Appendix D

DSM2 Delta Tidal Hydraulic and Water Quality Modeling Methods and Results

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Acronyms and Abbreviations

ADCPS	acoustic-Doppler current profiling system
AVMs	acoustic velocity meters
BLTM	USGS branch Lagrangian transport model
CCC	Contra Costa Canal
CCF	Clifton Court Forebay
CCWD	Contra Costa Water District
CDEC	California Data Exchange Center
cfs	cubic feet per second
Corps	U.S. Army Corps of Engineers
CSDP	Cross Section Development Program
CVP Tracy	central Valley Project Tracy Pumping Plant
D-1485	State Water Resources Control Board Decision 1485
DAT	data analysis team
DCC	Delta Cross Channel
DICU	Delta Island Consumptive Use
DMC	Delta-Mendota Canal
DO	dissolved oxygen
DOC	dissolved organic carbon
DWR	California Department of Water Resources
EIS/EIR	environmental impact statement/environmental impact report
EPA	U.S. Environmental Protection Agency
FDM	Fischer Delta Model
FOURPT	USGS four-point flow model
GORT	gate operations review team
GPS	global positioning system
HEC-DSS	Corps' Hydrologic Engineering Center data storage system
IEP	Interagency Ecological Program
KHz	kilohertz
MHz	megahertz
µS/cm	microSiemens per centimeter
MLLW	mean-low-low-water
MSSCG	Montezuma Slough salinity control gates
ORE	Ocean Research Equipment
PTM	particle-tracking model
PWT	Project Work Team
Reclamation	U.S. Department of the Interior, Bureau of Reclamation
RMA	Resource Management Associates
State Water Board	State Water Resources Control Board
SWP Banks	State Water Project Harvey O. Banks Pumping Plant
THM	trihalomethane
USGS	U.S. Geological Survey
UVM	ultrasonic velocity meter
VAMP	Vernalis Adaptive Management Plan
WQCP	water quality control plan

Appendix D

DSM2 Delta Tidal Hydraulic and Water Quality Modeling Methods and Results

This appendix presents an overview of the development and application of the Delta Simulation Model Version 2 (DSM2) that was used for evaluation of tidal hydraulic and water quality impacts from the South Delta Improvements Program (SDIP) baseline conditions and alternatives. The major sections describe the Sacramento–San Joaquin River Delta (Delta) modeling history, the modeling techniques for tidal hydraulics and water quality, the validation of the tidal hydraulics and salinity (measured as electrical conductivity [EC]) patterns, the inputs and assumptions for the SDIP simulations, the general tidal hydraulic and salinity results for the Delta, and the specific results for south Delta channels where effects from the increased State Water Project (SWP) Harvey O. Banks facility (SWP Banks) pumping and effects from the tidal gates are most likely to occur.

This report comprises four major sections:

- "Modeling History, Methods, and Validation" describes the development of DSM2 and its application in tidal hydraulic and salinity modeling, how the model works (methods), and the accuracy of the model in comparison to measured tidal hydraulic stage, flow and salinity conditions.
- "Tidal Hydraulics" explains how tides work in the Delta, describes the simulated tidal hydraulics at selected sites throughout the Delta, provides detailed simulated tidal hydraulics of the south Delta channels, and identifies the tidal effects of Central Valley Project (CVP) Tracy Pumping Plant (Tracy) and SWP Banks pumping as well as of the Vernalis Adaptive Management Plan.
- "Water Quality" describes the development, validation, and results of the QUAL module for simulating salinity (EC) and dissolved organic carbon (DOC) conditions.

Modeling History, Methods, and Validation

History of Delta Tidal and Salinity Measurements and Modeling

The California Department of Water Resources (DWR) and the U.S. Department of the Interior, Bureau of Reclamation (Reclamation) have been actively involved in Delta tidal stage and salinity measurements for more than 50 years and have conducted tidal hydraulic and salinity modeling for more than 30 years. Successful and reliable Delta tidal hydraulic and salinity modeling depends on a number of important components, which are briefly introduced and discussed below. The major ingredients for successful tidal hydraulic and salinity modeling are:

- accurate hydrology data to specify the river inflows, agricultural diversions and drainage flows, export pumping diversions, and resulting Delta outflow;
- accurate channel geometry, including the surface area, channel depths, and intertidal volumes;
- accurate tidal stage and flow records for specifying the downstream tidal boundary conditions and for calibrating the tidal stage variations and the tidal flows that move into and out of the Delta channels in response to the downstream tidal variations;
- accurate tidal salinity (EC) measurements for specifying the downstream tidal salinity conditions and for calibrating the tidal salinity variations and (indirectly) the tidal flows that move the salinity gradients in and out of the western Delta;
- reasonable approximations of the equations that describe the movement of water and salt as a function of the geometry, water surface slope, bottom friction forces and velocity (i.e., momentum) gradients in the channel network that can be solved numerically on a computer and displayed as informative graphics (i.e., a “model”); and
- creative and innovative users who understand the basic issues and questions that are being addressed with the application of these Delta tidal hydraulic and salinity models and who are able to illustrate and describe the results from the models.

The history of DWR and Reclamation efforts to improve and innovate in each of these areas to support more accurate and reliable Delta tidal hydraulic and salinity modeling will be briefly outlined. The information for reviewing these efforts comes from the annual reports that were required by the State Water Resources Control Board (State Water Board) in Order 9 of Decision 1485 (D-1485), which requested DWR and Reclamation to undertake an effort to establish improved methods for estimating Delta tidal flows and Delta salinity conditions (subsequently called “Methodology Progress Reports”). These studies of improved Delta flow and salinity methods were requested by State Water

Board to support the Rio Vista and Delta outflow objectives and the salinity (EC) objectives established for the Delta in D-1485.

DWR issued the first progress report in January of 1979 (25 years ago). These annual progress reports provide an excellent summary of DWR Delta flow and salinity modeling efforts and continue to be the best documentation of these modeling and measurement efforts. The complete annual reports from 1998 (19th annual) to 2004 (25th annual) as well as selected earlier sections are available on the DWR Modeling Website at:

http://baydeltaoffice.water.ca.gov/modeling/deltamodeling/annualreports.cfm.

Delta Hydrology Data

DWR developed the DAYFLOW data program to organize and standardize the daily hydrology data that were required to understand and evaluate historical Delta conditions. To provide an estimate of net Delta outflow, DWR Central District compiles the basic river inflows (for the Sacramento, San Joaquin, Cosumnes, Calaveras, and Mokelumne Rivers and Yolo Bypass, estimates of daily net channel depