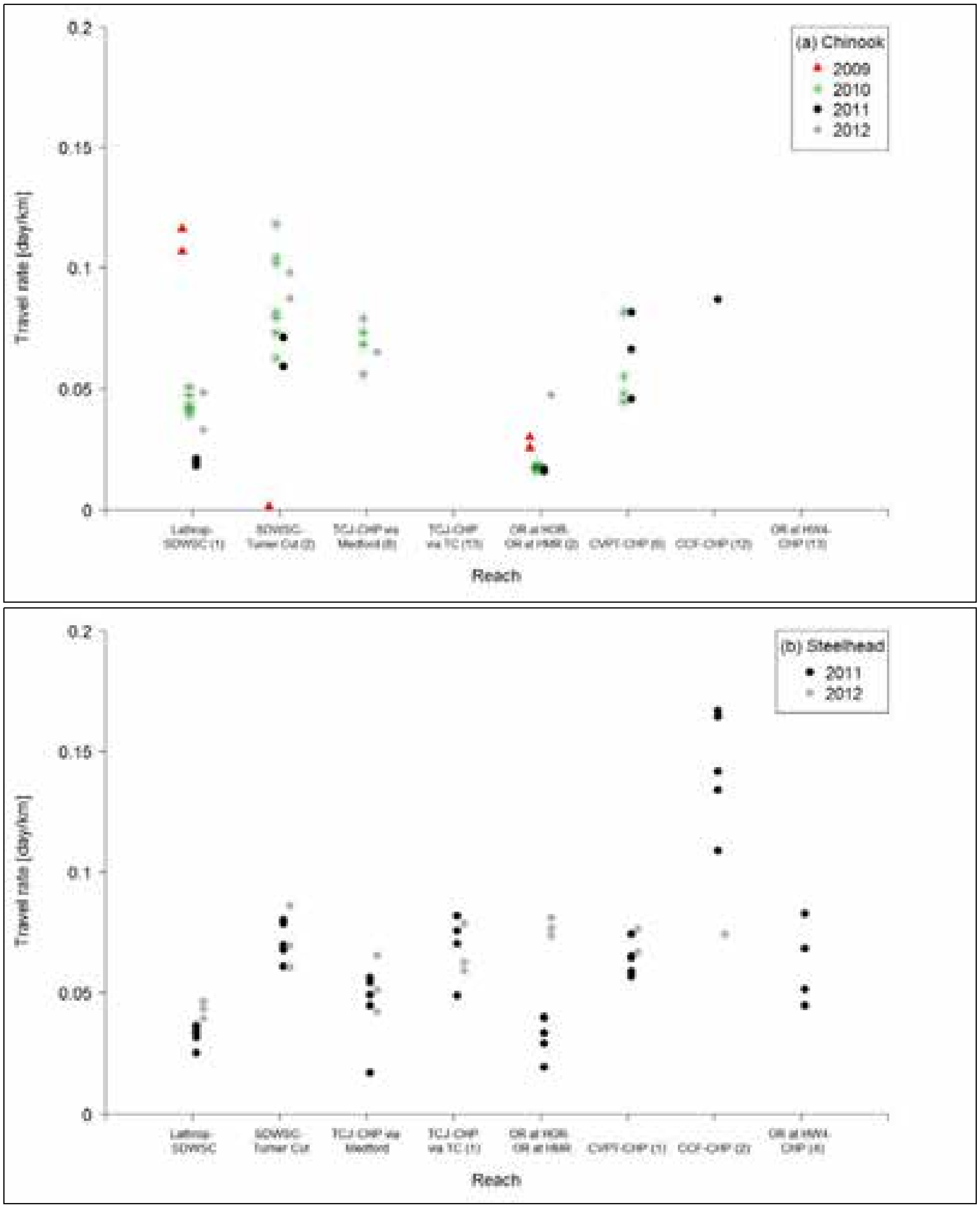


Figure E.5-1. Average Travel Rate (day/km) by Reach for Acoustic-tagged Fall-run Chinook Salmon (a) and Steelhead (b) Studies

Notes: Reach labels: Numbers in parentheses = number of releases with insufficient detections to measure travel rate. SDWSC = Stockton Deep Water Ship Channel; TCJ = Turner Cut junction; CHP = Chipps Island; OR = Old River; HOR = Head of Old River; HMR = Head of Middle River; CVPT= Central Valley Project Tank; CCF = Clifton Court Forebay (just inside entrance gates), HW4 = Highway 4. See Figure E.2-2 for site locations.
Sources: SJRGA 2010, 2011, 2013; Buchanan et al. 2015; Buchanan 2013, 2014.

E.5.2.1 Lathrop to SDWSC

Migration rate tends to be faster in the reach from Lathrop to the upstream entrance of the SDWSC than in reaches farther downstream for fall-run Chinook salmon, but not consistently (SJRGA 2010, 2011, 2013; Buchanan et al. 2015; Figures E.5-1a and E.2-2). Data from the first two years of the six-year steelhead AT study (2011, 2012) show that migration rates are faster for steelhead in this reach than farther downstream (Buchanan 2013, 2014; Figure E.5-1b). Chinook and steelhead that are in faster moving release groups tend to have higher probabilities of survival in the reach from Lathrop to SDWSC (Figure E.5-2), although the relationship is not consistent for all years and species (e.g., 2011 Chinook salmon versus 2011 steelhead, 2012 steelhead).

E.5.2.2 SDWSC to Turner Cut Junction

The reach between the upstream entrance of the SDWSC and the Turner Cut junction (Figure E.2-2) is predominantly tidal and, thus, the XT predator-prey model predicts that survival of prey (salmonids) will be proportional to migration rate, as prey slow down relative to predators (Anderson et al. 2005). Both fall-run Chinook salmon and steelhead have been observed to decrease their rate of travel in this reach relative to the previous, partly riverine reach (Figure E.5-1; SJRGA 2010, 2011, 2013; Buchanan 2013, 2014; Buchanan et al. 2015). Analysis of steelhead data from the first two years of the six-year study suggested a possible proportional relationship between survival and migration rate in this reach (Figure E.5-3; Buchanan 2013, 2014). However, analyses of Chinook data suggested little or no apparent relationship between migration rate and survival in this reach (2009 to 2012) other than 2012 (Figure E.5-3). No formal analysis relating survival to migration rate or the XT model has been performed for this reach of the San Joaquin River.

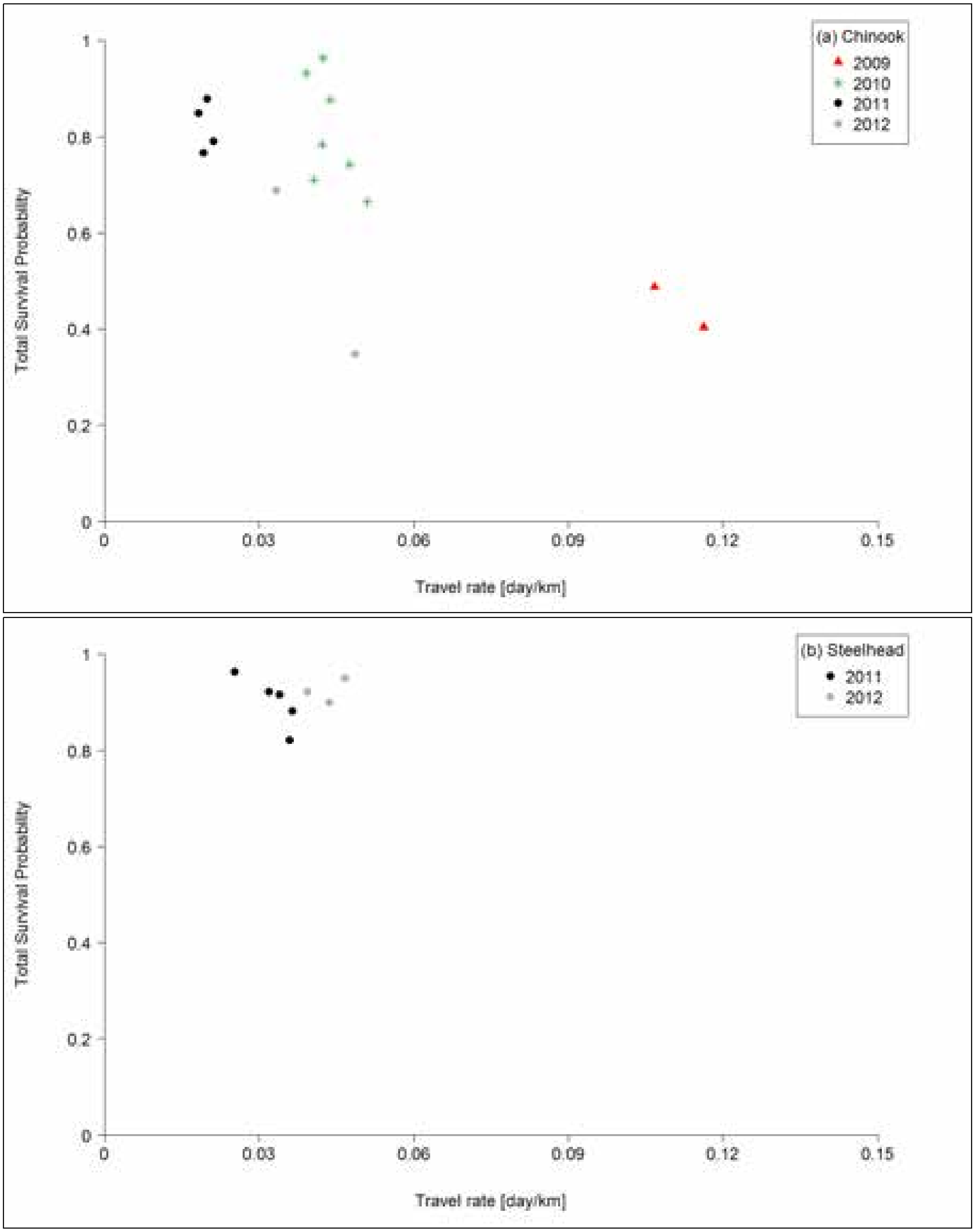


Figure E.5-2. Estimated Survival Probability Versus Travel Rate (day/km) in the San Joaquin River from Lathrop to the Acoustic Receiver at the Navy Drive Bridge in Stockton (near the start of the SDWSC), from Acoustic-tagged Salmon (a) and Steelhead (b) Studies

Source: SJRGA 2010, 2011, 2013; Buchanan et al. 2015; Buchanan 2013, 2014.

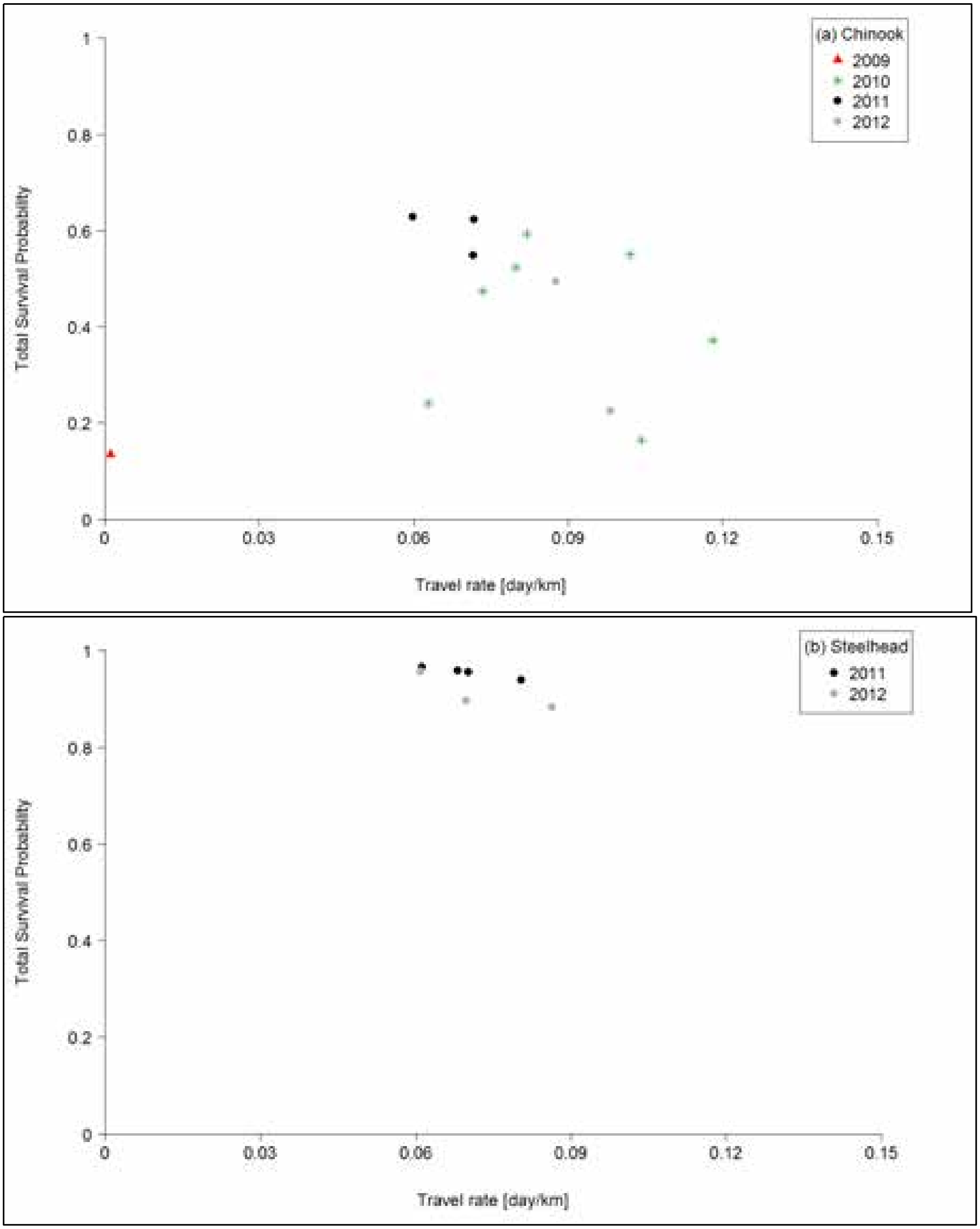


Figure E.5-3. Estimated Survival Probability Versus Travel Rate (day/km) in the San Joaquin River from the Acoustic Receiver at the Navy Drive Bridge in Stockton (near the start of the SDWSC) to Turner Cut Junction, from Acoustic-tagged Salmon (a) and Steelhead (b) Studies

Source: SJRGA 2010, 2011, 2013; Buchanan et al. 2015; Buchanan 2013, 2014.

E.5.2.3 Turner Cut Junction to Chipps Island

In 2010, average travel times from the Turner Cut junction to Chipps Island (Figure E.2-2) for fish that stayed in the San Joaquin River downstream of Turner Cut ranged from 2.8 to 4.9 days for acoustic-tagged juvenile Chinook salmon (SJRGA 2011). In 2011, there were too few fish detected at Chipps Island from this route to estimate travel time (SJRGA 2013). The assessment of any relationship between migration rate and survival in this reach is hampered for Chinook salmon because of sparse data and consistently low survival; the five data points available do not indicate a strong relationship (SJRGA 2011; Buchanan et al. 2015; Figure E.5-4). Steelhead data for the first two years of the six-year study are consistent with the XT model prediction of higher survival for faster moving fish (Buchanan 2013, 2014; Figure E.5-4). Overall, strong conclusions are not possible because of sparse data and potential differences between species.

E.5.2.4 Head of Old River to Head of Middle River

The reach of Old River from the head of Old River to the head of Middle River is 6 km (Figure E.2-2). Average travel time for Chinook salmon was relatively short in this reach compared to downstream reaches, and ranged from 0.1 days (2.4 hours) in 2010 and 2011 to 0.3 days (7 hours) in 2012 (Figure E.5-1a). Survival in this reach tends to vary between years more than within years. Within each year, there is little sign that release groups that move more quickly through the reach have higher survival; however, when combined over years, it appears that the faster moving groups have higher survival in general (Figure E.5-5a). Steelhead tended to move more slowly through this reach, and there was less variability in survival estimates for steelhead than for Chinook salmon (Figures E.5-1 and E.5-5). There is no indication that shorter travel times in this reach are associated with higher survival for steelhead, from a visual inspection of the data (Figure E.5-5b) (Buchanan 2013, 2014).

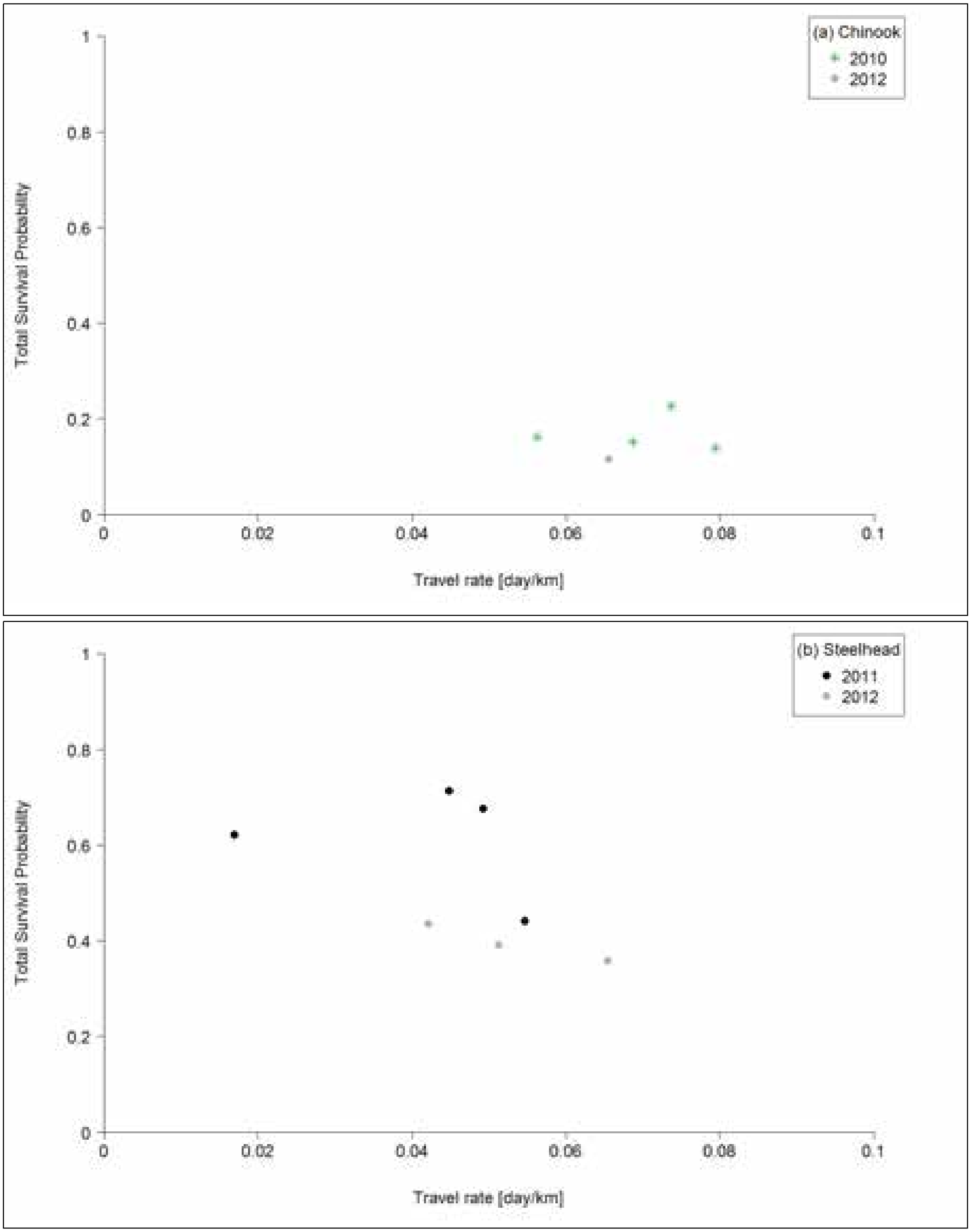


Figure E.5-4. Estimated Survival Probability Versus Travel Rate (day/km) from the Turner Cut Junction to Chipps Island, from Acoustic-tagged Salmon (a) and Steelhead (b) Studies

Note: For fish that remained in the San Joaquin River past Medford Island.
Sources: SJRGA 2011; Buchanan et al. 2015; Buchanan 2013, 2014.

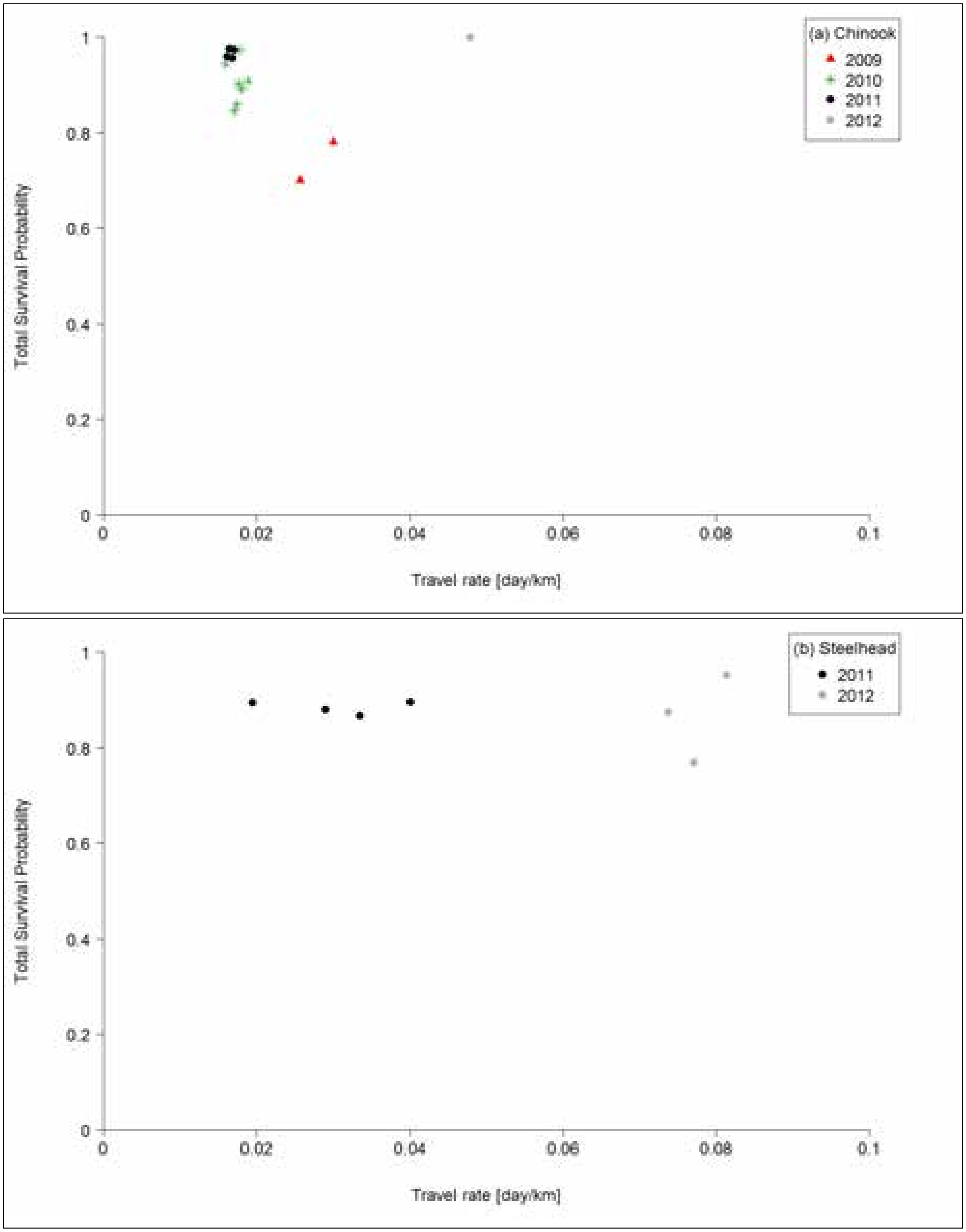


Figure E.5-5. Estimated Survival Probability Versus Travel Rate (day/km) in Old River from the Head of Old River to the Head of Middle River, from Acoustic-tagged Salmon (a) and Steelhead (b) Studies

Source: SJRGA 2010, 2011, 2013; Buchanan et al. 2015; Buchanan 2013, 2014.

E.5.2.5 Old River at Highway 4 to Chipps Island

The reach from Highway 4 on Old River to Chipps Island includes the lower Old River and San Joaquin River, and either the lower Middle River or Frank's Tract and False River, depending on the route taken by the fish (Figures E.2-2 and E.4-2). There were too few observations of travel time from acoustic-tagged Chinook salmon for a comparison to survival for that species. For steelhead, estimates are available only for 2011, because too few steelhead used the Old River route in the 2012 AT study to measure travel time through this reach. For 2011 steelhead, there is no indication that faster moving fish had higher survival, and instead the opposite is indicated (Figure E.5-6). However, strong conclusions are not possible for either species because of insufficient data.

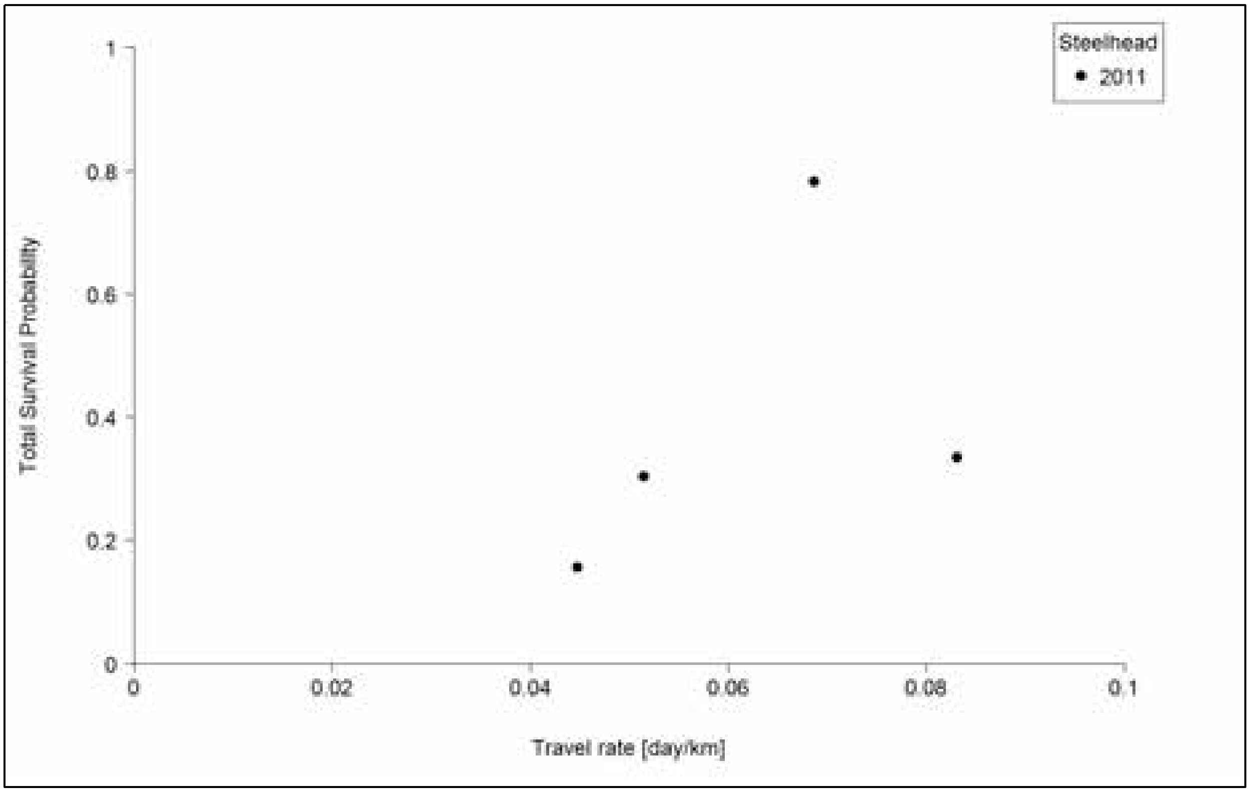


Figure E.5-6. Estimated Survival Probability Versus Travel Rate (day/km) from Old River at Highway 4 to Chipps Island, from Acoustic-tagged Steelhead Studies

Note: For fish that remained in the San Joaquin River past Medford Island.
Source: Buchanan 2013.

E.5.2.6 Mossdale to Jersey Point

Analysis conducted by the SST used simple linear regression to compare survival estimates of CWT fall-run Chinook salmon from the Mossdale area of the San Joaquin River to Jersey Point with travel time. The survival data are actually differential recovery rates (DRRs) of CWT fish released in 1996 to 2006 upstream in the San Joaquin River (i.e., Mossdale, Durham Ferry, or Dos Reis) relative to those released at Jersey Point, and recovered in the Chipps Island trawl or in ocean fisheries (Figure E.2-2; Newman 2008). Under assumptions of common sampling and conditional capture probabilities in the trawl and fisheries between the paired upstream and downstream releases, the DRR estimates survival between the upstream release site and Jersey Point; see Newman (2008) and SJRGA (2013) for more information on these data. Travel time was calculated as a weighted average of observed delay from release to recapture, for all individuals recaptured from a release group; Dos Reis release groups and ocean recoveries were omitted from the travel time calculations (S. Greene, personal communication). Comparison of the DRR to average travel time showed no significant relationship between travel time and survival for these CWT data (P=0.5157; r=0.17; Figure E.5-7).

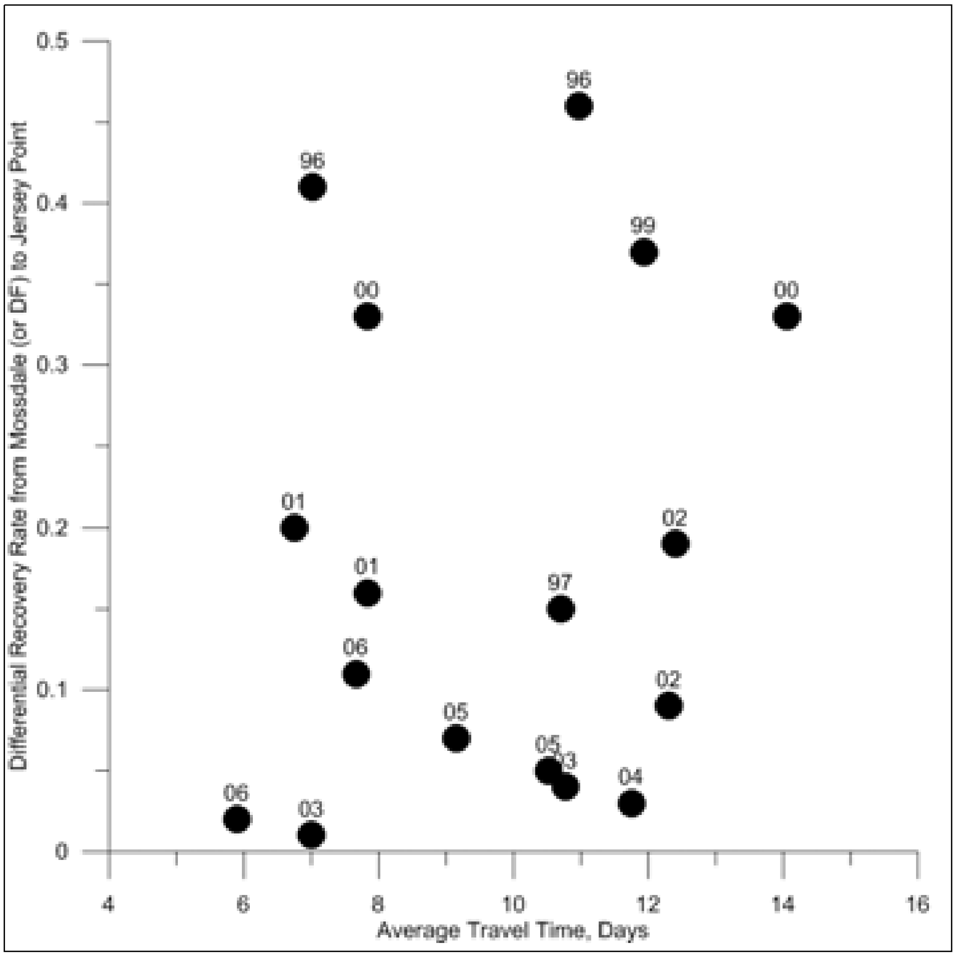


Figure E.5-7. Average Travel Time of Specific Releases of Fall Chinook Salmon Versus an Estimate of Survival Based on a Ratio of Recovery Fractions for Upstream Releases to Downstream Releases at Jersey Point for the Mossdale to Jersey Point Reach

Notes: Releases were conducted from 1995 to 2006. The Differential Recovery Rate was developed and computed by the USFWS (Newman 2008). Data plotted by Sheila Greene (Westlands Water District).

E.5.3 SUMMARY: KNOWLEDGE GAPS ON MIGRATION RATE

Several knowledge gaps exist regarding the relationship between migration rate and survival of juvenile salmonids in the Delta, and how this relationship may be influenced by water project operations. Although there are several years of data on survival and migration rate in some reaches of the San Joaquin River, we do not yet have a general understanding of the relationship between migration rate and survival in all regions of the Delta. This knowledge gap is a result of:

- Few estimates of either or both survival probabilities and migration rate in some regions of the Delta, especially the San Joaquin River downstream of Turner Cut and the Interior Delta.
- Interannual and spatial variability in either or both survival probabilities and migration rate.
- Incomplete analysis of existing acoustic telemetry data, including consideration of additional effects of hydrological conditions such as water temperature, flow, and water velocity; analyses are planned or ongoing, but are not yet complete.

Furthermore, additional information is needed about the following issues:

- The relationship between migration rate and survival through reaches in OMR and through the facilities.
- Mechanisms for increased mortality resulting from lower migration rate.
- The extent to which predicted changes in hydrological conditions resulting from water project operations may result in changes in migration rate, and consequently influence survival.
- The benefit-risk tradeoff for faster migration rate, which reduces exposure time to predators in the South Delta and, thus, potentially increases immediate survival rate, but also potentially decreases future survival rate in the ocean due both to less time spent rearing prior to ocean entry and to accelerated ocean-entry timing, possibly before seasonably favorable ocean conditions have become established.

E.6 SURVIVAL AS A FUNCTION OF EXPORT RATE

The conceptual model links mortality to exports via effects of exports on Delta hydrodynamics, the effect of hydrodynamics on route selection and migration rate, and the effect of route and rate on survival. The conceptual model also links exports to mortality via direct mortality at the facilities from pre-screen mortality, entrainment mortality or impingement on screens, and within-facility mortality. Via both direct and indirect effects, possibly including linkages that are not analyzed here, the conceptual model predicts that survival in the Delta will depend at least partly on export rate. This section provides a review of available information for evidence of a relationship between export rate and survival through and within the Delta. Direct mortality is considered in detail in Section E.3. Here, we review findings on survival in various regions relative to export rate.

Increased export rates are expected to draw more fish into the Interior Delta and into the water export facilities, and via direct mortality to decrease migration survival through the Delta to Chipps Island. Due to spatial heterogeneity in the effect of exports on Delta hydrodynamics, it is expected that some routes will exhibit a stronger negative effect of increased export rates than others. Likewise, different regions of the Delta may exhibit different relationships between exports and survival.

In this section, predictions from the conceptual model are identified and considered in light of findings relative to Chinook salmon and steelhead. Findings come mostly from peer-reviewed literature and technical reports, but we also present new compilations of data from CWT and AT studies of San Joaquin River fish; the data used in these compilations are described in Section E.2.

E.6.1 SUMMARY: CONCEPTUAL MODEL PREDICTIONS ON SURVIVAL AS A FUNCTION OF EXPORT RATE

The conceptual model predicted that increased export rates would result in decreased survival through the Delta to Chipps Island. Findings from CWT and AT data for Chinook salmon have been inconsistent, and data are limited for steelhead.

- A negative relationship between export rate and through-Delta survival was found for Sacramento River fall-run Chinook salmon from CWT data (Newman 2003), although more recent AT data from late-fall-run Chinook salmon showed no relationship (Perry 2010).
- CWT data from San Joaquin River fall-run Chinook salmon provided moderate evidence of a positive relationship between through-Delta survival and export rates, but may be due to high correlation between exports and San Joaquin River inflow (Newman 2008; SJRGA 2006).
- AT data from San Joaquin River fall-run Chinook salmon provide moderate evidence that high export rates are associated with low through-Delta survival, but there are few observations at high export rates, and considerable variability in survival estimates at low export rates.
- Comparison of CWT ocean recovery rates with measures of hydrodynamics, including export rates, found no evidence of a relationship, but Delta survival was not modeled separately from ocean survival (Zeug and Cavallo 2013).
- Only two years of steelhead AT data have been analyzed, and they depict an indeterminate relationship between export rates and through-Delta survival.

The conceptual model predicts increased entrainment mortality as a result of increased exports. Evidence is indirect.

- This has been observed indirectly via entrainment mortality estimates based on salvage for Chinook salmon from the Sacramento and San Joaquin rivers, but depends on assumed values of pre-salvage survival (Kimmerer 2008; Zeug and Cavallo 2014); see Section E.3.

- Higher rates of entering the CVP (i.e., moving past the trash racks) have been observed with higher CVP flows for both juvenile Chinook salmon and steelhead (Karp et al. 2014); however, for both species, the efficiency of the secondary louver system at the CVP was also higher at higher channel velocities (controlled by exports) (Bowen et al. 2004; Karp et al. 2014). Thus, there is evidence that higher export rates bring more juvenile salmonids into the CVP and improve the louver efficiency; these two components counteract to limit the overall effect of export rates on entrainment mortality, based on these two studies (unpublished).

The conceptual model predicts variable effects of exports on survival in different regions of the Delta. Data are limited but generally support the prediction.

- The relative success of the Interior Delta route compared to a Sacramento River mainstem route to Chipps Island was negatively related to export rate, but a model that omitted export rate accounted for the variability in the data equally well as the exports models (Newman and Brandes 2010).
- This has been observed in a provisional assessment by the SST of AT data from San Joaquin River fall-run Chinook salmon: there is evidence of a negative relationship between exports and survival from the Turner Cut junction to Chipps Island, but not from Mossdale to the Turner Cut junction. However, there are very few observations at high export rates.
- The two years of San Joaquin River steelhead AT data show no obvious relationship between export rates and survival except for increased survival through the CVP to Chipps Island for higher CVP export rates (Figure E.6-7).

E.6.2 FINDINGS ON CONCEPTUAL MODEL LINKAGES AND PREDICTIONS: EFFECTS OF EXPORTS ON SURVIVAL

E.6.2.1 Effects of Exports on Survival of Chinook Salmon

Through-Delta Survival

Our basis of knowledge regarding exports and through-Delta survival for juvenile Chinook salmon is low. Multiple directed field studies have collected data to evaluate this relationship; results from these studies are available in both peer-reviewed literature and agency reports. Additional results are newly compiled for this report. Evidence from these sources is inconsistent.

The VAMP study was designed to explore how Delta survival of fall-run Chinook salmon from the San Joaquin River is affected by exports and inflow in the presence of a barrier at the head of Old River. However, as discussed in Section E.2, the treatments needed to distinguish the role of exports from the role of inflow were not obtained; flow and exports were correlated during the VAMP study and, thus, effects of these two factors were confounded (Figures E.2-6 and E.2-7). The one exception was the VAMP study in 2006, which succeeded in de-coupling flow and export treatments using one treatment of high flow and low exports (1,500 cfs, first release group) and a second treatment of high flow and high exports (6,000 cfs, second release group). The survival estimates to Jersey Point were 0.12 for the first release group (low exports) and 0.02 for the second release group (high exports), but the difference was not statistically significant. Recovery numbers were reduced from the 2006 releases due to the closed or restricted ocean fishery in 2008 and 2009, which may have resulted in lower precision of estimates and lower ability to detect any significant differences in survival. Furthermore, the period of high exports coincided with higher water temperatures, and so any effect of exports was confounded with temperature effects.

The analysis of survival, exports, and inflow using CWT data found that survival of San Joaquin River Chinook salmon through the Delta increased with inflow (Newman 2008). Newman reports “little evidence for any association between exports and survival”; however, Figure 26 and Table 14 from Newman (2008) indicate some evidence for a positive association between exports and survival (i.e., 79% probability of a positive association from Dos Reis to Jersey Point). Newman (2008) also found a 67% probability of a positive association between flow in the upper Old River and survival from Old River near its head to Jersey Point. Previous analysis of the CWT data by the U.S. Fish and Wildlife Service also found a possible positive relationship between exports and survival of San Joaquin River Chinook salmon (SJRGA 2006); Newman (2008) hypothesized that the perceived positive association may be due to positive correlation between exports and inflow (correlation coefficient = 0.88).

Zeug and Cavallo (2013) compared four models representing competing but not mutually exclusive hypotheses about factors affecting an index of joint Delta survival and ocean survival using ocean recovery rates of fall-run Chinook salmon. The models and the variables included in each were release-specific (water temperature, FL, release location, barrier status at head of Old River), hydrologic (seven-day average of inflow and exports, and proportion salvaged at the export facilities), water quality (ammonium concentration, ratio of dissolved inorganic nitrogen to dissolved inorganic phosphorous, and turbidity), and ocean productivity (Wells’ Index). The models found to have the most support were the release-specific and water quality models for San Joaquin River Chinook salmon, and the water quality model for Sacramento River Chinook salmon. Ammonia concentrations had significant effects for both Sacramento River and San Joaquin River fish, but opposite relationships were observed in the two rivers (negative effect in the Sacramento River and positive effect in the San Joaquin River), possibly caused by lower and less variable concentrations of ammonia in the San Joaquin River. The hydrologic model (inflow, exports, proportion salvaged) was given negligible support compared to the alternative models for both San Joaquin River and Sacramento River fish (Zeug and Cavallo 2013). Zeug and

Cavallo (2013) suggest tidal flux and the use of ocean recovery data were possible factors influencing the lack of a detectable inflow effect, as well as the fact that the data they used came after initiation of water operations designed to protect juvenile salmonids. The results of Zeug and Cavallo (2013) are inconsistent with those of Newman (2008), who found a significant effect of inflow on Delta survival using differential recoveries at Chipps Island and in the ocean fishery for upstream and downstream groups released in the Delta. However, a key difference in methodology between Newman (2008) and Zeug and Cavallo (2013) is that the former modeled only the probability of Delta survival, whereas the latter modeled the joint probability of Delta and ocean survival. Despite this methodological difference, the differences in results warrant additional analyses using more recent data, in particular using the acoustic telemetry data collected from 2008 to 2015.

For Sacramento River late-fall-run Chinook salmon, Newman and Brandes (2010) reported evidence of a negative relationship between exports and the relative survival of fish released in the Interior Delta to those released in the Sacramento River mainstem (Figure E.6-1). However, they also reported equal support for a model that replaced exports with the ratio of exports to flow, and more or nearly equal support for a simpler model that excluded exports entirely (Newman and Brandes 2010). They suggest that the indeterminacy of the modeling results may have resulted from a low signal-to-noise ratio in the data. In particular, a large amount of the variability observed in the relative survival estimates was unexplained by exports (R^2=0.21 for the non-hierarchical model; Figure E.6-1). Newman (2003) reported a negative effect of exports on survival of Sacramento River fall-run Chinook salmon through the Delta, as well as significant effects of flow, salinity, temperature, tide, turbidity, and position of the DCC gate. Perry (2010) modeled survival of AT late-fall-run Chinook salmon migrating through various routes in the Sacramento River as a function of flow, exports, and fish length, and found no effect of exports on survival in Interior Delta routes (i.e., DCC and Georgiana Slough); he did not explore the possible effect of exports on survival in mainstem routes.

Simple single-variable graphical analyses performed by the SST using both CWT and AT data from San Joaquin River Chinook salmon also show equivocal patterns in survival and exports (Figures E.6-2 through E.6-4). Based on the CWT data, survival to Jersey Point appears to increase as exports increase for exports less than approximately 4,000 cfs, despite considerable variability not explained by export rate (Figure E.6-2); however, this pattern does not appear to hold for the AT data, and is complicated by an unbalanced study design of export levels (i.e., many low export observations and few high) and the correlation between flow and exports (Figure E.2-8). Unlike for CWT data, there does not appear to be a positive relationship between exports and survival using only AT data. Whether this is due to changes in study methodology or to changes in the system over time is not known (most CWT studies predated AT studies).

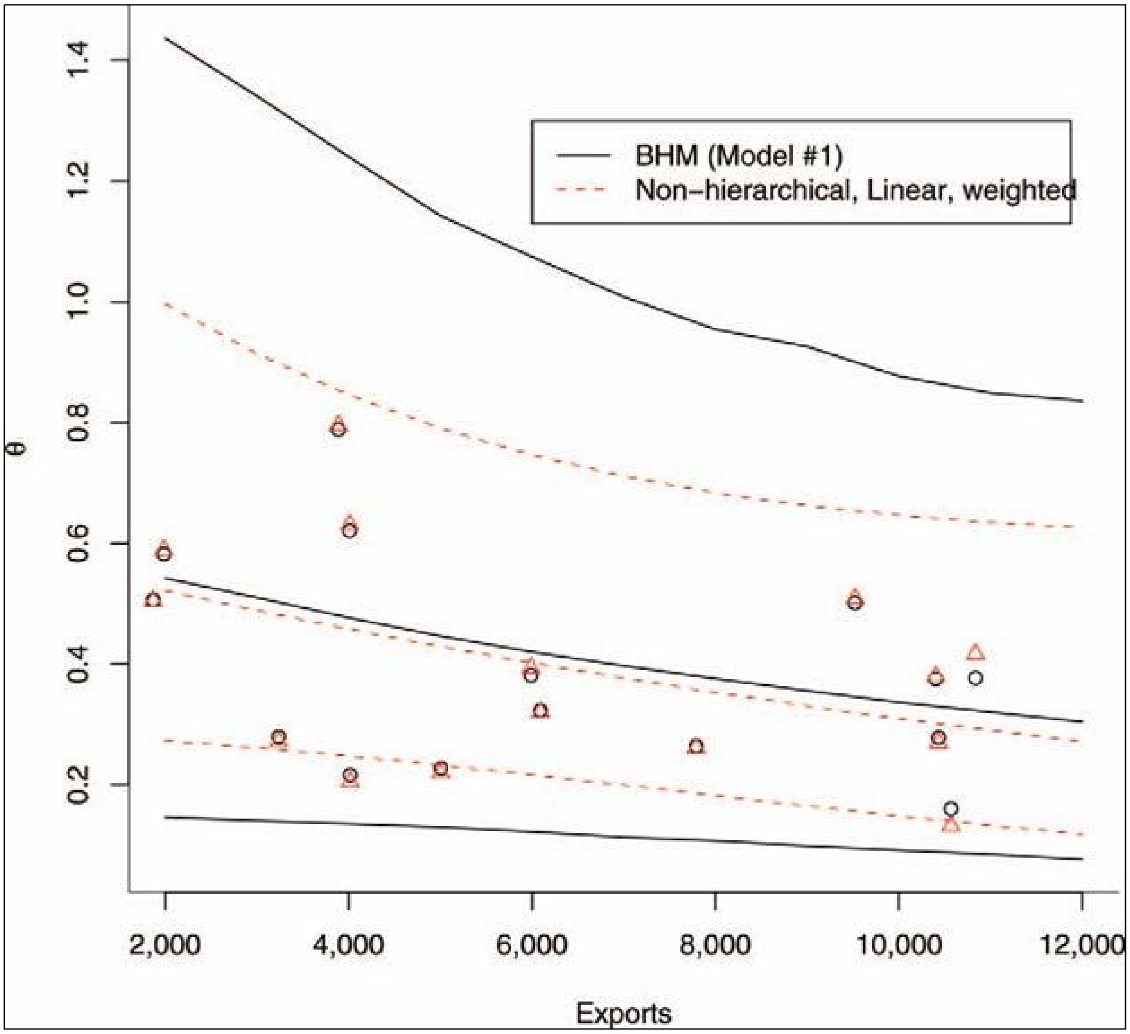


Figure E.6-1. Expected Values and 2.5–97.5% Prediction Intervals for Theta at Different Levels of Exports Produced By Bayesian Hierarchical Model (BHM) 1 (Solid Lines) and the Non-hierarchical Model (Dashed Lines) Using Chipps Island and Combined Ocean and Inland Recoveries

Notes: The circles denote posterior mean fitted values for θ *from the BHM, the triangles maximum likelihood estimates.* θ *= relative recovery of Interior Delta (Georgiana Slough) release to Sacramento River mainstem (Ryde) release.* R^2*=0.21 (non-hierarchical model).*
Source: Newman and Brandes 2010

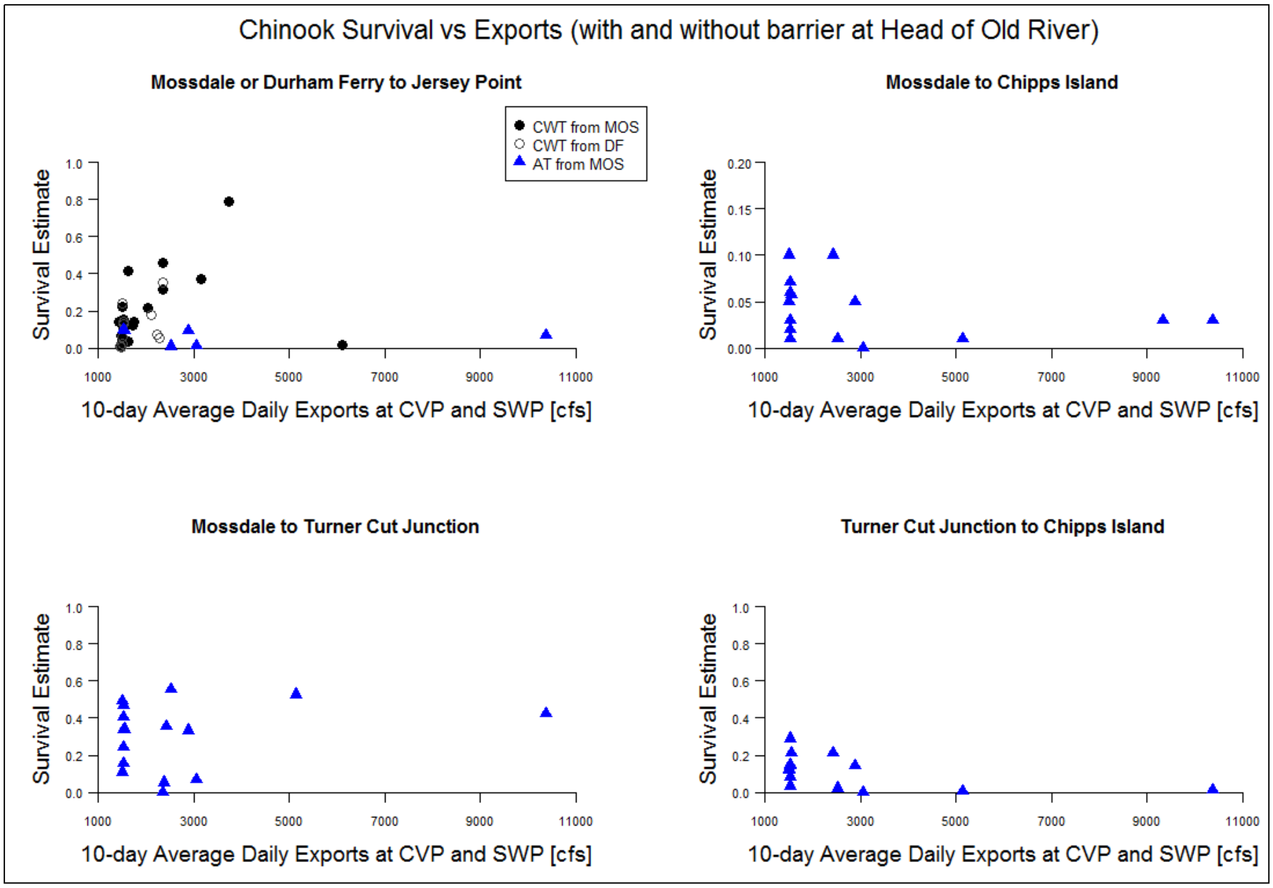


Figure E.6-2. Estimated Survival of Fall-run Chinook Salmon Based on CWT or AT Data, Versus the 10-day Average of Daily Exports at CVP and SWP, Regardless of Barrier Status at the Head of Old River

Notes: Exports rates are measured from the final day of release at Durham Ferry or Mossdale, downloaded from www.water.ca.gov/dayflow/. Before 2002, SWP omits Byron Bethany Irrigation District intake (BBID); in 2002, SWP = Banks Pumping Plant flow; after 2002, SWP includes BBID. Survival from Mossdale or Durham Ferry to Jersey Point and Chipps Island includes all routes.

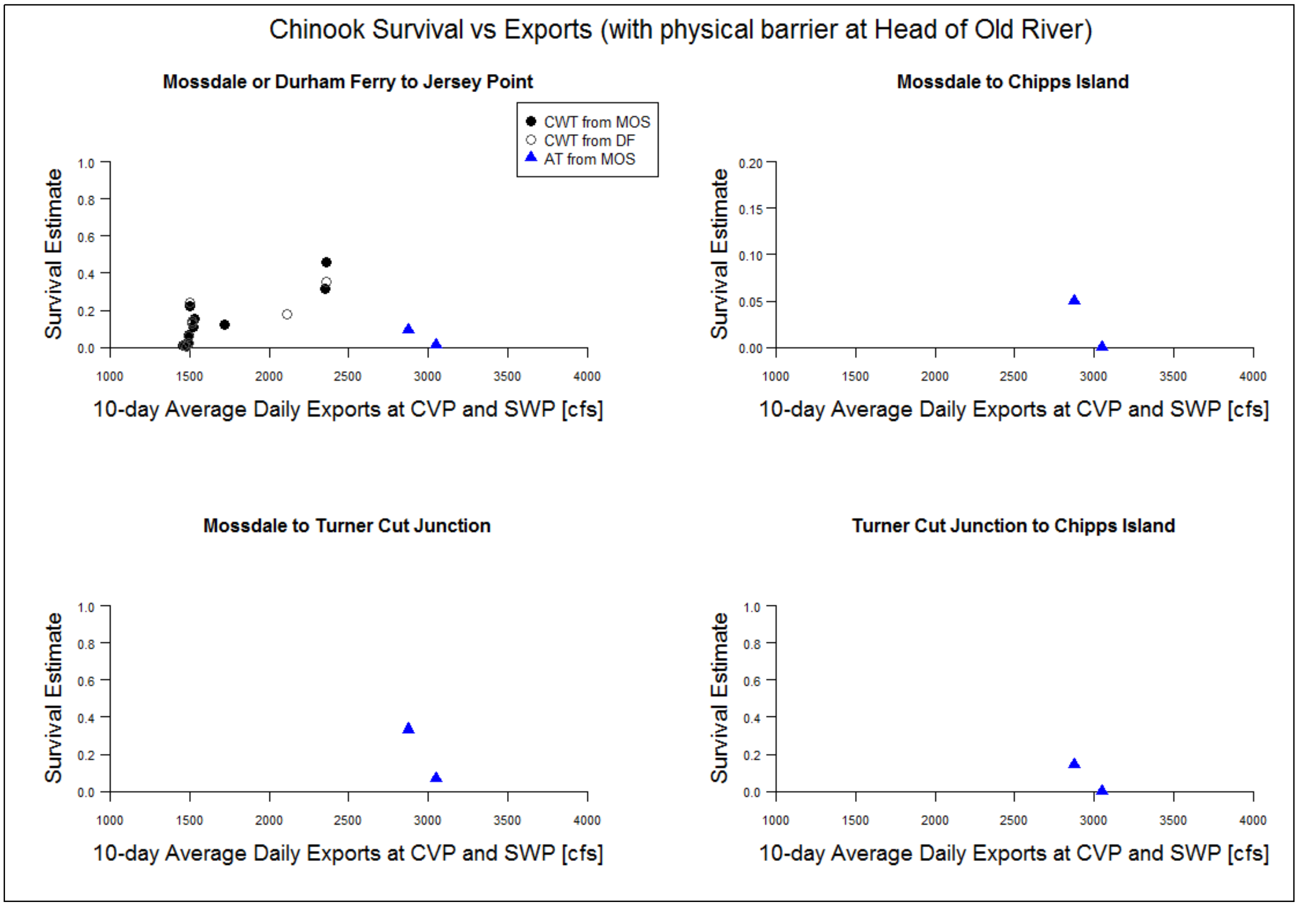


Figure E.6-3. Estimated Survival of Fall-run Chinook Salmon Based on CWT or AT Data, Versus the 10-day Average of Daily Exports at CVP and SWP, in the Presence of a Physical Barrier at the Head of Old River

Notes: Exports rates are measured from the final day of release at Durham Ferry or Mossdale, downloaded from www.water.ca.gov/dayflow/. Before 2002, SWP omits BBID intake; in 2002, SWP = Banks Pumping Plant flow; after 2002, SWP includes BBID. Survival from Mossdale or Durham Ferry to Jersey Point and Chipps Island includes all routes.

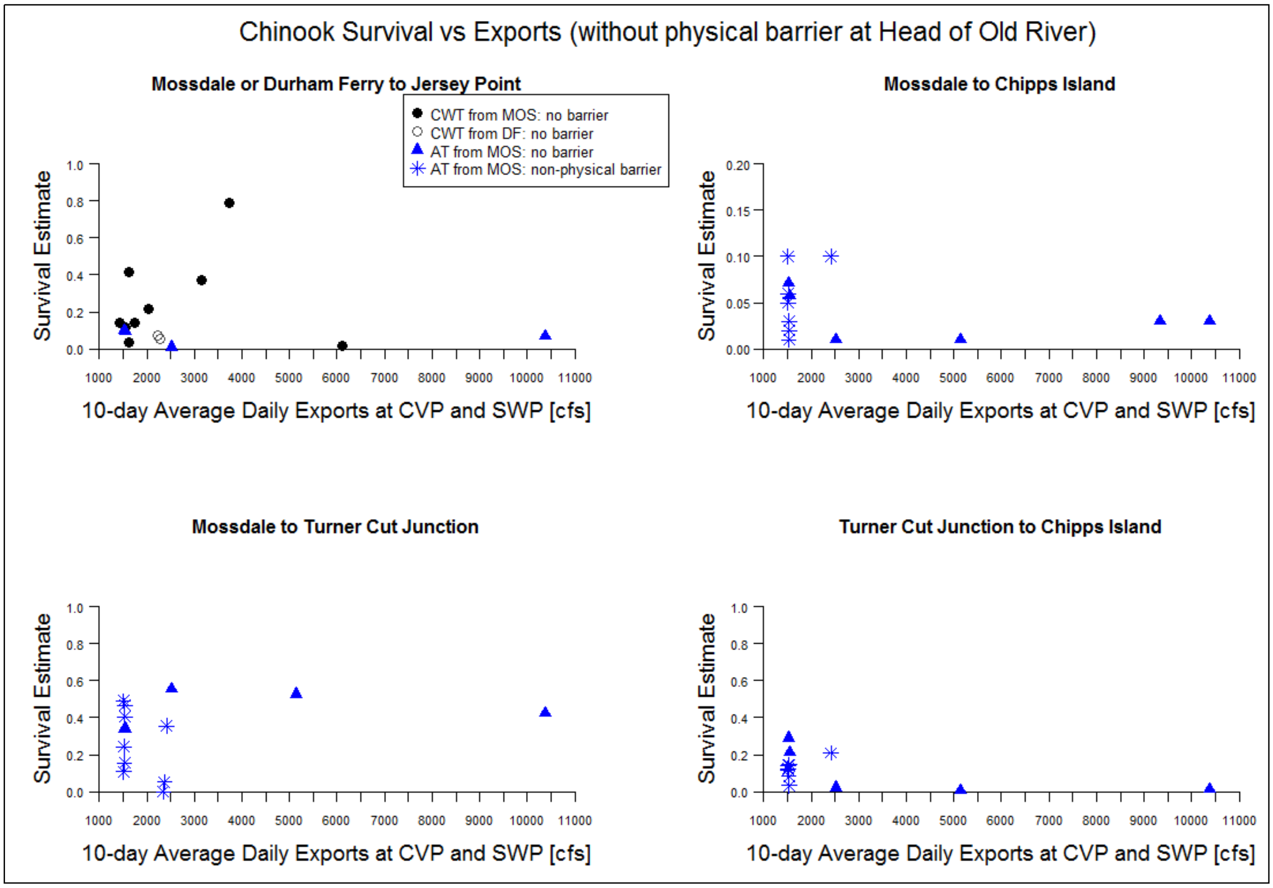


Figure E.6-4. Estimated Survival of Fall-run Chinook Salmon Based on CWT or AT Data, Versus the 10-day Average of Daily Exports at CVP and SWP, in the Presence of Either a Non-physical Barrier or No Barrier at the Head of Old River

Notes: Exports rates are measured from the final day of release at Durham Ferry or Mossdale, downloaded from www.water.ca.gov/dayflow/. Before 2002, SWP omits BBID intake; in 2002, SWP = Banks Pumping Plant flow; after 2002, SWP includes BBID. Survival from Mossdale or Durham Ferry to Jersey Point and Chipps Island includes all routes

Using either CWT or AT data alone or combined, there is considerable variation in survival estimates from Mossdale to Jersey Point for export levels less than 4,000 cfs, whereas the survival estimates for higher export levels are consistently low (upper left plots in Figures E.6-2 and E.6-4). Similar patterns are observed for survival from Mossdale to Chipps Island from AT data (top right plots in Figures E.6-2 and E.6-4). This pattern is consistent with a factor-ceiling relationship, in which high levels of exports restrict the range of survival values, but low levels of exports impose no such restriction, and other factors control survival at low export levels. However, although the data suggest such a relationship may be possible based on a visual inspection of the scatterplots, it is important to note that there are only two observations for export levels greater than 4,000 cfs, and the low survival estimates observed for these two export levels are well within the range of observations at lower export levels.

Although it is possible that both the observed survival estimates for high export levels (i.e., greater than 4,000 cfs) were low because high export rates impose a low maximum survival, it is also possible that the limited range of the observed survival estimates was due only to chance. To explore that possibility, the SST ran simulations by randomly selecting two observations, without replacement, from the pool of estimated survival probabilities from low export levels (less than 4,000 cfs), and computed the frequency of observing only estimates less than the maximum observed for the higher export levels (i.e., ≤ 0.07). The event of observing only survival estimates ≤ 0.07 occurred in only 10% of 100,000 simulations, indicating a low probability of observing two such low estimates only by chance. This exercise supports the hypothesis that a high export rate imposes a maximum on through-Delta survival, although there remains uncertainty about the value of the maximum survival possible and the range of export levels that impose such a maximum.

Reach-Specific Survival

Our basis of knowledge regarding evidence of a relationship between exports and reach-specific Delta survival for juvenile Chinook salmon is low. While multiple directed field studies have collected data to evaluate this relationship, compiled results from these studies are first presented primarily in this report, where it is a preliminary conclusion. Our understanding is low due to inconsistent results and sparse data.

Survival of juvenile Chinook salmon from Mossdale to Turner Cut junction is quite variable for low export levels, but relatively high (0.42 to 0.52) for export levels greater than 4,000 cfs (bottom left plots in Figures E.6-2 and E.6-4). At export levels less than 4,000 cfs, it appears that factors other than the export rate drive the variability in survival between Mossdale and Turner Cut junction. It is possible that the export rate limits the maximum possible survival in this lower range of export levels, but the data give no indication of a relationship between export levels and maximum survival rate for these export levels. The relatively high survival estimates observed in this reach for higher export levels (greater than 4,000 cfs) are inconsistent with a factor-ceiling relationship. However, it is consistent with a positive relationship between inflow and survival in this reach, based on the assumption that high exports depend on high inflow; in fact, the inflow values for these two data points were both greater than 10,000 cfs, whereas the average inflow for all data in this plot was approximately 5,000 cfs. Attempting to theorize about the nature of the relationship between exports and survival in this reach when the export rate is high demonstrates the danger of making inference based on insufficient data (in this case, only two data points). Furthermore, hydrological model simulations reported in Volume 1, Appendix B show little effect of exports on flow and velocity in the San Joaquin River between the head of Old River and Turner Cut (Figure E.2-2), compared to the Interior Delta, so any effect of exports on survival in this region is likely to be indirect.

There is some indication that survival from Turner Cut to Chipps Island may decrease with increasing exports (Figures E.6-2 and E.6-4), but there is considerable variability in survival estimates at the lowest export level (1,500 cfs). Again, this is consistent with a factor-ceiling relationship, in which the export rate restricts the maximum survival possible while other variables control the mean survival. However, as on other spatial scales, there are only two observations at exports greater than 5,000 cfs. Further analysis is warranted that accounts for barrier status at the head of Old River and intra-annual variation. Additional years of data are likely to be required to clarify any relationship between exports and survival.

Facility Survival

Our basis of knowledge regarding the conceptual model's linkage between exports and facility survival is medium. Multiple directed field studies have collected data to evaluate this relationship, and the results from these studies are published primarily in agency reports. Additionally, multiple peer-reviewed articles have quantified the relationship between exports and direct mortality of Chinook salmon at the facilities. However, uncertainties remain about the magnitude and variability of pre-screen mortality at the CVP.

The effect of exports on survival through the water export facilities has been studied indirectly by the effect of water velocity through the facility on louver efficiency and entrance to the facilities. Higher louver efficiencies are equated with lower mortality in the facility. At the CVP, higher louver efficiencies have been shown during periods of higher velocity (e.g., 5.58 ft/s vs. 0.33 ft/s) in the facility, which is a result of high export rates (Bates and Vinsonhaler 1957; Karp et al. 1995; Bowen et al. 2004; Sutphin and Bridges 2008). Karp et al. (2014) observed higher facility entrance rates of acoustic-tagged Chinook salmon during higher flows, compared to increased looping behavior in front of track racks and in bypass channels during low or medium flows. Because export rates influence flow at this location, this finding suggests that survival through the facility may be higher at higher export rates. However, these studies compared louver efficiency with flows or channel velocity rather than export rates directly, and so the conclusions about export rate are indirect.

Findings from statistical comparisons of export rates to survival or recovery rates are mixed. During the VAMP study (2000 to 2011), low export rates were maintained during the spring outmigration, resulting in low primary velocities at the Tracy Fish Collection Facility at the CVP; increasing the primary bypass ratio (ratio of average water velocity at entrance of bypass No. 4 to average water velocity in the Tracy Fish Collection Facility primary channel) during these times resulted in increased secondary channel velocities, and higher recovery rates of Chinook salmon (Sutphin and Bridges 2008). In the CCF, Gingras (1997) found greater efficiencies and higher survival for Chinook salmon in the CCF when exports were higher. Nevertheless, visual inspection of simple scatterplots compiled by the SST of estimated facility survival, from the entrance at the CVP trash racks or CCF radial gates to

Chipps Island, plotted against export rates, show no well-defined trend, based on AT data from the VAMP study (2008 to 2011) and the 2012 Chinook tagging study in the South Delta (Figure E.6-5). For survival from the CVP trash racks to Chipps Island, both the highest and lowest survival estimates were observed for the lowest levels of exports (top row, Figure E.6-5). This suggests that at very low export levels, a combination of factors that are not directly related to exports determine survival through the CVP. However, for average CVP export rates greater than 2,000 cfs (or combined exports greater than 5,000 cfs), survival from the CVP trash rack to Chipps Island was between 0.10 and 0.25, suggesting that export rates in this range may impose a restriction on the survival probabilities possible; nevertheless, there does not appear to be a relationship between export rate and average survival probability (Figure E.6-5). It is possible that a related factor determines survival at these export levels. Additional observations in this range (e.g., CVP greater than 2,000 cfs) may provide more insight into the relationship between exports and survival through the CVP facility. For survival through the CCF to Chipps Island, Chinook salmon survival was at or near 0 for all observations, except for one of the highest export levels (Figure E.6-5). No survival estimates are available from the SWP trash racks to Chipps Island because acoustic telemetry receivers were not placed at the SWP except in 2008, when estimated survival was confounded with premature tag failure.

On a population level, Zeug and Cavallo (2014) explored the factors affecting salvage of juvenile Chinook salmon into the CVP and SWP, and found that increased export rate was associated with increased salvage rates at both facilities for Chinook salmon from both San Joaquin River and Sacramento River releases. By estimating entrainment and direct mortality at the facilities from the salvage numbers, they concluded that increased exports results in increased facility mortality (including pre-screen mortality, entrainment mortality, and within-facility mortality). Kimmerer (2008) came to similar conclusions for winter-run Chinook salmon, and found that the estimated proportion of winter-run juveniles exiting the Delta that were salvaged increased with increased export flows. The proportion of total loss in the Delta due to exports depends on pre-salvage survival (i.e., survival from pre-screen mortality and mortality due to entrainment in the canals) (Kimmerer 2008; Zeug and Cavallo 2014). Zeug and Cavallo (2014) also noted that relating water diversions to the proportion of population loss due to entrainment is complicated by having few observations at higher export rates (i.e., only three observations of San Joaquin River entrainment mortality for exports greater than 3,531 cfs).

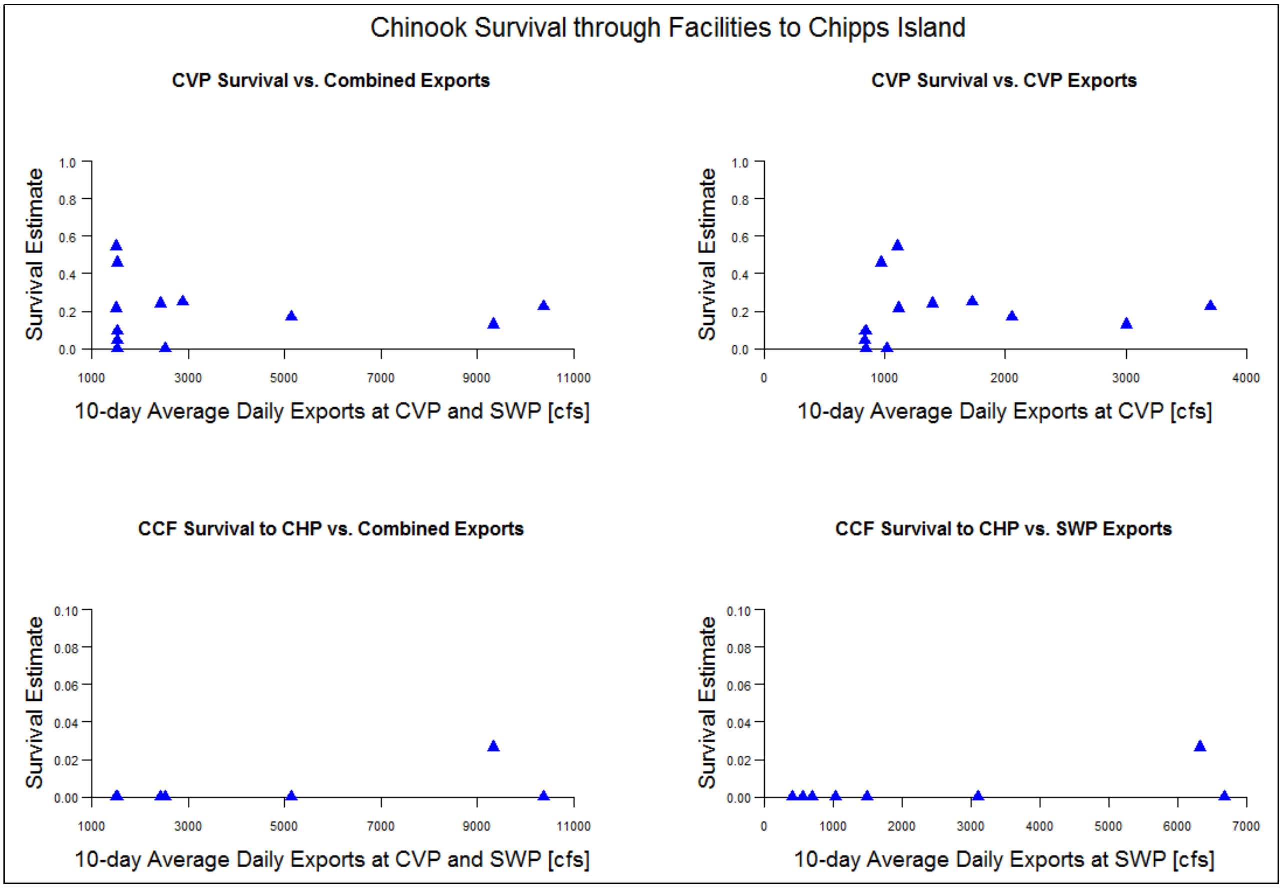


Figure E.6-5. Estimated Survival of Fall-run Chinook Salmon Based on AT Data (2008, 2010-2012 Studies), Versus the 10-day Average of Daily Exports at CVP and SWP

Notes: Survival is from trash racks for CVP, and from radial gates at entrance to CCF for SWP. Survival from the CCF to Chipps Island is through the SWP. Exports rates are measured from the final day of release at Durham Ferry, downloaded from www.water.ca.gov/dayflow/. Export rate at SWP includes Byron Bethany Irrigation District intake.

Summary: Chinook Salmon

In summary, there is not clear and consistent evidence of a relationship between the combined export rate from the CVP and SWP and survival of San Joaquin origin fall-run Chinook salmon through the Delta. Comparisons of survival to export rates are complicated by the high correlation (up to r=0.98 in historical data) between inflow and exports and the sparse data available for higher export rates (e.g., greater than 4,000 cfs). For San Joaquin River salmon, Newman (2008) found "little evidence for any association between exports and survival" through the Delta, and hypothesized that a possible positive relationship observed in a previous analysis (SJRGA 2006) may have been driven by the positive correlation between exports and inflow. Zeug and Cavallo (2013) also found no evidence of a relationship between exports (combined with other hydrological metrics) and ocean recovery rates, which reflect the combination of both Delta survival and ocean survival and capture; however, it is possible that any effect on Delta survival was swamped by variability in ocean survival and capture. Visual inspection of AT survival data shows no clear evidence of a relationship between exports and mean survival through the Delta. The AT data are consistent with a factor-ceiling relationship, in which higher levels of exports limit the possible maximum survival probability, especially through the downstream reaches of the Delta; however, because very few observations are available for higher export rates (e.g., greater than 2,000 cfs), it is not possible to make firm conclusions. For Sacramento River salmon, there is some evidence of a negative relationship between exports and through-Delta survival for fall-run Chinook salmon migrating from the Sacramento River in spring (Newman 2003). Some evidence of a relationship between exports and survival has been found for late-fall-run Chinook salmon migrating from the Sacramento River in the winter; however, other models that omitted exports had similar support in Newman and Brandes (2010), and Perry (2010) found no evidence of a relationship. For facility survival, louver efficiency experiments at the CVP (Bates and Vinsonhaler 1957; Karp et al. 1995; Bowen et al. 2004; Sutphin and Bridges 2008) and pre-screen mortality studies at the CCF (Gingras 1997) suggest that survival may be higher through the facilities when exports are higher; also, salvage rates at the water export facilities from the mainstems of San Joaquin River and Sacramento River and northern Interior Delta release points are positively associated with exports (Zeug and Cavallo 2014). However, there was only limited indication from the available AT data of higher facility survival at higher export rates. A formal analysis of AT data is ongoing but not yet completed, and may provide insight into the relationship between survival and exports. However, sparse observations at high export levels (e.g., greater than 4,000 cfs) combined with small sample sizes at the export facilities will limit inference even from a formal analysis of the existing AT data.

E.6.2.2 Effects of Exports on San Joaquin River Steelhead

No formal analysis of steelhead survival through the South Delta is available in the literature, although annual survival estimates are available in agency reports for two study years. Thus, the basis of knowledge for the conceptual model's linkage between exports and steelhead regional survival and facility survival is low. Analysis of four additional years of steelhead data is ongoing or planned.

Visual inspection of the two years of survival estimates of acoustic-tagged steelhead through the South Delta (i.e., from Mossdale to Jersey Point or Chipps Island) shows an indeterminate relationship between combined export rates and survival (Figure E.6-6). Survival from Mossdale to Chipps Island is slightly higher for higher levels of exports (greater than 3,500 cfs), but also higher for the lowest levels of exports observed during the two study years (2011 and 2012). However, there was little variability in export levels during the study periods in these two years compared to the variability observed during the multi-decade Chinook studies (Figures E.6-2 and E.6-6). The survival estimates from Mossdale to Chipps Island include both the route through the San Joaquin River and the route through salvage at the facilities. Restricted only to the San Joaquin River route from Mossdale to the Turner Cut junction, there was no indication of a relationship between exports and survival (Figure E.6-6). From the Turner Cut junction to Chipps Island, and including routes from the Turner Cut junction through the salvage facilities, the pattern mimics the pattern for survival through the entire South Delta: survival decreases as exports increase from approximately 2,500 cfs to 3,000 cfs, but is higher for export rates greater than 3,500 cfs (Figure E.6-6). It is not known from only two years of data if the non-linear relationship observed is representative of all conditions, or if the variability in the survival estimates primarily reflects other variables such as inflow, barrier status at the head of Old River, fish condition, or other factors, or simply interannual and seasonal variability. There is no suggestion of a factor-ceiling relationship between exports and survival on any spatial scale, based on visual inspection of Figure E.6-6. More years of survival estimates from steelhead at a variety of exports levels, including both higher and lower export levels, will be required to assess the relationship between exports and survival for steelhead.

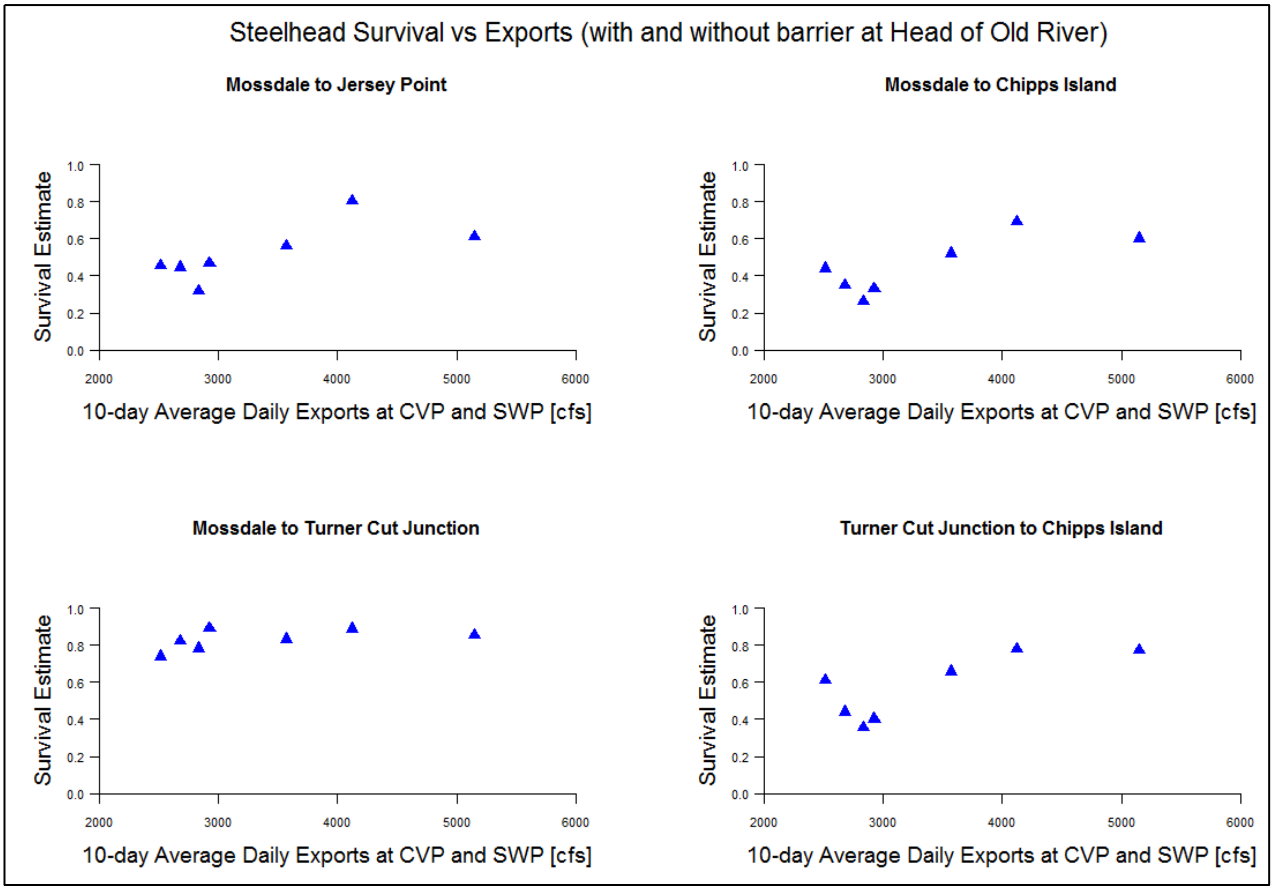


Figure E.6-6. Estimated Survival of Steelhead Based on AT Data (2011 and 2012 Study Years), Versus the 10-day Average of Daily Exports at CVP and SWP, Regardless of Barrier Status at the Head of Old River

Notes: Exports rates are measured from the final day of release at Durham Ferry, downloaded from www.water.ca.gov/dayflow/. Export rate at SWP includes BBID intake. Survival from Mossdale to Jersey Point and Chipps Island includes all routes.

Survival of steelhead through the facilities shows some relationship to export rates. Karp et al. (2014) observed higher probability of entering the CVP facility (i.e., pass through the trash racks) by acoustic-tagged steelhead when exports through the CVP were higher, and Bowen et al. (2004) found higher efficiency of the secondary louver system at the CVP when exports were higher; these findings suggest that survival through the region of the Delta near the export facilities may be affected by export rates, although the combination of these two factors (facility entrance and louver efficiency) may limit the strength of such a relationship. Visual inspection of simple SST scatterplots of estimated facility survival to Chipps Island (from entrance at the CVP trash racks or CCF radial gates) plotted against export rates for acoustic-tagged steelhead shows a positive association between the CVP export rate (≤ 4,000 cfs) and survival through the CVP to Chipps Island (Figure E.6-7). For survival from the CCF radial gates to Chipps Island, the relationship with either combined exports or SWP exports is similar to that observed for CVP survival of Chinook salmon (Figure E.6-5): a wide range of survival estimates is observed for low export rates while the few observations at higher export rates have relatively high survival (0.75 to 0.86) with little variation (bottom row, Figure E.6-7). However, there are insufficient data to adequately characterize a relationship, both because there are only three observations at combined export rates greater than 4,000 cfs and because two years of observations are insufficient to reflect interannual variability. No survival estimates are available from the SWP trash racks to Chipps Island because acoustic telemetry receivers were not located at the SWP facility.

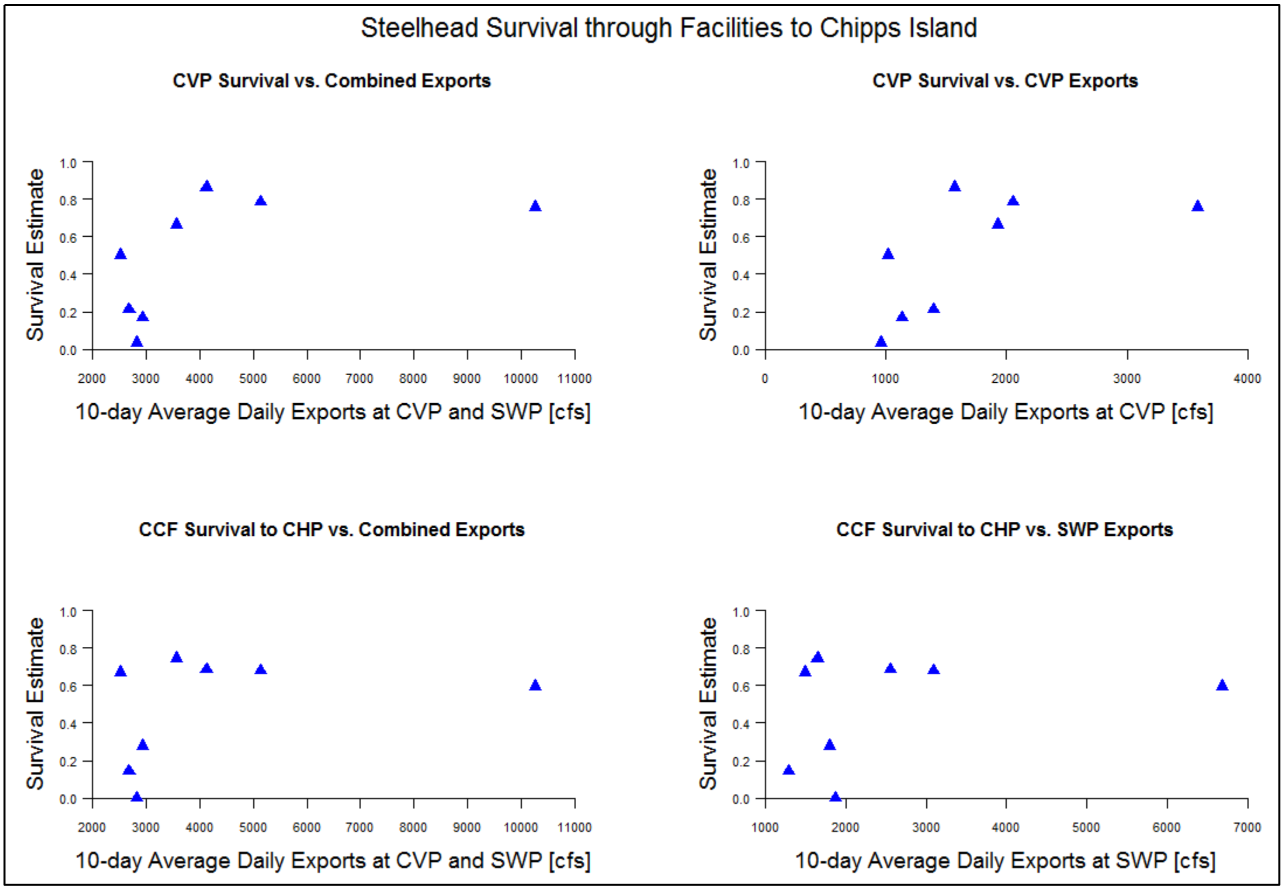


Figure E.6-7. Estimated Survival of Steelhead Based on AT Data (2011 and 2012 Studies), Versus the 10-day Average of Daily Exports at CVP and SWP

Notes: Survival is from trash racks for CVP, and from radial gates at entrance to CCF for SWP. Survival from the CCF to Chipps Island is through the SWP. Exports rates are measured from the final day of release at Durham Ferry, downloaded from www.water.ca.gov/dayflow/. Export rate at SWP includes BBID intake.

E.6.3 SUMMARY: KNOWLEDGE GAPS ON SURVIVAL AS A FUNCTION OF EXPORT RATE

There are a number of gaps in our understanding of how Delta survival depends on export rates.

- The influence of export rates on the relative survival in different routes through the Delta for San Joaquin River salmonids.
- The interannual and within-season variability in survival at high export rates on various spatial scales.
- The mechanism for lower survival observed in the lower reaches of the San Joaquin River route (i.e., Turner Cut junction to Chipps Island) for higher export rates.
- The dependency of a survival-exports relationship on the presence of a physical barrier at the head of Old River.
- The effect of exports on survival apart from an effect of San Joaquin River inflow (inflow and exports have been highly correlated in past studies).

- The effect of exports on mortality mechanisms, including predator distribution and abundance.
- Incomplete multi-year analysis of existing Chinook salmon and steelhead AT data (analysis is ongoing); however, conclusions will remain uncertain due to limited observations at high export levels and correlation between exports and inflow, and possibly other variables (e.g., water temperature).
- The component of Delta mortality that is due to indirect effects of exports, compared to direct mortality at the facilities.
- Variability in pre-salvage survival, including pre-screen mortality (unknown at the CVP), entrainment mortality, and within-facility mortality, and how these responses depend on export rate.

E.7 SURVIVAL AS A FUNCTION OF OMR REVERSE FLOW

The conceptual model links flow through the Old and Middle rivers to survival via the influence of OMR reverse flow management on migration route selection and migration rate. Specifically, increased negative OMR flow is expected to draw (i.e., act as a flow cue) fish from the Sacramento River or lower San Joaquin River into the Interior Delta and toward the facilities, and to prevent fish that have entered the Interior Delta from navigating northward through Delta channels to the Delta exit (Figure E.2-1). Thus, increased negative OMR flow is expected to decrease through-Delta survival of Sacramento River and San Joaquin River fish. On the other hand, for San Joaquin River fish that have already entered the Interior Delta at the head of Old River, increased negative OMR flow may result in faster entry to salvage facilities at the CVP and SWP and, therefore, may be associated with higher survival from the head of Old River to Chipps Island via the Old River route. However, the SST did not look specifically at the effects of OMR reverse flows on survival. The effect of OMR reverse flows on survival in the Delta remains a knowledge gap. Additional analyses should be done to evaluate the effect of OMR reverse flows on survival.

E.8 SURVIVAL AS A FUNCTION OF SAN JOAQUIN RIVER INFLOW

The conceptual model links survival to San Joaquin River inflow via the effect of inflow on Delta hydrodynamics, route selection, and migration rate in the Delta. Higher inflow is expected to increase survival through regions of poor habitat such as the Interior Delta, and to discourage selection of migration routes that use the Interior Delta and fish facilities. Higher inflow may also increase migration rate through regions of beneficial habitats, which may result in lost growth potential during Delta migration and consequently lower survival upon exiting the Delta; we do not consider post-Delta survival specifically here.

The presence of the physical rock barrier at the head of Old River depends largely on San Joaquin River inflow: it cannot be installed for flows greater than 5,000 cfs, and cannot be operated (e.g., without overtopping and potential wash-out) for flows greater than

7,000 cfs. The present configuration of the barrier (2012, 2014 to 2016) includes eight culverts. Because the barrier restricts route selection at the head of Old River and may affect downstream survival due to flow effects and predator distribution, this restriction means that any effect of San Joaquin River inflow on survival may depend on the status of the barrier. In addition, the effect of inflow is expected to be stronger in the upstream reaches of the San Joaquin River or Interior Delta because tides override the influence of San Joaquin River inflow on hydrodynamics further downstream.

In this section, predictions from the conceptual model relating to survival as a function of inflow are identified and reviewed considering findings for Chinook salmon and steelhead. Findings come mostly from peer-reviewed literature and technical reports, but we also present new compilations of data from CWT and AT studies of San Joaquin River fish; the data used in these compilations are described in Section E.2.

E.8.1 SUMMARY: CONCEPTUAL MODEL PREDICTIONS ON SURVIVAL AS A FUNCTION OF SAN JOAQUIN RIVER INFLOW

The conceptual model predicted a positive relationship between San Joaquin River inflow and through-Delta survival. Findings have been inconsistent for Chinook salmon, and data are limited for steelhead.

- A positive relationship was found between Vernalis inflow and Delta survival of Chinook salmon, based on Chipps Island and ocean recoveries of CWTs (Newman 2008).
- Analysis of CWT recoveries from ocean recoveries alone showed no effect of Vernalis inflow on the joint probability of Delta and ocean survival for Chinook salmon, but Delta survival was not modeled separately from ocean survival (Zeug and Cavallo 2013; inflow was assessed in combination with exports).
- Comparison of adult escapement to the San Joaquin River basin between 1951 and 2012 with San Joaquin River flow at Vernalis two and a half years before adult return showed a positive association (years 1951 to 2003; SJRGA 2007; updated by the SST through 2012).
- Visual inspection by the SST of the few years of AT data available shows that higher Delta inflow at Vernalis does not always result in higher survival to Chipps Island, especially for Chinook salmon.

The conceptual model predicted a stronger relationship between San Joaquin River inflow and survival in upstream regions of the San Joaquin River and Interior Delta compared to downstream regions. Data are limited.

- Only AT data are available for assessing this prediction.
- Chinook salmon data show different trends in regional survival with San Joaquin River inflow (positive trend for Mossdale to Turner Cut junction, negative trend for

Turner Cut junction to Chipps Island), but formal analysis is lacking for the relative strengths of these trends.

- In contrast, the two years of steelhead AT data show no effect of San Joaquin River inflow on survival from Mossdale to Turner Cut junction and a positive association between inflow and survival from Turner Cut junction to Chipps Island.

E.8.2 FINDINGS ON CONCEPTUAL MODEL LINKAGES AND PREDICTIONS: EFFECTS OF SAN JOAQUIN RIVER INFLOW ON SURVIVAL

E.8.2.1 Effects of San Joaquin River Inflow on Survival of Chinook Salmon

Through-Delta Survival

The basis of knowledge regarding the conceptual model's linkages between San Joaquin River inflow at Vernalis and through-Delta survival of San Joaquin River Chinook salmon is medium. Although multiple directed field studies have collected data to evaluate this relationship, and the results from these studies are in peer-reviewed literature, agency reports, and this report, the relationship has become uncertain as more recent result have been considered. The predictability of the relationship may depend on whether a physical barrier is installed at the head of Old River. The extent to which other operations (e.g., export rates) affect the relationship between San Joaquin river inflow and through-Delta survival is unknown.

Comparison of adult escapement to the San Joaquin River basin between 1951 and 2003 with San Joaquin River flow at Vernalis two and a half years before adult return showed a positive association ($P < 0.01$), with higher adult escapement associated with higher San Joaquin River inflow ($r^2=0.40$ without the barrier in place at head of Old River; SJRGA 2007). An updated comparison performed by the SST using adult escapement data from 1951 to 2012 found similar results, although with a lower r^2 of 0.30. This finding is consistent with the hypothesis that higher Delta inflow from the San Joaquin River results in higher juvenile survival through the Delta. However, because adult escapement represents mortality factors throughout the life history, this finding is not unique to that hypothesis; for example, region-scale weather patterns may influence spawning, incubation, rearing, and ocean survival as well as juvenile through-Delta survival, and may also influence Delta inflow.

Newman (2008) found a significant effect of San Joaquin River inflow at Vernalis in predicting fall-run Chinook salmon survival to Jersey Point, with higher inflows associated with higher survival estimates, based on CWT data. However, because the barrier at the head of Old River could not be installed when flows were high, the effect of inflow is confounded with the effect of the barrier; Newman (2008) recommended further exploration. Zeug and Cavallo (2013) found no support for a hydrologic model (including both exports and inflow) of an index of joint Delta survival and ocean survival using ocean recovery rates, compared to a water quality model; it is possible that any effects on Delta survival were swamped by variability in ocean survival.

Single-variable graphical analyses performed by the SST suggest that the range of possible survival values may increase up to a point as inflow at Vernalis increases, when the status of the barrier at the head of Old River is not accounted for, despite considerable variation in observed survival under most inflow values (Figure E.8-1). Based on CWT data for which survival index estimates were available for inflows up to approximately 28,000 cfs, survival to Jersey Point appears generally to increase for inflow less than 19,000 cfs and decrease for inflow greater than 19,000 cfs (Figure E.8-1); observations at high inflows were all in years without the HORB, which cannot be installed when inflow greater than 5,000 cfs or operated for inflow greater than 7,000 cfs. In such years without a barrier, fish may have migrated either via the San Joaquin River or Old River, including through the facilities. When a physical barrier was installed at the head of Old River, there appears to be a stronger effect of flow on survival to Jersey Point, based primarily on the CWT data, with higher survival typically observed with higher inflow (up to approximately 6,500 cfs) (Figure E.8-2). Results from AT data are similar to CWT results for similar values of inflow at Vernalis, although no AT data are available for inflow greater than approximately 12,000 cfs and only one year of AT data are available in the presence of the physical barrier (top row of plots in Figures E.8-1 and E.8-2).

It is apparent that understanding the effect of inflow on survival in the Delta requires accounting for the presence or absence of the barrier at the head of Old River. For example, 2011 was a high flow year and 2012 was a low flow year, but survival estimates to Chipps Island in the high flow year (2011) were similar to those in the low flow year (2012) (Figure E.2-3). The HORB was absent in 2011 because of the high flows; although most acoustic-tagged Chinook salmon reaching the head of Old River continued migrating down the San Joaquin River, approximately 40% entered Old River at that junction, and survival to Chipps Island was low in both routes (≤ 0.04) (SJRGA 2013). The barrier was in place during the low flow year of 2012, and most tagged Chinook salmon remained in the San Joaquin River, but survival was very low (Figure E.2-3). This pattern is consistent with an interaction between an inflow effect and a barrier effect, in which the effect of inflow depends on the barrier. However, distinguishing between an inflow effect and a barrier effect, and describing any interaction between them, is complicated because the HORB cannot be operated or installed during high flow conditions. Thus, any barrier-inflow interaction effect must be interpreted only for inflow less than 5,000 cfs (the highest inflow for which the barrier may be installed).

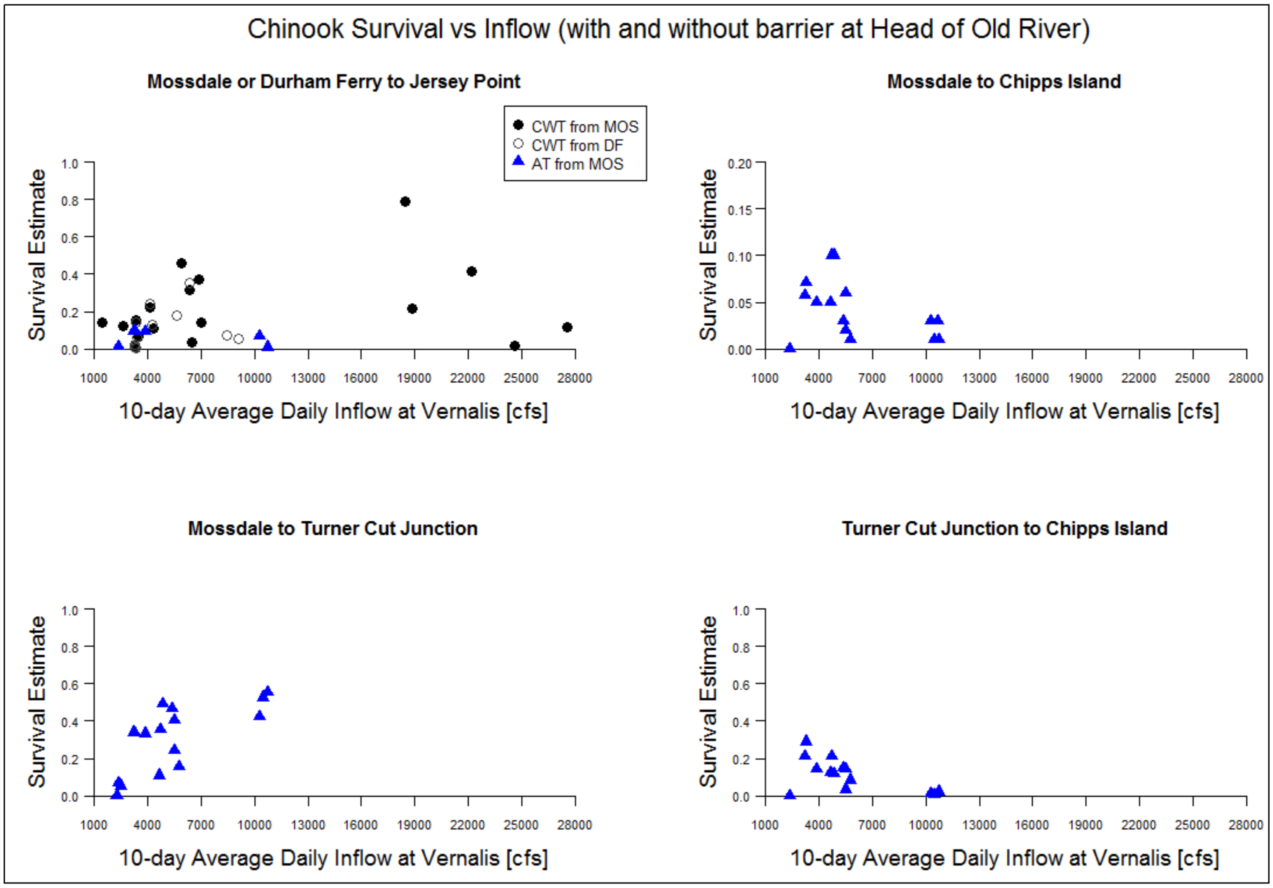


Figure E.8-1. Estimated Survival of Fall-run Chinook Salmon Based on CWT or AT Data, Versus the 10-day Average of Daily Average Inflow at Vernalis, Regardless of Barrier Status at the Head of Old River

Notes: Inflow data are measured from the final day of release at Durham Ferry or Mossdale, downloaded from www.water.ca.gov/dayflow/. Survival from Mossdale or Durham Ferry to Jersey Point and Chipps Island includes all routes.

Reach-Specific Survival

Our basis of knowledge regarding the conceptual model's linkage between San Joaquin River inflow and region-specific survival of juvenile Chinook salmon is low. Multiple directed field studies have collected data to evaluate this relationship but the analysis of these data relative to inflow is ongoing, and presently is described only in this report. The extent to which operations affect the relationship between San Joaquin River inflow and reach-specific survival is unknown.

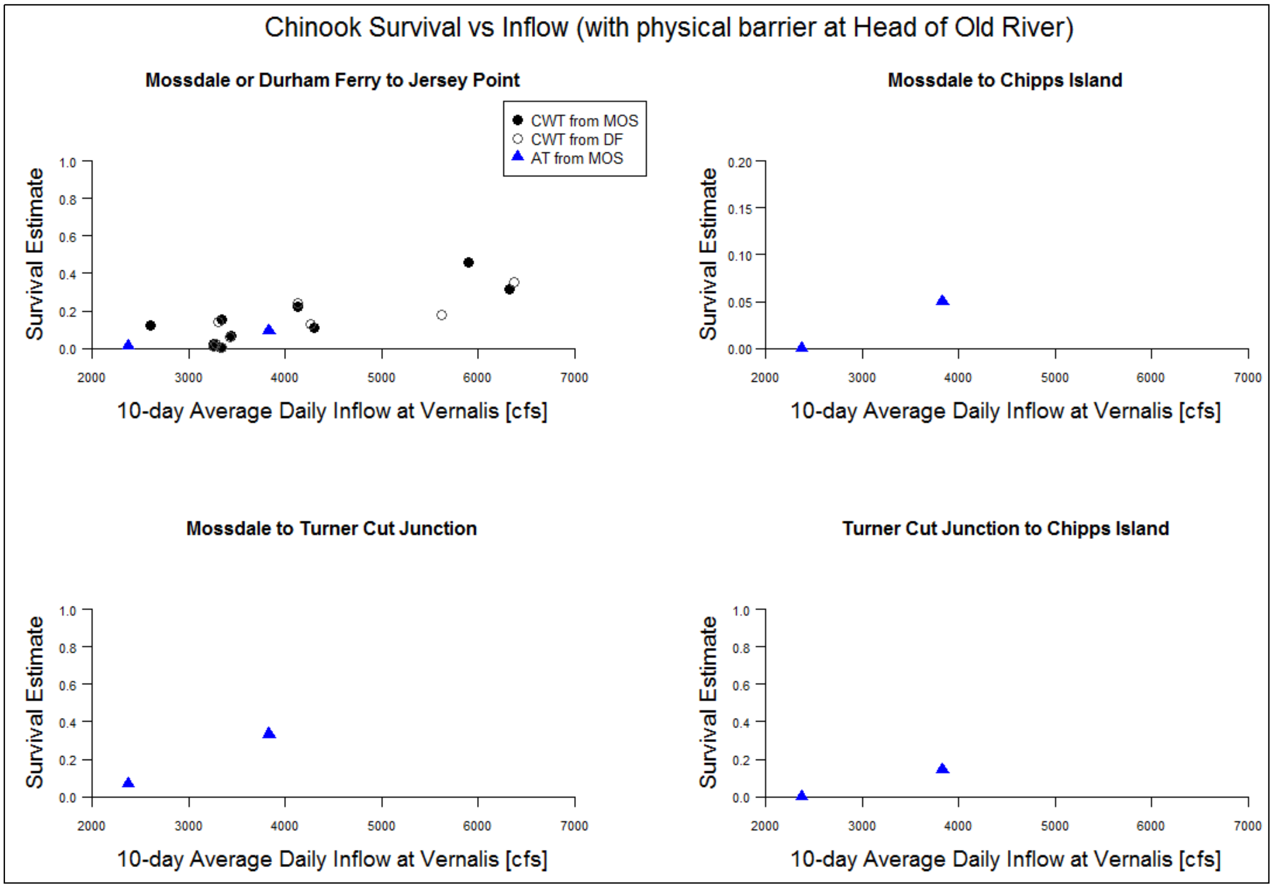


Figure E.8-2. Estimated Survival of Fall-run Chinook Salmon Based on CWT or AT Data, Versus the 10-day Average of Daily Average Inflow at Vernalis, in the Presence of a Physical Barrier at the Head of Old River

Notes: Inflow data are measured from the final day of release at Durham Ferry or Mossdale, downloaded from www.water.ca.gov/dayflow/. *Survival from Mossdale or Durham Ferry to Jersey Point and Chipps Island includes all routes.*

Most estimates of survival in individual reaches between Mossdale and Chipps Island come from AT data (with the exception of CWT data from 1991), most of which were taken during periods of low inflow (Figure E.8-1), and all but two of which from studies without a physical barrier at the head of Old River (Figures E.8-2 and E.8-3). There were only four observations of AT survival for inflow greater than 10,000 cfs (all from 2011), and no observations with inflow between 7,000 cfs and 10,000 cfs. For inflow less than 7,000 cfs, there is considerable variability in AT survival estimates in all three spatial regions or scales considered: Mossdale to Chipps Island, Mossdale to Turner Cut junction, and Turner Cut junction to Chipps Island. Nevertheless, there appears to be a positive relationship between inflow and survival from Mossdale to Turner Cut, and a negative relationship from Turner Cut to Chipps Island (based only on AT data), especially when no physical barrier was installed at the head of Old River (Figure E.8-3). The three observations for inflow greater than 10,000 cfs (all without a physical barrier at the head of Old River), however, show considerably less variability in survival estimates: estimated survival from Mossdale to

Turner Cut junction was relatively high (range = 0.42 to 0.55) for these inflow values compared to lower inflow values, while estimated survival from Turner Cut junction to Chipps Island was very low (range = 0.01 to 0.02) for inflow greater than 10,000 cfs, and lower than all but one estimates for inflow less than 7,000 cfs (Figure E.8-1). A positive effect of inflow in the more riverine sections is consistent with findings for late-fall-run Chinook salmon in the Sacramento River (Michel et al. 2015).

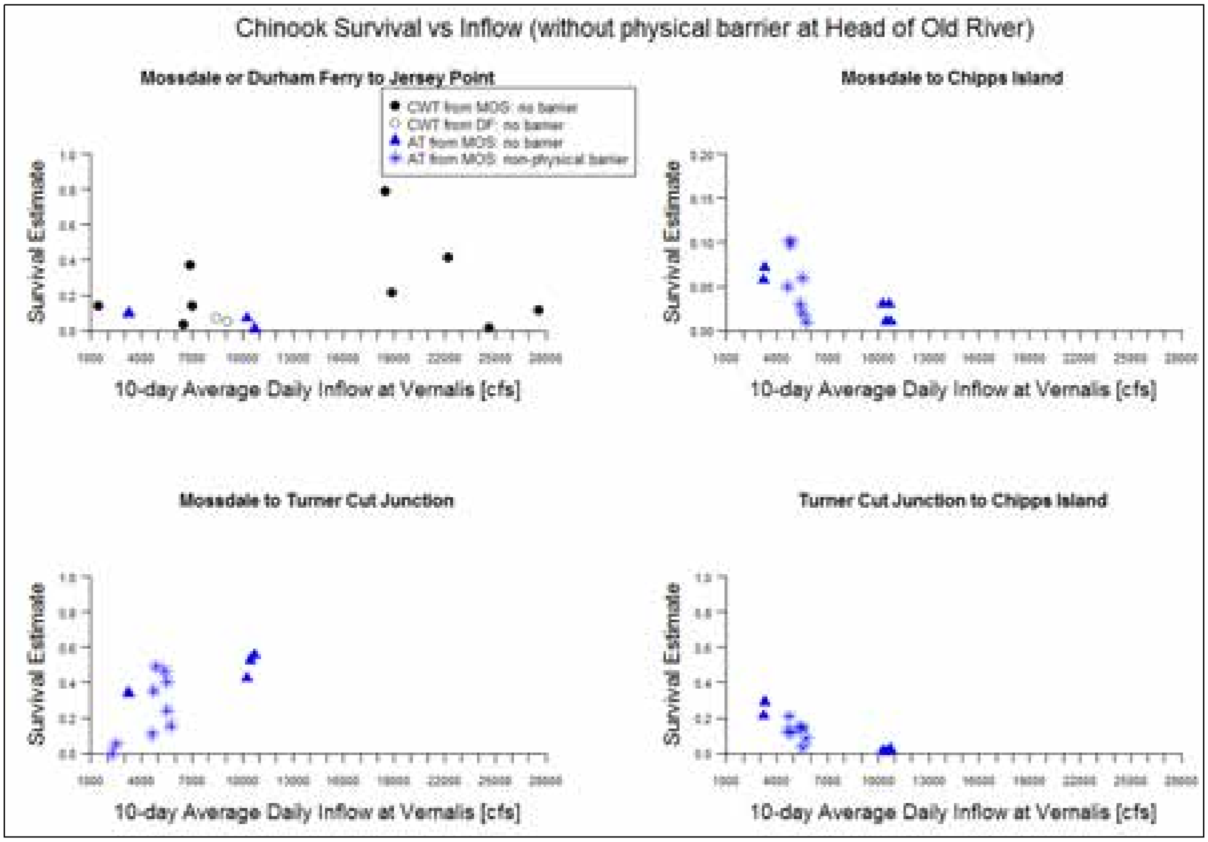


Figure E.8-3. Estimated Survival of Fall-run Chinook Salmon Based on CWT or AT Data, Versus the 10-day Average of Daily Average Inflow at Vernalis, in the Presence of Either a Non-physical Barrier or No Barrier at the Head of Old River

Notes: Inflow data are measured from the final day of release at Durham Ferry or Mossdale, downloaded from www.water.ca.gov/dayflow/. Survival from Mossdale or Durham Ferry to Jersey Point and Chipps Island includes all routes.

Without the barrier in place, a relatively strong positive relationship between inflow and survival appears to exist for the reach between Mossdale and the Turner Cut junction, whereas there appears to be a negative relationship between flow at Vernalis and survival from Turner Cut to Chipps Island (Figure E.8-3). However, these results are based on only visual inspection of data from only four to five years, depending on the reach. With a physical barrier in place, there are only two survival estimates available on this spatial scale (Figure E.8-2), which are too few observations to characterize the variability in reach-specific survival in the presence of a physical barrier. Thus, it is not currently possible to determine the relationship between Vernalis inflow, the barrier, and survival in different regions of the Delta. The lack of reach-specific survival estimates in the presence of a physical barrier is considered a data gap, as is the lack of estimates of reach-specific survival at high inflow levels. More estimates in the presence of the physical barrier will be available when recent data (2014 to 2016) have been analyzed. A rigorous analysis of the spatial pattern of survival and inflow observations, combined with barrier, tag type, and correlation between export and inflow, and based on additional data at higher inflow levels and with and without the physical barrier, is required to adequately address the relationship between inflow and survival in the Delta for Chinook salmon.

Facility Survival

The basis of knowledge regarding the conceptual model linkages between San Joaquin River inflow and facility survival of juvenile Chinook salmon is low. Although no formal field studies have been conducted on this specific question, analyses of relevant data from existing studies have been published in peer-reviewed literature and in this report; the nature of the data mean that findings are indirect. The extent to which operations affect the relationship between San Joaquin River inflow and facility survival is unknown.

Zeug and Cavallo (2014) investigated the effect of San Joaquin River inflow on entrainment of San Joaquin River fall-run Chinook salmon in the CVP and SWP, based on CWT release sizes and salvage numbers. They found no effect of inflow on entrainment at the SWP. At the CVP, they found a positive association between flow and the probability of observing any fish in salvage (Zeug and Cavallo 2014). This finding is counter to expectations, but may partially reflect positive correlation between exports and inflow during CWT studies (see Section E.1.3).

No formal studies have been found relating facility survival to San Joaquin River inflow. The available AT survival estimates from the CVP trash racks to Chipps Island for acoustic-tagged Chinook salmon demonstrate considerable variability and no obvious pattern (SST data compilations). However, survival through the CVP was more variable (and included the highest estimates) for the lower levels of inflow (less than 7,000 cfs); all estimates through CVP were ≤ 0.22 for inflow greater than 10,000 cfs (Figure E.8-4). However, estimates were available for only a limited range of inflow values (Figure E.8-4). All but one of the estimates of survival from the CCF to Chipps Island was 0; the single non-zero estimate was for inflow = 10,690 cfs (Figure E.8-4). It is worth noting that if survival from the CCF to Chipps Island via the SWP is low overall, then it would require a relatively large number of tagged study fish attempting to use that route to reliably observe a survival estimate greater than 0. Low inflow at Vernalis may limit the probability of reaching the CCF, and thus lower the effective sample size available for estimating CCF-Chipps Island survival, and increase the chance of observing a survival estimate of 0 through this route. This may explain why the only non-zero estimate of survival from CCF to Chipps Island via the SWP was for a relatively high inflow value (10,690 cfs) compared to the other observations available (Figure E.8-4). Low inflow at Vernalis may lower the probability of taking the CCF route either by increasing mortality before reaching the CCF, or by increasing the probability of taking another route (e.g., San Joaquin River route or CVP); further analysis of the existing data may provide insight in this issue.

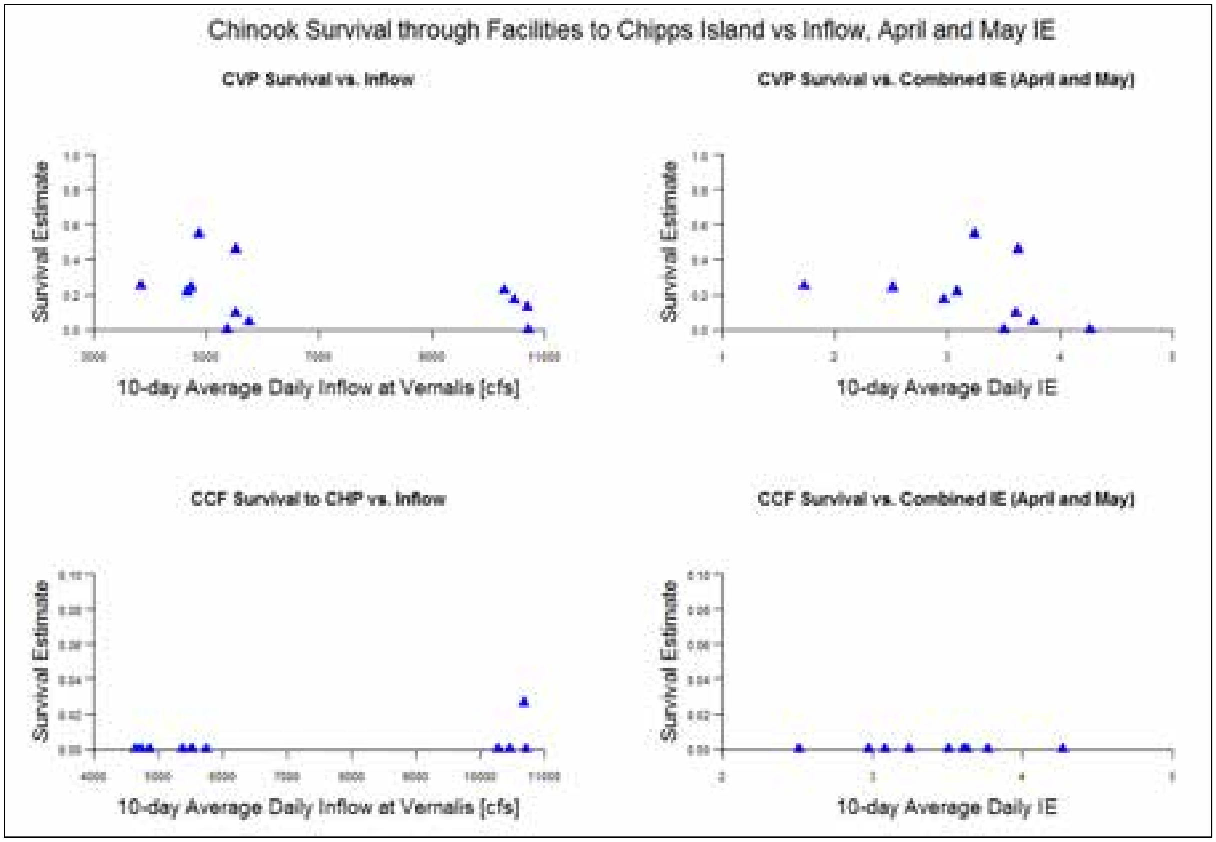


Figure E.8-4. Estimated Survival of Fall-run Chinook Salmon Based on AT Data (2008, 2010 – 2012 Studies), Versus the 10-day Average of Inflow or I:E (only April and May Releases for I:E)

Notes: Survival is from trash racks for CVP, and from radial gates at entrance to CCF for SWP. Survival from the CCF to Chipps Island is through the SWP. I:E = Inflow at Vernalis/Exports, where exports = CVP + SWP, regardless of barrier status at the Head of Old River. Inflow and exports rates are measured from the final day of release at Durham Ferry, downloaded from www.water.ca.gov/dayflow/. Export rates at SWP include BBID intake.

E.8.2.2 Effects of San Joaquin River Inflow on Steelhead

Our basis of knowledge regarding the conceptual model's linkage between San Joaquin River inflow and through-Delta, reach-specific, and facility survival for steelhead is low. A single multi-year field study has collected data to evaluate this relationship but only the first two years of data are currently available (in an agency report), and they are compared to inflow only in this report. The extent to which operations affect the relationship between San Joaquin River inflow and steelhead survival is unknown.

Visual inspection by the SST of the few steelhead data available show an overall increase in survival from Mossdale to Jersey Point or Chipps Island as San Joaquin River inflow increases (Figure E.8-5). The increase is noticeable on the reach scale from the Turner Cut junction to Chipps Island, but not from Mossdale to the Turner Cut junction. Of the two years of steelhead data, 2011 was a high flow year in which the HORB was absent, and 2012 was a low flow year in which the barrier was installed and operating. Survival to the Turner Cut junction was similar in both years (Figure E.8-5). Overall, survival to Chipps Island was slightly lower in 2012 (Figure E.2-3). The spatial pattern observed for steelhead is in contrast to the pattern observed for fall-run Chinook salmon, where a positive relationship between inflow and survival was observed from Mossdale to the Turner Cut junction, but a possible negative relationship was observed from the Turner Cut junction to Chipps Island (Figure E.8-1). One difference between Chinook salmon and steelhead from the acoustic telemetry studies is that steelhead have been observed successfully reaching Chipps Island after entering the Interior Delta at Turner Cut, whereas only one acoustic-tagged Chinook salmon that has entered Turner Cut has been observed at Chipps Island in four years of studies (e.g., Figure E.4-4). Survival through both the CVP and the SWP to Chipps Island was higher for higher inflow levels in these two years (Figure E.8-6). This observation is consistent with findings that louver or salvage efficiency is positively associated with bypass velocity at the CVP for Chinook salmon (e.g., Karp et al. 1995; Sutphin and Bridges 2008). However, two years of data for steelhead are insufficient to characterize a relationship between inflow and survival because of possible interacting factors (e.g., barrier status, water temperature) and interannual variability.

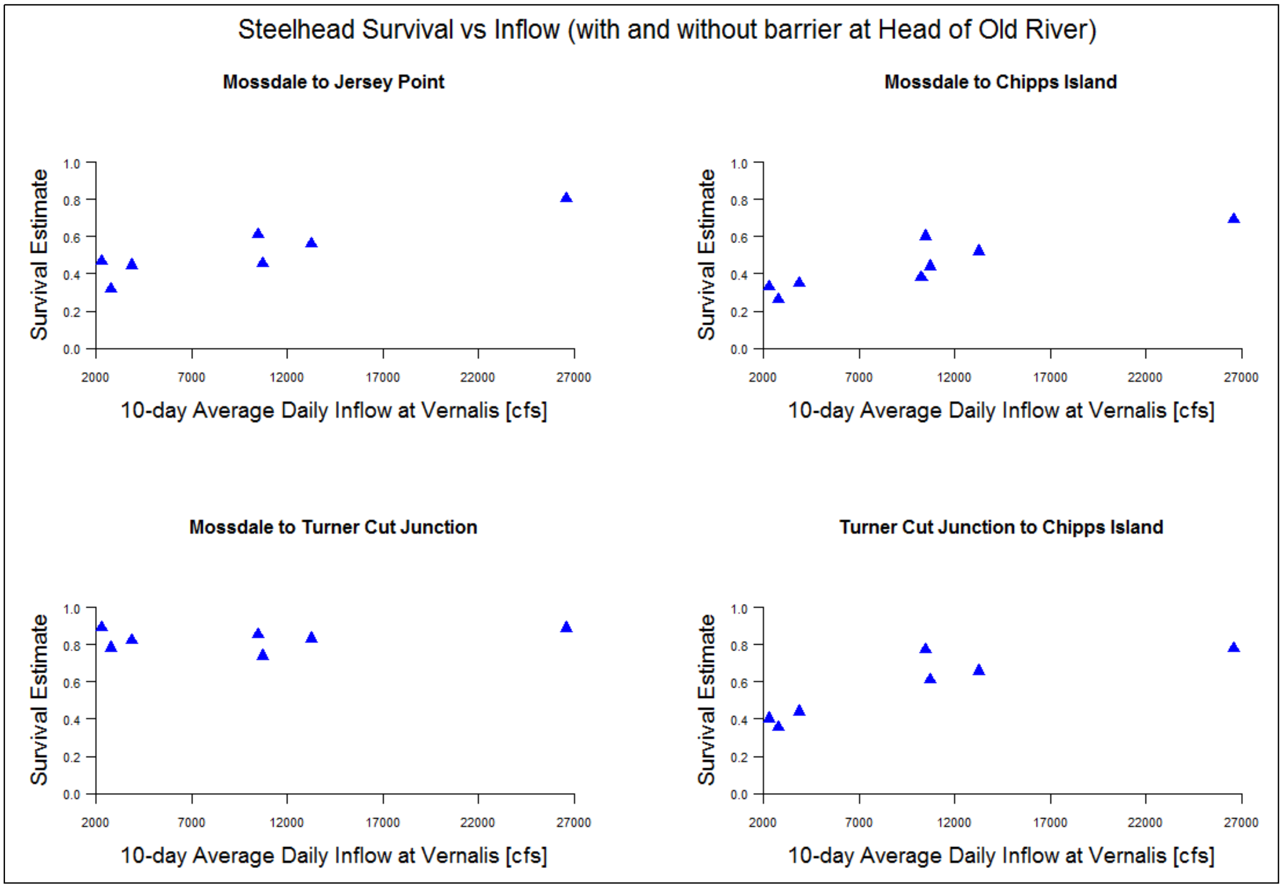


Figure E.8-5. Estimated Survival of Steelhead Based on AT Data (2011 and 2012 Study Years), Versus the 10-day Average of Daily Average Inflow at Vernalis, Regardless of Barrier Status at the Head of Old River

Notes: Inflow data are measured from the final day of release at Durham Ferry, downloaded from www.water.ca.gov/dayflow/. Survival from Mossdale to Jersey Point and Chipps Island includes all routes.

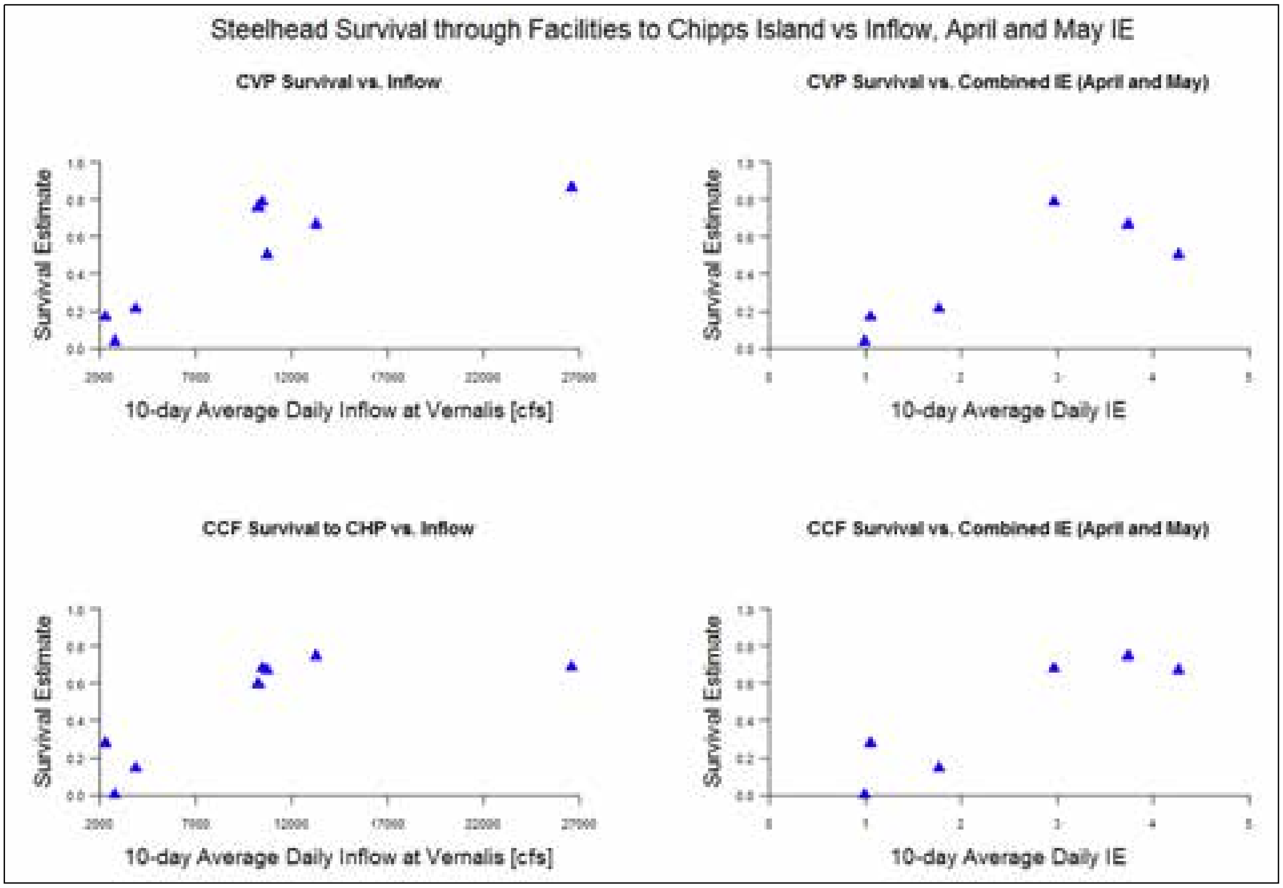


Figure E.8-6. Estimated Survival of Steelhead Based on AT Data (2011 – 2012), Versus the 10-day Average of Inflow or I:E (only April and May Releases for I:E)

Notes: Survival is from trash racks for CVP, and from radial gates at entrance to CCF for SWP. Survival from the CCF to Chipps Island is through the SWP. I:E = Inflow at Vernalis/Exports, where exports = CVP + SWP, regardless of barrier status at the Head of Old River. Inflow and exports rates are measured from the final day of release at Durham Ferry, downloaded from www.water.ca.gov/dayflow/. Export rates at SWP include BBID intake.

E.8.3 SUMMARY: KNOWLEDGE GAPS ON SURVIVAL AS A FUNCTION OF SAN JOAQUIN RIVER INFLOW

Several knowledge gaps exist in our understanding of how Delta survival of migrating salmonids depends on San Joaquin River inflow.

- Interannual and within-season variability in survival in different regions at high inflow levels and/or in the presence of the physical barrier at the head of Old River.
- Insufficient observations of survival on various spatial scales at higher inflow levels.
- Insufficient observations of survival on various spatial scales in the presence of a physical barrier at the head of Old River.
- The mechanisms for lower survival observed in the lower reaches of the San Joaquin River route (i.e., Turner Cut junction to Chipps Island) for higher inflow levels.

- The dependency of a survival-inflow relationship on the presence of a physical barrier at the head of Old River.
- The effect of inflow on survival apart from an effect of water exports.
- The effect of inflow on mortality mechanisms, including temperature and predator distribution and abundance.
- Incomplete multi-year analysis of existing Chinook salmon and steelhead AT data, although conclusions will remain uncertain due to limited observations at high export levels and correlation between exports and inflow, and possibly other variables (e.g., water temperature).

E.9 SURVIVAL AS A FUNCTION OF SACRAMENTO RIVER INFLOW

The conceptual model links survival to Sacramento River inflow via inflow effects on migration route selection and migration rate. In particular, higher Sacramento River inflow is predicted to reduce the proportion of fish entering the Interior Delta via Georgiana Slough or the DCC by pushing the tidal prism downstream, and survival to Chipps Island is anticipated to be higher in the Sacramento River mainstem routes than in Interior Delta routes (Figure E.2-1). These two predictions together yield a prediction of higher survival to Sacramento River resulting from higher Sacramento River inflow.

E.9.1 Summary: Conceptual Model Predictions on Survival as a Function of Sacramento River Inflow

The conceptual model predicted that increased Sacramento River inflow is associated with increased survival to Chipps Island for Chinook salmon migrating from the Sacramento River.

- CWT recovery rates and through-Delta survival estimates from AT data are consistent with this prediction (Newman and Rice 2002; Newman 2003; Perry 2010).
- Inflow was observed to have a stronger effect on survival in the riverine reaches of the Sacramento River and less effect in the estuarine or tidal reaches (Michel et al. 2015).
- Both the Perry (2010) model and the Newman (2003) model predict that the flow-survival relationship “flattens out” as discharge increases.
- Salvage rates (and by assumption, entrainment mortality rates) of CWT fish have been found to be negatively associated with Sacramento River inflow by Zeug and Cavallo (2014), but no significant relationship was found by Kimmerer (2008).

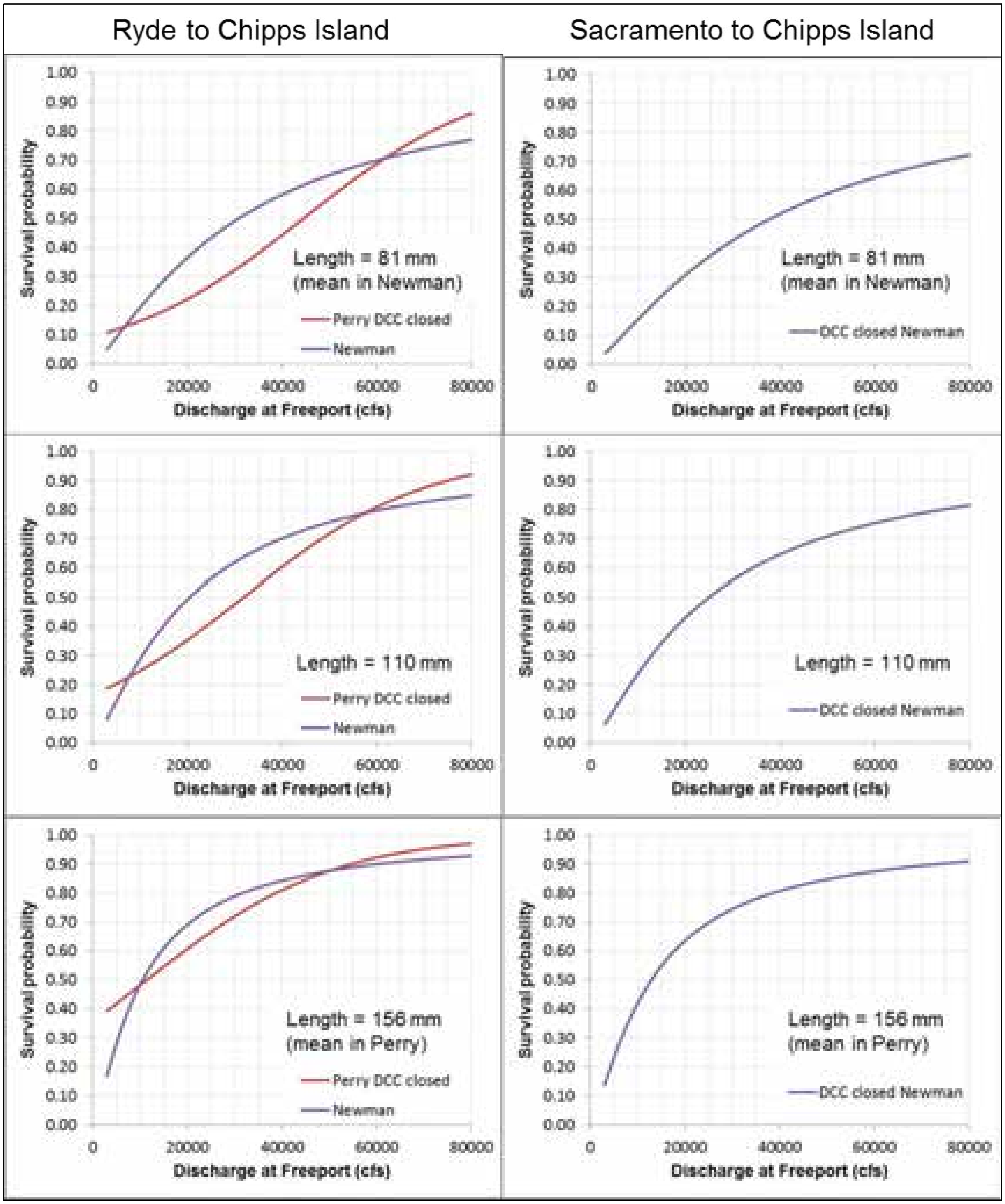
E.9.2 FINDINGS ON CONCEPTUAL MODEL LINKAGES AND PREDICTIONS: EFFECTS OF SACRAMENTO RIVER INFLOW ON SURVIVAL

E.9.2.1 Through-Delta and Regional Survival

The basis of knowledge regarding Sacramento River inflow and through-Delta and regional survival is high. Multiple field studies have collected data to evaluate this relationship; results have been published in peer-reviewed literature, agency reports, and doctoral dissertations. The extent to which other operations (e.g., export rates) affect the relationship between Sacramento River inflow and through-Delta survival is unknown.

The relationship between Sacramento River inflow and survival through the Delta for Sacramento River Chinook salmon has been explored separately by Newman (2003) and Newman and Rice (2002) using CWT data from fall-run Chinook salmon, and Perry (2010) using AT data for late-fall-run Chinook salmon. Newman and Rice (2002) report a slight positive effect of Sacramento River flow on survival, but caution that the flow effect was confounded by salinity. Newman (2003) modeled survival of fall-run Chinook salmon with a mean size of 81 mm using Sacramento River discharge measured at Freeport and found a positive effect of flow on survival, along with significant effects of exports, tide, temperature, salinity, turbidity, and position of the DCC gate. Perry (2010) modeled survival of late-fall-run Chinook salmon with a mean size of 156 mm using Sacramento River discharge just downstream of Georgiana Slough; he found a positive relationship between Sacramento River discharge below Georgiana Slough and survival in both the Sacramento River mainstem and Sutter and Steamboat sloughs for late-fall-run Chinook salmon, as well as between fish length and survival (Figure E.2-1 and Figure E.9-1). Additionally, Michel et al. (2015) reported higher survival of acoustic-tagged late-fall-run Chinook salmon through the riverine reaches of the Sacramento River when flow was higher, but no effect of flow in the more tidal or estuarine reaches; the flow comparison was based on a single high-flow year compared to multiple low-flow years.

To explore both the CWT data and the AT data further, in 2015, Russell Perry (U.S. Geological Survey [USGS]) plotted the estimated flow-survival models from both the Newman (2003) study and the Perry (2010) study using a standardized measure of fish length and river discharge (flow), and controlling for river reach and DCC operations (R. Perry, personal communication) (Figure E.9-1). Both models were available for the Sacramento River reach from Ryde to Chipps Island (Figure E.2-1), either with the DCC closed (Perry [2010] model) or with the DCC status unspecified (Newman [2003] model) (left-hand column of Figure E.9-1). Only the Newman (2003) model was available for the reach from Sacramento to Chipps Island and when the DCC was closed (right-hand column of Figure E.9-1). The CWT model from Newman (2003) was very similar to the AT model from Perry (2010) when standardized for reach and a common fish size. In particular, the general trend is that the marginal increase in survival per unit increase in flow tends to decrease as flow increases. That is, the flow-survival relationship “flattens out” as discharge increases. This relationship was observed for both river reaches.



Ryde to Chipps Island

Sacramento to Chipps Island

Figure E.9-1. Predicted Survival in the Sacramento River from Ryde to Chipps Island as Function of Sacramento River Discharge at Freeport for Different-sized Fish, for the Perry (2010) Model and the Newman (2003) Model

Note: The relationships from both studies have been extended beyond the range of observed data used to estimate the relationships with respect to both fish size and discharge. Source: R. Perry, USGS.

Perry noted that FL, Freeport discharge, and DCC position were included as covariates for the Newman plots. All other covariates (i.e., salinity, hatchery temperature and release temperature, turbidity, tides, and exports) were set to mean values. Newman (2003) did not include DCC position as a covariate for survival for the Ryde to Chipps Island reach. For Perry (2010), survival was based on discharge of the Sacramento River below Georgiana Slough. Discharge below Georgiana Slough was then related to Freeport flow using a regression equation provided to Perry by John Burau (USGS). The flow-survival relationship is plotted at the median of release-specific intercepts. Perry noted that the relationships from both studies have been extended beyond the range of observed data used to estimate the relationships, both for fish size and for river discharge.

E.9.2.2 Facility Survival

Our basis of knowledge regarding the linkages between Sacramento River inflow and facility survival is low. Two peer-reviewed publications address this linkage between Sacramento River inflow and salvage, but results were conflicting and the extent to salvage is an indicator of facility loss is unknown.

Kimmerer (2008) and Zeug and Cavallo (2014) investigated the effect of Sacramento River inflow on salvage rates for CWT hatchery Chinook salmon. Kimmerer (2008) found no relationship between proportional salvage or total salvage and Sacramento River flow for winter-run Chinook salmon. Zeug and Cavallo (2014) found that the probability of collecting any fish in salvage was negatively associated with Sacramento River inflow for both CVP and SWP, and the number of fish salvaged was also negatively associated with inflow for CVP for winter-run, late-fall-run, and fall-run Chinook salmon. If it is true that salvage and entrainment consistently vary together, this finding suggests that entrainment mortality is also negatively associated with Sacramento River inflow.

E.9.3 SUMMARY: KNOWLEDGE GAPS ON SURVIVAL AS A FUNCTION OF SACRAMENTO RIVER INFLOW

Knowledge gaps on survival as a function of Sacramento River inflow include:

- Relationship between Sacramento River inflow and survival to Chipps Island for winter and spring Chinook salmon runs.
- Insufficient observations of survival in different regions under high-flow conditions for some salmon runs (e.g., late-fall run in more tidal regions of the Delta; winter and spring runs).
- The extent to which salvage is an index of entrainment and facility mortality; this requires knowing the magnitude and variability in pre-screen mortality at the CVP.

E.10 SURVIVAL AS A FUNCTION OF DELTA E:I

The conceptual model links survival to Delta exports and Delta inflow via direct mortality and effects on hydrodynamics, and resulting effects of hydrodynamics on migration route and rate. Exports are expected to have a negative effect on survival, and inflow a positive effect on survival. Thus, as the ratio of exports to inflow increases, survival is expected to decrease. Direct mortality in the facilities affects only fish that enter the Interior Delta, so the relative survival in the Interior Delta route to survival in the Sacramento River mainstem route is expected to also decrease as the ratio of exports to inflow increases.

E.10.1 SUMMARY: CONCEPTUAL MODEL PREDICTIONS ON SURVIVAL AS A FUNCTION OF DELTA E:I

The conceptual model predicted that survival through the Delta will decrease as Delta E:I increases. Findings have generally shown a negative relationship between E:I and survival for Sacramento River Chinook salmon, but evidence is sometimes weak or the relationship is non-statistically significant:

- A small, non-statistically significant negative effect of E:I on survival of fall-run Chinook (Newman and Rice 2002).
- Models using E:I to account for variation in CWT recovery data had approximately the same, or less, support from the data as models that used exports (E) and inflow (I) separately for late-fall-run Chinook salmon (Newman and Brandes 2010) and fall-run, late-fall-run, and winter-run Chinook salmon (Zeug and Cavallo 2014).
- A stage-structured life-cycle model found a negative effect of E:I on survival through the Delta for fall-run Chinook salmon (Cunningham et al. 2015).

E.10.2 FINDINGS ON CONCEPTUAL MODEL LINKAGES AND PREDICTIONS: EFFECTS OF DELTA E:I ON SURVIVAL

Our basis of knowledge for the conceptual model's linkages between Delta E:I and survival in the Delta is high. Multiple field studies have collected data relevant to this question, and results have been published in peer-reviewed literature and a technical report. Some of the studies have used Sacramento River inflow rather than the combined Delta inflow from the Sacramento and San Joaquin rivers.

Newman and Rice (2002) found that increases in the ratio of exports to Sacramento River inflow was associated with lower survival of Sacramento River fall-run Chinook salmon through the lower Sacramento River Delta, but the effect was small and not statistically significant. For late-fall-run Chinook salmon released into the northern Interior Delta (i.e., Georgiana Slough), Newman and Brandes (2010) reported nearly equal support for three models of the relative survival of Interior Delta releases to Sacramento River mainstem releases that used either the ratio of exports to Sacramento River inflow, exports, or no exports. Zeug and Cavallo (2014) found that E:I explained less variation in salvage rates of hatchery CWT fish from the Sacramento River than using measures of exports and inflow separately.

Cunningham et al. (2015) used data on salmon stock abundance (adult escapement and juvenile-run estimates) to calibrate a life-cycle model for Sacramento River Chinook salmon, and concluded that juvenile outmigration survival through the Delta depended on the ratio of exports to inflow for fall-run Chinook salmon, but not for the spring run or winter run. For the fall run, Delta survival was estimated to decrease as E:I increased (Cunningham et al. 2015).

E.10.3 SUMMARY: KNOWLEDGE GAPS ON SURVIVAL AS A FUNCTION OF DELTA E:I

Knowledge gaps on survival as a function of Delta E:I include:
- Assessment of existing AT data for a relationship between Delta E:I and survival through the Delta.
- The role of interannual variability in the relationship between Delta E:I and Delta survival.
- The difference in the relationship between Delta E:I and Delta survival for different runs of salmon.

E.11 SURVIVAL AS A FUNCTION OF SAN JOAQUIN RIVER I:E

The San Joaquin River I:E is the ratio of San Joaquin River inflow at Vernalis to exports. The conceptual model predicts that for fish migrating from the San Joaquin River, Delta survival will increase with inflow and decrease with exports; thus, survival is expected to increase with I:E. Inasmuch as inflow and exports have variable effects in different regions of the Delta, the strength of the relationship between I:E and survival may vary in different regions of the Delta. The I:E-survival relationship may also depend on the status of the barrier at the head of Old River.

E.11.1 SUMMARY: CONCEPTUAL MODEL PREDICTIONS ON SURVIVAL AS A FUNCTION OF SAN JOAQUIN RIVER I:E

The conceptual model predicted that Delta survival increases with I:E, and that the relationship may depend on the status of the barrier at the head of Old River. Findings show a complicated relationship with considerable variability, based mostly on provisional visual inspection of scatterplots.
- CWT Chinook data show increased through-Delta survival for higher levels of I:E, up to approximately I:E=3, in the presence of a physical barrier at the head of Old River, but no relationship in the absence of the barrier (SJRGA 2007).

- AT Chinook data show a similar pattern for I:E less than 3, but mostly in the absence of a physical barrier at the head of Old River.
- Both CWT and AT Chinook data show more variable but mostly lower through-Delta survival estimates for I:E between 3 and 5, all in the absence of a physical barrier at the head of Old River.
- Few observations from tagging data are available for I:E greater than 5, and all are from CWT data.
- Comparison of adult Chinook salmon escapement to the San Joaquin River basin between 1951 and 2003 with San Joaquin River I:E two and a half years before adult return showed a positive association (years 1951 to 2003, SJRGA 2007; updated by the SST through 2012); I:E values ranged up to greater than 300 during this time period, although most observations were less than 10.

The conceptual model predicted that the relationship between I:E and survival may vary in different regions of the Delta.

- AT Chinook salmon data, in the absence of a physical barrier at the head of Old River, show a positive trend in survival between Mossdale and the Turner Cut junction with I:E, a negative trend for survival between Turner Cut junction and Chipps Island, and no relationship for survival through the facilities to Chipps Island.
- AT steelhead data show no relationship between I:E and survival from Mossdale to Turner Cut, and a possible positive relationship for survival from Turner Cut junction to Chipps Island and from either the CVP trash racks or the CCF radial gates through salvage to Chipps Island.

E.11.2 FINDINGS ON CONCEPTUAL MODEL LINKAGES AND PREDICTIONS: EFFECTS OF SAN JOAQUIN RIVER I:E ON SURVIVAL

E.11.2.1 Effects of San Joaquin River I:E on Survival of Chinook Salmon

Through-Delta Survival

The basis of knowledge regarding the conceptual model linkages between San Joaquin River I:E and through-Delta survival of Chinook salmon is low. Multiple field studies have collected data to evaluate this relationship; most results are presented in agency reports or in this report.

The 2006 VAMP report compared a CWT survival index (Durham Ferry or Mossdale to Jersey Point) to the San Joaquin River I:E for San Joaquin River Chinook salmon, and found a significant positive association when the HORB was in place (slope = 0.2182, $P < 0.05$, $r^2=0.26$); no significant relationship was observed without the barrier in place (SJRGA 2007). Using VAMP CWT data, the California Department of Fish and Game (CDFG 2005) found weak negative correlation between the CWT survival index and the ratio of Delta exports to inflow at Vernalis (r^2=0.16) with the HORB in place, and concluded that inflow had a stronger effect on juvenile survival of fall-run Chinook salmon through the Delta than the ratio of exports to inflow. The 2006 VAMP report also compared adult Chinook salmon escapement to the San Joaquin River basin between 1951 and 2003 with San Joaquin River I:E, measured between April 15 and June 15, two and a half years before adult return, and found a positive association between I:E and adult return ($P < 0.01$, r^2=0.56 without the barrier; SJRGA 2007). Values of I:E ranged up to greater than 300 during this time period, although most observations were less than 10. This analysis from the VAMP report was updated by the SST using adult escapement data through 2012 and found similar results (r^2=0.51). Similarly, CDFG (2005) found a negative correlation between adult escapement (years 1970 to 2002) and the ratio of Delta exports to Vernalis flow two and a half years prior to adult return (r^2=0.44). These findings on adult escapement are consistent with the hypothesis that higher San Joaquin River I:E results in higher juvenile survival through the Delta, assuming that returning salmon were all three years old. However, because adult escapement represents mortality factors throughout the life history, this finding is not unique to that hypothesis; for example, region-scale weather patterns, which may influence I:E to some extent, may also influence spawning, incubation, rearing, and ocean survival as well as juvenile through-Delta survival.

The available estimates of survival through the Delta, from either CWT or AT data, were plotted against the ten-day average I:E (Figures E.11-1 through E.11-3). Visual inspection of SST scatterplots of the available survival estimates through the Delta to Jersey Point show that most estimates are for ten-day average I:E less than 5 (top left plots in Figures E.11-1 through E.11-3). Ignoring the status of the barrier at the head of Old River, there is considerable variability in survival for I:E less than 5 (Figure E.11-1). However, the maximum observed survival estimate to Jersey Point increased to 0.46 as I:E increased from 1 to 3, while only low survival estimates (range = 0.01 to 0.14) were observed for I:E of approximately 4. The highest survival estimate to Jersey Point (0.79, from CWT data in 1995) was observed for I:E = 5.0; lower estimates were observed for I:E = 9.4 and approximately 16 to 18, but these estimates were nevertheless higher than many of the survival estimates for I:E less than 5 (top left plot, Figure E.11-1). All estimates for I:E greater than 4.5 were from CWT studies. Estimated survival to Jersey Point tended to increase with one-day average I:E when the head of Old River physical barrier was installed, but no estimates for I:E greater than 3 were observed with the physical barrier (top left plot, Figure E.11-2). For survival to Jersey Point, a similar pattern in survival estimates was observed for I:E as for inflow for I:E less than 5: a general increase in the maximum observed survival estimate, and considerable variability about the mean survival estimate below this maximum (compare top left plots in Figures E.11-1 and E.8-1). There is less similarity between the I:E plot and the exports plot (compare top left plots in Figures E.11-1 and E.6-2); although there is considerable variability in survival estimates for export rates less than approximately 3,000 cfs, there is no indication that the range (e.g., maximum) of possible survival values depends on exports, as there is for I:E less than 3.

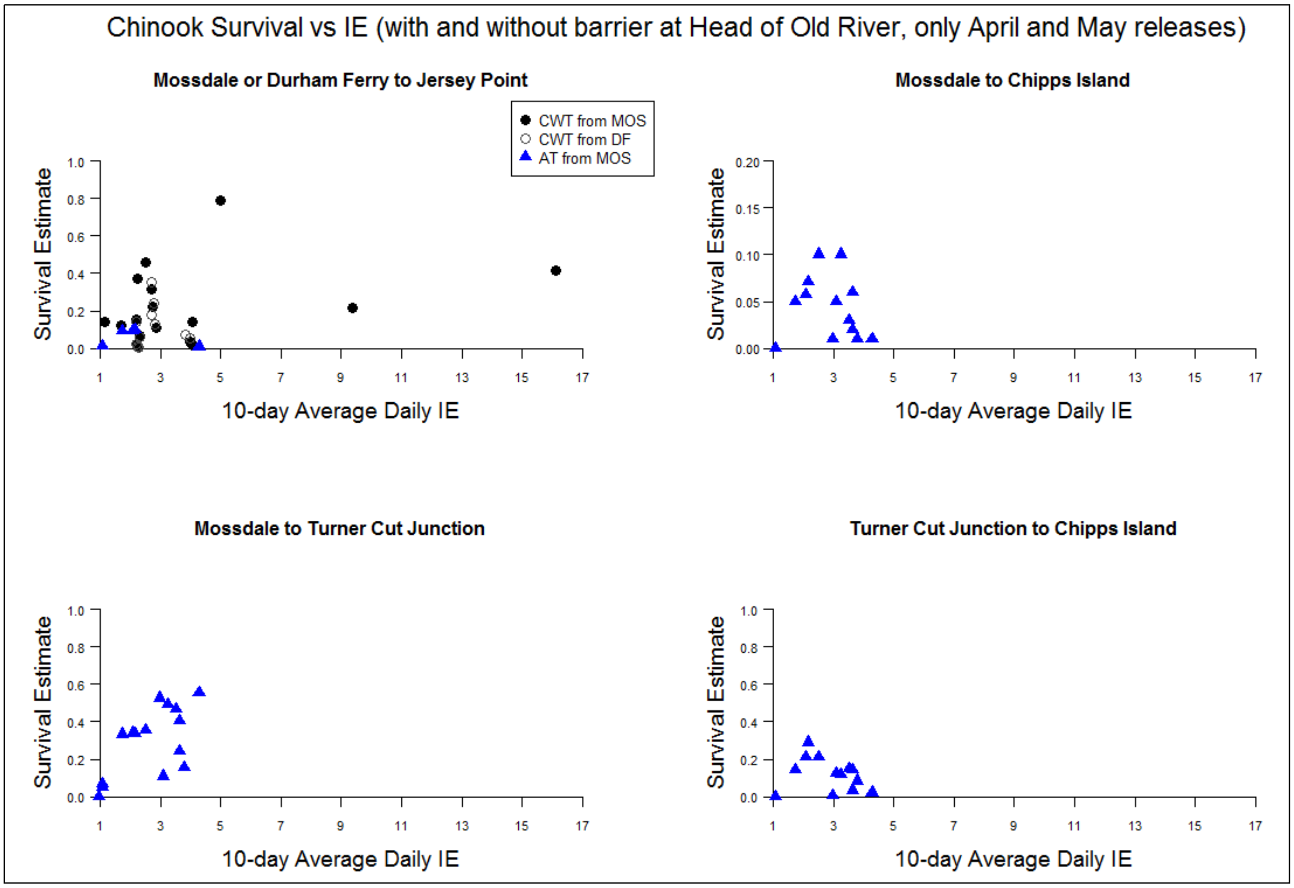


Figure E.11-1. Estimated Survival of Fall-run Chinook Salmon Based on CWT or AT Data, Versus the 10-day Average of I:E for April and May Releases

Notes: I:E = Inflow at Vernalis/Exports, where exports = CVP + SWP, regardless of barrier status at the Head of Old River. Inflow and exports rates are measured from the final day of release at Durham Ferry or Mossdale, downloaded from www.water.ca.gov/dayflow/. Before 2002, SWP omits BBID intake; in 2002, SWP = Banks Pumping Plant flow; after 2002, SWP includes BBID. Survival from Mossdale or Durham Ferry to Jersey Point and Chipps Island includes all routes.

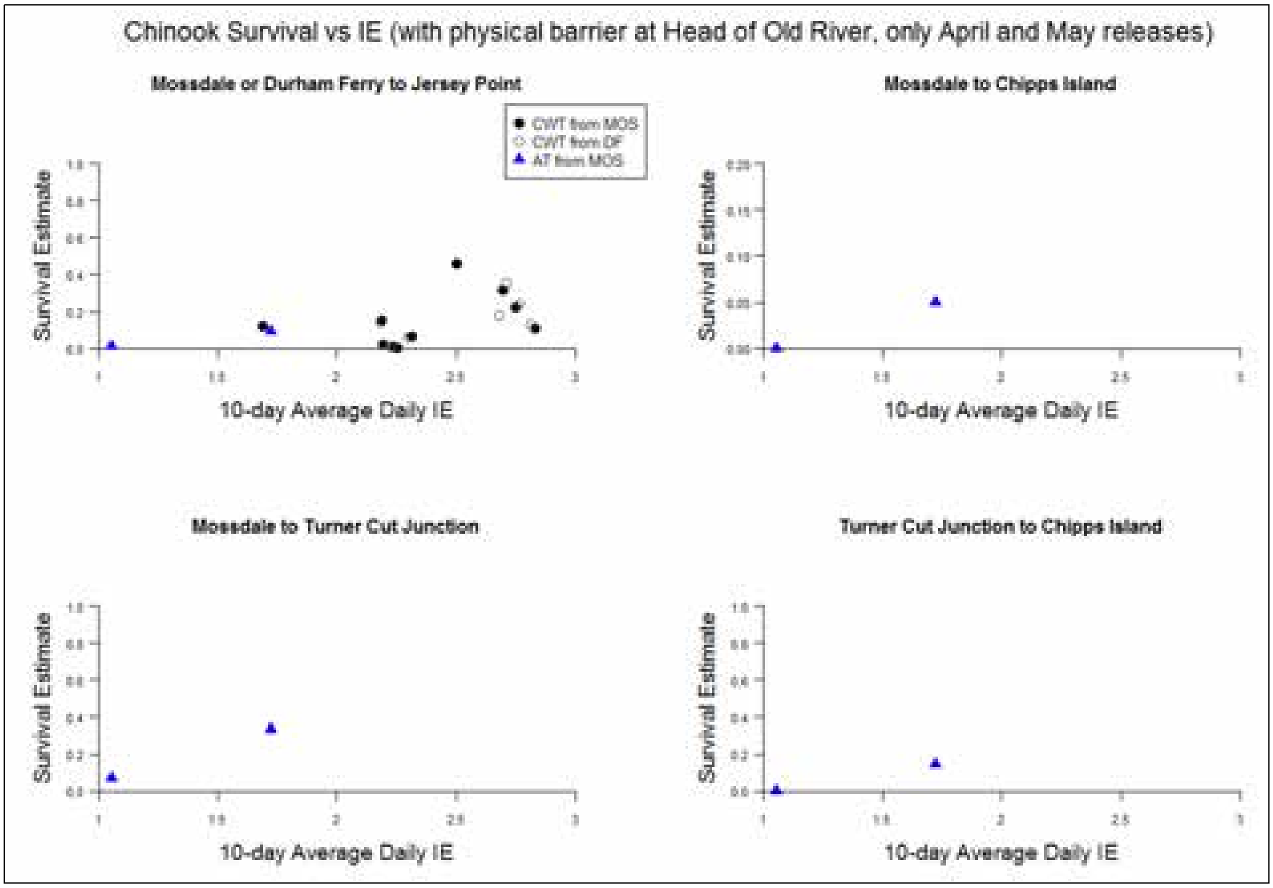


Figure E.11-2. Estimated Survival of Fall-run Chinook Salmon Based on CWT or AT Data, Versus the 10-day Average of I:E for April and May Releases

Notes: I:E = Inflow at Vernalis/Exports, where exports = CVP + SWP, in the presence of a physical barrier at the Head of Old River. Inflow and exports rates are measured from the final day of release at Durham Ferry or Mossdale, downloaded from www.water.ca.gov/dayflow/. Before 2002, SWP omits BBID intake; in 2002, SWP = Banks Pumping Plant flow; after 2002, SWP includes BBID. Survival from Mossdale or Durham Ferry to Jersey Point and Chipps Island includes all routes.

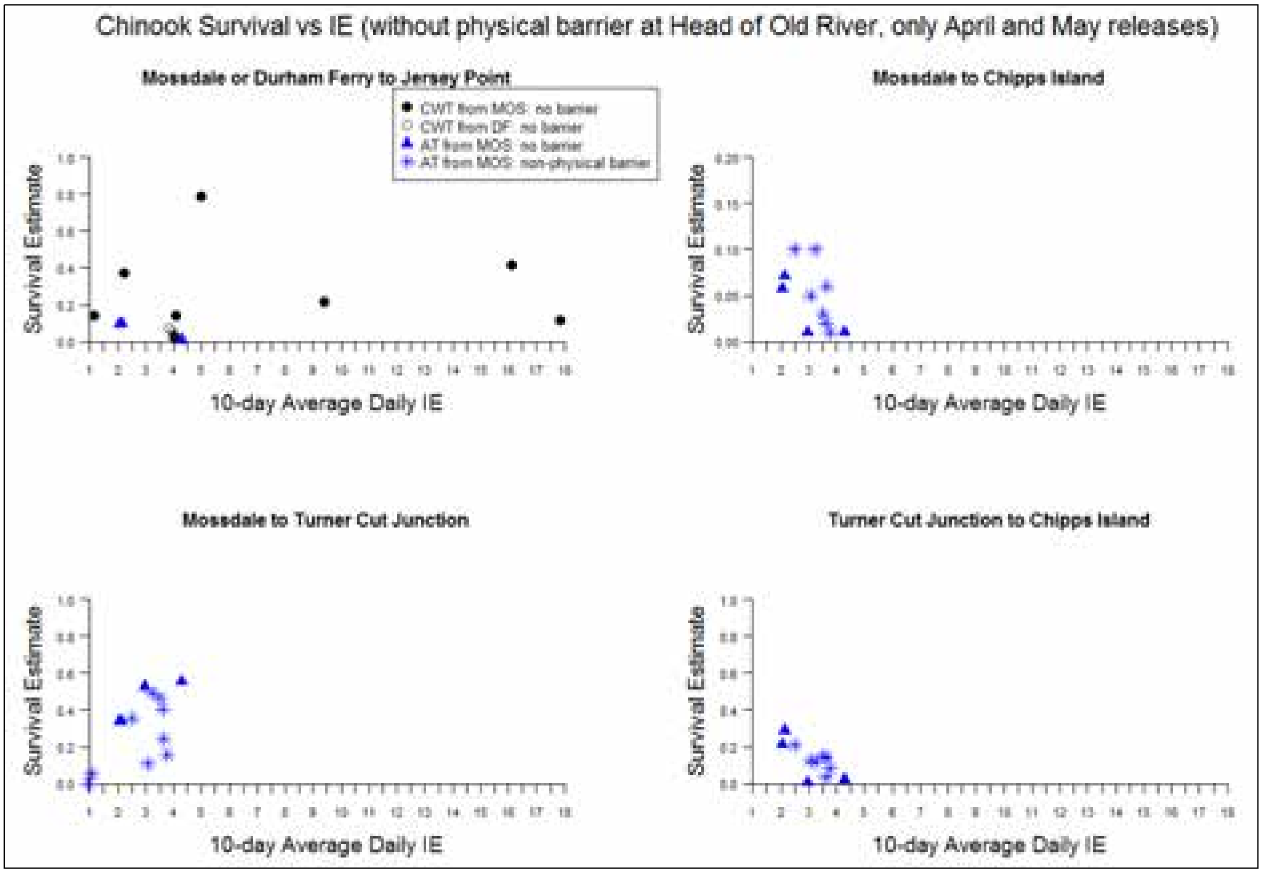


Figure E.11-3. Estimated Survival of Fall-run Chinook Salmon Based on CWT or AT Data, Versus the 10-day Average of I:E for April and May Releases

Notes: I:E = Inflow at Vernalis/Exports, where exports = CVP + SWP, in the presence of either a non-physical barrier or no barrier at the Head of Old River. Inflow and exports rates are measured from the final day of release at Durham Ferry or Mossdale, downloaded from www.water.ca.gov/dayflow/. Before 2002, SWP omits BBID intake; in 2002, SWP = Banks Pumping Plant flow; after 2002, SWP includes BBID. Survival from Mossdale or Durham Ferry to Jersey Point and Chipps Island includes all routes.

Reach-Specific Survival

The basis of knowledge regarding the conceptual model linkages between San Joaquin River I:E and reach-specific survival of Chinook salmon is low. Multiple years of field studies have collected data to evaluate this relationship, but all results relative to I:E and reach-specific survival are first presented in this report and, thus, are preliminary.

On the reach level, survival estimates are available only from AT data, and only for ten-day average I:E less than 5; all but two estimates were in the absence of the physical barrier at the head of Old River. Between Mossdale and Turner Cut junction, both the average and the maximum survival estimates tended to increase as I:E increased from 1 to 4.3 (bottom left plots, Figures E.11-1 and E.11-3). Between Turner Cut junction and Chipps Island, the survival estimates were maximized for I:E of approximately 2, and then steadily decreased as I:E increased to 4.3 (bottom right plots, Figures E.11-1 and E.11-3). Similar patterns were observed for inflow in both reaches (bottom row plots, Figures E.8-1 and E.8-3), and for exports between Turner Cut junction and Chipps Island (bottom right plots, Figures E.6-2 and E.6-4). However, a different pattern was observed for survival between Mossdale and Turner Cut junction against exports (bottom left plots, Figures E.6-2 and E.6-4). It is not apparent how much the similarity between the I:E plots and the inflow plots may reflect the relatively stable export rates across annual release groups during some of the AT studies, or, alternatively, the correlation between inflow and export rates observed among the CWT and AT studies, and the dependence of HORB installation on low inflows. A more comprehensive analysis is required that accounts for the covariation between inflow and export rates, annual variability combined with differing numbers of release groups in different years, and the status of the HORB.

Facility Survival

The basis of knowledge regarding the conceptual model linkages between San Joaquin River I:E and facility survival of Chinook salmon is low. Multiple years of field studies have collected data that are relevant to this relationship but do not directly measure facility survival; results are published in peer-reviewed literature and in this report (SST analyses) and, thus, are preliminary.

Zeug and Cavallo (2014) compared salvage models for CWT Chinook salmon using inflow and water diversion rates (exports) as separate factors to models using the ratio of exports to inflow, and found that the ratio (E:I) did not account for the variability in salvage rates as well as including inflow and exports separately. The available AT survival estimates from San Joaquin River Chinook salmon from the CVP trash racks to Chipps Island for acoustic-tagged Chinook demonstrate considerable variability relative to I:E (SST analyses). Most exhibit very low survival estimates for I:E greater than 3, but the highest survival estimates also occurred for I:E greater than 3 (Figure E.8-4). All Chinook salmon AT estimates of survival through the CCF and SWP to Chipps Island during April and May (the period of interest for the I:E ratio) were 0, so no relationship is apparent between I:E and survival from the CCF to Chipps Island via the SWP (Figure E.8-4).

E.11.2.2 Effects of San Joaquin River I:E on Survival of Steelhead

The basis of knowledge regarding the conceptual model linkages between San Joaquin River I:E and survival of steelhead is low for all spatial scales. Two years of relevant data from a multi-year study are available, but analysis relative to I:E has been presented only in this report and, thus, is preliminary.

For the two years of survival estimates from steelhead (2011 and 2012), patterns of survival compared to the I:E ratio show a small increase in survival estimates from Mossdale to either Jersey Point or Chipps Island as I:E increases for April and May releases. The survival increase was observed in the region from the Turner Cut junction to Chipps Island, but not from Mossdale to the Turner Cut junction (Figure E.11-4). Survival through the facilities tended to increase as I:E increased in these two years (Figure E.11-4). As with consideration of the relationship between inflow or exports and survival, more years of steelhead survival estimates are required to confidently characterize the relationship between I:E and survival.

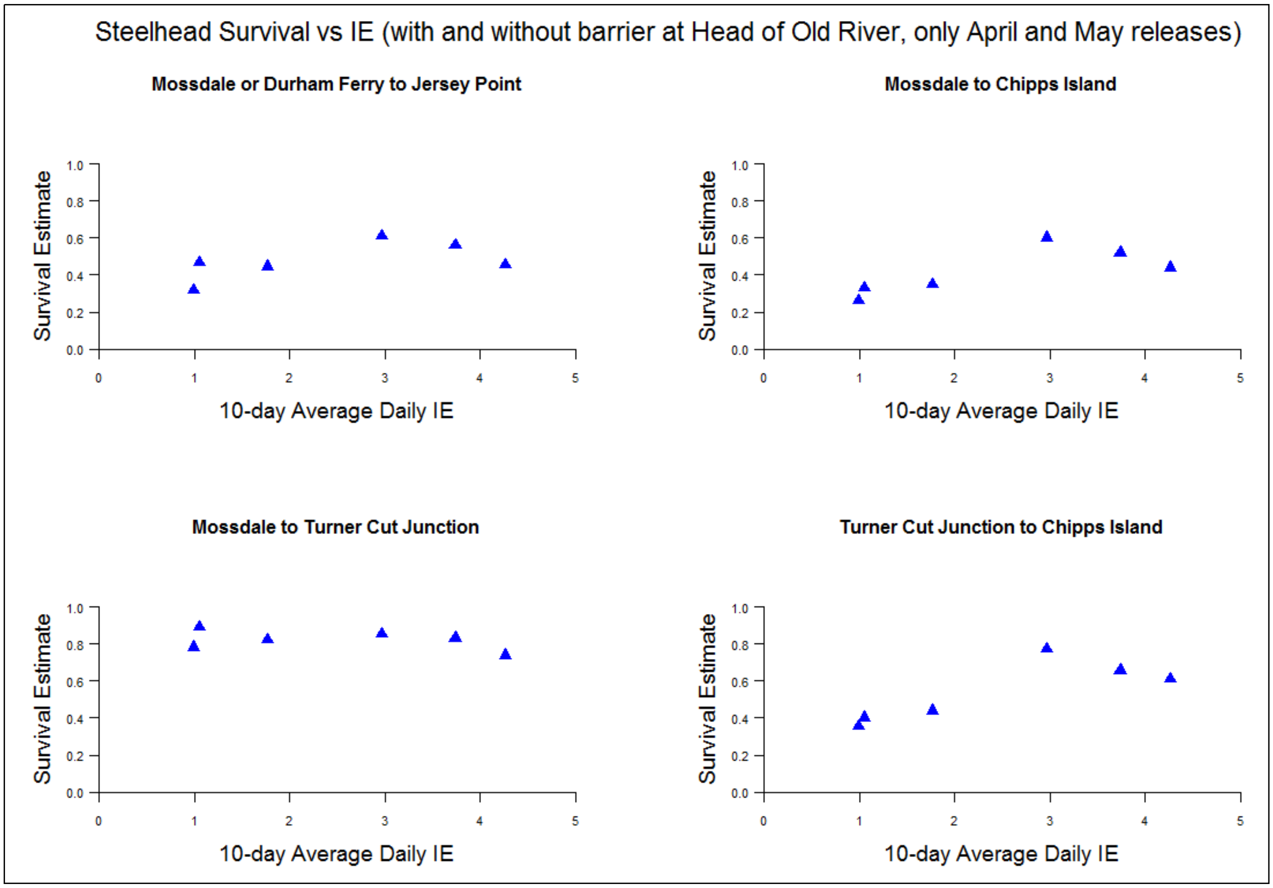


Figure E.11-4. Estimated Survival of Steelhead Based on AT Data (2011 and 2012 Study Years), Versus the 10-day Average of I:E, for April and May Releases

Notes: I:E = Inflow at Vernalis/Exports, where exports = CVP + SWP, regardless of barrier status at the Head of Old River. Inflow and exports rates are measured from the final day of release at Durham Ferry, downloaded from www.water.ca.gov/dayflow/. Export rate at SWP includes Byron Bethany Irrigation District intake. Survival from Mossdale to Jersey Point and Chipps Island includes all routes.

E.11.3 Summary: Knowledge Gaps on Survival as a Function of San Joaquin River I:E

Gaps exist in our understanding of how survival in the Delta varies as a function of San Joaquin River I:E.

- The actual nature of the relationship between I:E and survival, including whether there is a consistent I:E value that optimizes survival.

- Extent to which the perceived relationship between I:E and survival depends on the relatively stable export levels for most observations to date.
- Variability in survival through the Delta and in various reaches for high levels of I:E.
- Reach-specific survival in the presence of a physical barrier at the head of Old River.
- Incomplete multi-year analysis for Chinook salmon and steelhead.

E.12 SURVIVAL AS A FUNCTION OF GATE AND BARRIER OPERATIONS

Temporary, operable, and non-physical barriers are used as part of CVP and SWP operations during the salmonid migration; for a more complete description of the barriers used in the Delta, see Appendix A. In the South Delta, three temporary agricultural barriers are installed during spring in Old River at Tracy, Middle River, and Grant Line Canal (Figure E.12-1). Additionally, a temporary rock barrier is installed in some years at the head of Old River to prevent juvenile salmonids from entering Old River. However, it usually includes culverts that allow limited flow and fish to pass through the barrier into Old River (eight culverts in recent years). The present barrier at the head of Old River cannot be installed when flows are greater than 5,000 cfs and, if installed, cannot be operated if flows are greater than 7,000 cfs. In 2009 and 2010, an experimental non-physical barrier (bioacoustic fish fence) was installed at the head of Old River in place of the rock barrier. In the North Delta, use of a non-physical barrier has been investigated at Georgiana Slough, and an operable barrier (radial gates) is in place at the DCC (Figure E.12-2). Radial gates are also used to regulate water flow into the CCF outside the SWP (Figure E.3-1).

The conceptual model predicts that survival 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, Georgiana Slough, DCC gates). Because barriers use underwater structures that may attract predators, the conceptual model predicts that mortality may be higher in the region of the barrier when the barrier is in place than when it is absent, but also that the level of mortality will depend on other factors such as flow.

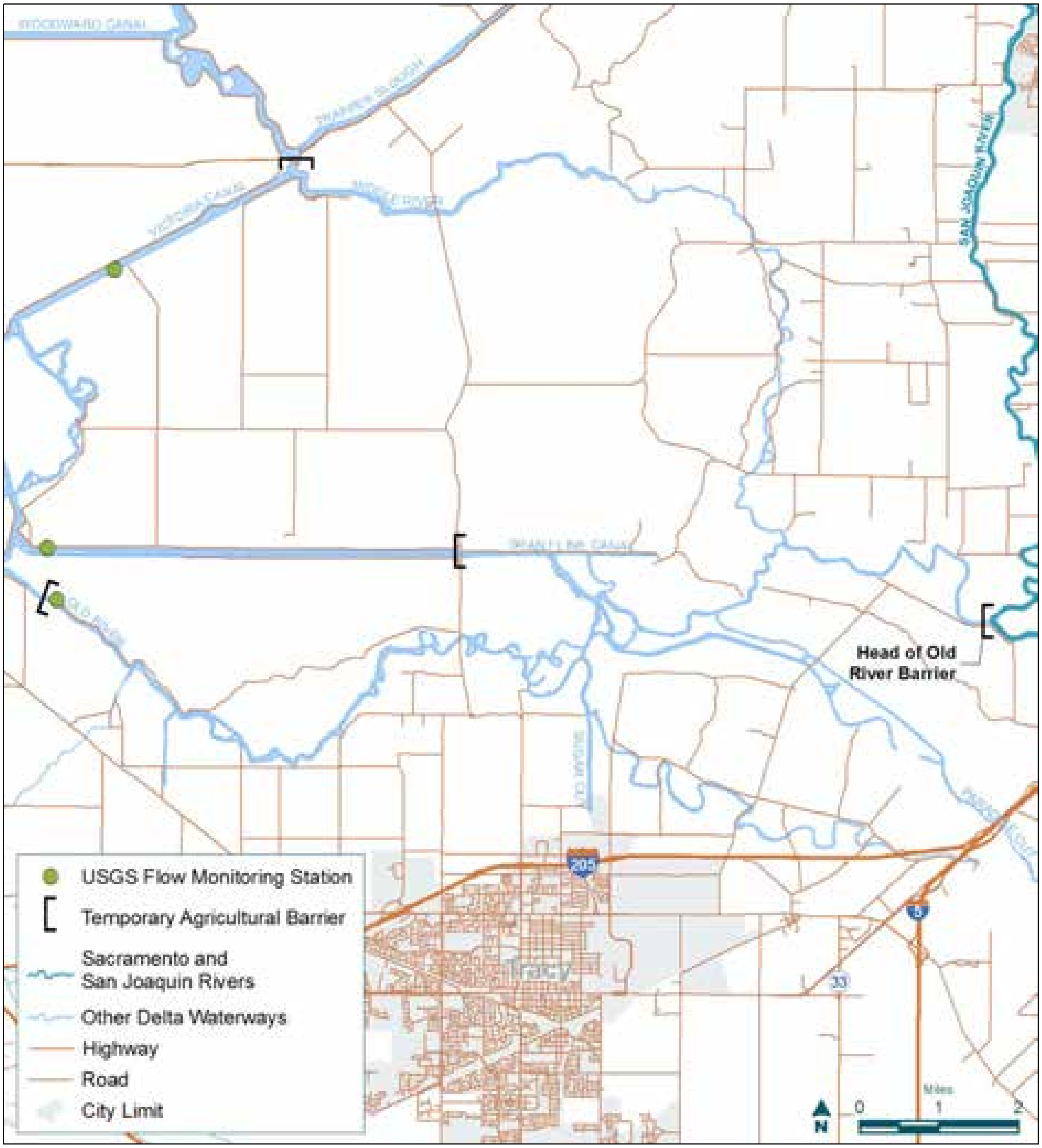


Figure E.12-1. Map of South Delta Showing Temporary Agricultural Barriers

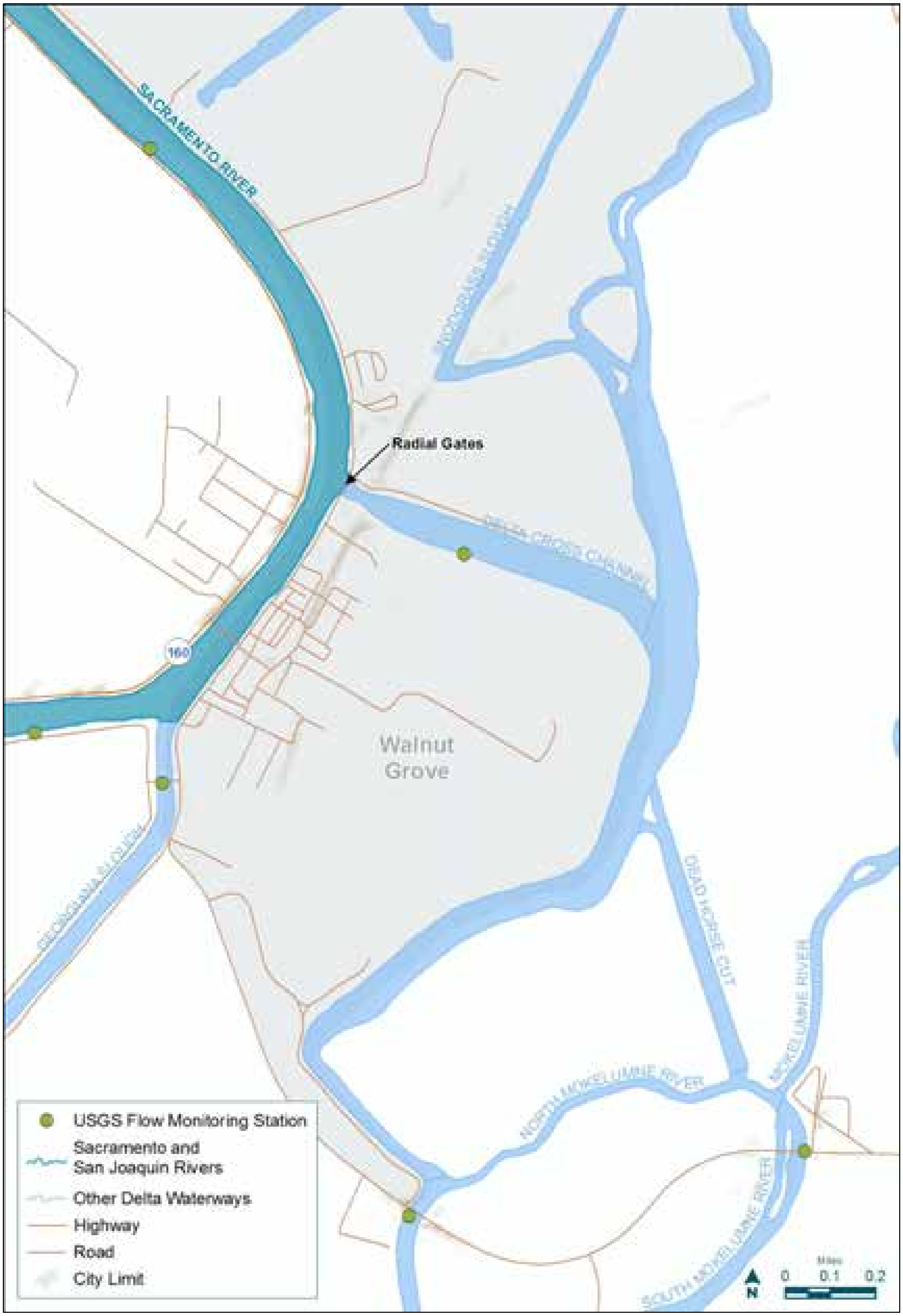


Figure E.12-2. Map of Sacramento River at Delta Cross Channel and Georgiana Slough

E.12.1 SUMMARY: CONCEPTUAL MODEL PREDICTIONS ON SURVIVAL AS A FUNCTION OF GATE AND BARRIER OPERATIONS

- The SST did not review literature and data on the effects of the temporary barriers on juvenile salmon survival.
- Increased predation rate estimates have been observed in the vicinity of the head of Old River when either the physical and non-physical barrier was in place (Bowen et al. 2009; Bowen and Bark 2012; CDWR 2015).
- The graphs presented in this section reflect the status (presence or absence) of the temporary barriers at the time the tagged release groups passed through the South Delta.

E.12.2 FINDINGS ON CONCEPTUAL MODEL LINKAGES AND PREDICTIONS: EFFECTS OF GATE AND BARRIER OPERATIONS ON SURVIVAL

The basis of knowledge regarding the conceptual model linkages between gate and barrier operations and survival is low for the South Delta temporary agricultural barriers and medium for the HORB. Several studies have been conducted on effectiveness of these barriers on fish guidance and/or survival, either in the Delta overall or in the region of the barrier, and published in agency reports. Effects on survival of these barriers are addressed briefly in this report. Effects on survival of other barriers and gates (e.g., DCC gate, Georgiana Slough, CCF radial gates) have not been evaluated in this report.

In the SJRGA (2013) report, the effect of the temporary agricultural barriers in Old River near Tracy, Middle River, and Grant Line Canal on juvenile salmon migration rate and survival was evaluated as a separate study complementary to the 2011 acoustic-tagging study. Survival and travel time 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 the barriers on survival and travel time were confounded with other temporally varying conditions (e.g., flow, exports, water temperature). In particular, installation of all three barriers began near the time of increase in combined export rates (approximately June 1) from less than 4,000 cfs to greater than 8,000 cfs. Total survival through the Delta to Chipps Island, as well as survival through the Old River route to Chipps Island, was higher for smolts passing Mossdale after the installation began for the OMR agricultural barriers; travel time to the CCF was also shorter after installation of the OMR barriers began (SJRGA 2013). The only effect observed of 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). In summary, from this single year of study, the effect of the temporary agricultural barriers was limited and somewhat paradoxical (e.g., shorter travel time and higher survival through the Old River route after barrier installation). In interpreting these findings, it is important to note that other factors 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 1 to 4 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. The SST did not spend time discussing the effects of the temporary barriers on juvenile salmon survival; however, the graphs presented in this section reflect the status (presence or absence) of the temporary barriers at the time the tagged release groups passed through the South Delta.

The effect of a physical rock barrier or a non-physical barrier on predation risk in the vicinity of the head of Old River was investigated using acoustic-tagged juvenile Chinook salmon and steelhead in 2009 to 2012 (CDWR 2015). The rock barrier was found to increase predation risk in the vicinity of the head of Old River in 2011; the non-physical barrier was found to increase predation risk when it was operational in 2009 but not in 2010. Predation risk was monitored using two-dimensional tracks of acoustic-tagged juvenile salmonids and assumed behavioral differences between salmonids and predatory fish.

The impact of the physical HORB on hydrodynamics and survival is discussed at length in various parts of this document (Appendix B, Appendix D, Section D.3.2, and Sections E.4, E.6, E.8, and E.11 of this appendix, and in some of the management questions). We also included some discussion on the impact of the DCC and Georgiana Slough on juvenile salmon movement into the Interior Delta (Perry et al. 2010). Results of studies of non-physical barriers at the head of Old River and Georgiana Slough are discussed in Appendix D. Due to time constraints, the SST has not been able to discuss in depth the effect of these barriers on survival. In addition, we did not evaluate the effect of CCF operations or the effects of OMR reverse flow on survival through the Delta. The effect of the CCF gate operation on survival is difficult to discern as fish may linger in the area until the gates open (SJRGA 2011).

E.12.3 SUMMARY: KNOWLEDGE GAPS ON SURVIVAL AS A FUNCTION OF GATE AND BARRIER OPERATIONS

Knowledge gaps on survival as a function of gate and barrier operations include:

- A review of existing literature and data regarding the effect of gate and barrier operations on survival in the Delta has not been performed.
- Most AT survival data are in the absence of a physical barrier at the head of Old River.
- Distinguishing between a barrier effect and an inflow effect for San Joaquin River fish is complicated by the fact that the HORB cannot be installed or operated at high inflows.

- A comprehensive analysis of available data that combines inflow, exports, and barrier status has yet to be completed for AT Chinook and steelhead data from the San Joaquin River.
- Studies to confirm predation and estimate predation rates near the barriers and at other locations; present estimates depend on assumed behavior differences between predators and juvenile salmonids, but behavior has been shown to overlap between predators and salmonids.

E.13 DISCUSSION AND CONCLUSIONS

The conceptual model predicted that survival of juvenile salmonids migrating through the Delta is:

- Lower during periods of higher export rates
- Higher during periods of higher inflows
- Higher during periods of higher San Joaquin River I:E or lower Delta E:I
- Lower for fish that migrate through the Interior Delta, and especially for those that pass near or through the export facilities
- Higher for fish that move faster through a region

This review has identified varying levels of support for these predictions. The concept of higher survival during higher inflow is supported by tagging studies of juvenile salmonids on some spatial scales but not on others. Inflow appears to affect survival more in the upstream reaches where the environment is more riverine, and less in the downstream reaches that are more tidal. The conclusion is that although inflow is an important factor in juvenile salmonid migration survival through the Delta, it is not the only factor influencing survival, and it is unlikely that survival can be controlled through inflow alone.

The effect of exports on survival is less obvious. The installation and operation of the water export system introduced a new mortality factor for migrating salmonids via entrainment in the pumping facilities or other direct mortality at the facilities. Efforts have been made to minimize direct mortality, including fish guidance away from pumps and into salvage facilities, and pumping schedules designed to limit the attraction of migrating fish to the facilities. Assessing the effects of these actions is hampered by several considerations. First, there is little direct data on fish mortality from canal entrainment, pre-screen mortality (at the CVP), or within-facility mortality. Instead, estimates of loss are computed based on salvage counts or salvage rates, and assumed parameters that represent pre-screen or within-facility mortality, some but not all of which are based on historical tagging studies; thus, loss estimates are constrained to increase as the effectiveness increases of an impact-reduction action that can promote migration survival (i.e., salvage). The quality of the assumed relationship between salvage and loss may vary between and within water years and salmon runs, making it difficult to monitor effects of management decisions on direct mortality with accuracy and precision. Second, there is considerable uncertainty about the population-level effects of direct mortality (i.e., the proportion of the migrating population that actually enters and is lost at the facilities). Third, all the spatially precise acoustic telemetry data and much of the CWT data come from the period when export facilities have been operated to limit negative impacts on migrating salmon populations. This means there is relatively little variability in export rates during the salmon outmigration, and thus little opportunity to detect a survival relationship with export rate. It is notable that even during the period of export operations reductions designed to improve salmon survival, salmon survival has remained low through the Delta (especially for San Joaquin River fall-run Chinook salmon). This pattern indicates that the short-term modifications in export operations that have been implemented are not sufficient to boost survival through the Delta to desired levels, perhaps because of coincident factors such as predation by non-native species, large-scale habitat change, the pelagic organism decline, and climate change. There also remain questions of making inferences from tagged hatchery fish to the untagged hatchery or wild populations. Additional analyses that incorporate a wider range of life stages (e.g., smolt-adult return rates or spawner-recruit relationship) may be necessary to adequately relate the available small-scale tagging results to populations of interest.

A considerable amount of tagging data has been collected from salmon migrating through the Delta; several years of steelhead data have been collected as well. Clear and obvious results are not available for most conceptual model predictions, however. One reason is that analysis of the acoustic telemetry tagging data is not yet complete; implementation of the annual survival model has yet to be completed for some study years, and the multi-year analyses necessary for detecting relationships are also ongoing. Another reason is that the Delta ecosystem is complex and relationships between factors such as inflow, exports, and survival are unlikely to be simple and easily observable. Inflow and export rates often vary together, along with water temperature and status of barriers and gates. Other factors that have not been considered in this report may also covary with inflow and export rates, such as fish condition, water quality, and the composition and size of the community of both predators and alternative prey. This makes it difficult if not impossible to separate the effects of one factor from another. Observational data in particular will not yield precise results, especially in the short term. Experiments in which the combination of inflow and export rates is controlled have the potential to uncouple the effects of these two factors, but the influence of other factors means that any such experiment will need to be implemented over a long period of time to achieve adequate replication, during which there is a potential for large-scale regime change or even population extirpation.

An additional complication is the fact that the data that form the basis of most conclusions are from tagged hatchery fish, rather than the untagged wild populations that are the target of management. This type of surrogacy is common in population dynamics studies, but differences between hatchery and wild fish and potential effects of tagging a fish nevertheless make forming inferences for the untagged wild population somewhat risky.

Additional considerations of these and other types of surrogacy are discussed further in Volume 2.

What is the potential for more data to clarify relationships to be helpful for management? To some extent, the answer to this question depends on the objectives and range of policies available. For example, there appears to be little relationship between exports and survival of San Joaquin River fall-run Chinook salmon through the Delta for export rates less than 4,000 cfs. There is moderate evidence that survival is consistently low for export rates greater than 4,000 cfs, but there are only two observations for this higher range of export rates, and the variability in survival estimates at lower export levels suggests that two observations are too few to adequately represent the possible distribution of survival for the higher range. If we want to be sure that survival is very low under conditions of high export levels, then more observations must be taken at high export levels. On the other hand, if those high export levels are far outside the range of levels being considered by managers, then taking more data to characterize the survival response at those levels is of limited use.

In this appendix, we have investigated the relationship between water export operations and survival of juvenile salmonids migrating through the Delta. We explored several mechanisms by which water project operations may affect survival, namely direct mortality at the facilities, migration route, and migration rate. We also examined patterns in survival, inflow, and export data for evidence of correlative relationships independent of migration route and rate. We used our conceptual model to predict relationships that we expected to see in the data, and where feasible, incorporated findings from the ecological literature or other systems into our review. Nevertheless, assessment of the support for a conceptual model of how a particular system works necessarily requires examining data from that actual system, and so a statistical assessment of data from the Delta was required. We used existing statistical assessments from published journal articles and agency reports, and briefly discussed preliminary and informal statistical assessment of data newly compiled by the SST for this report.

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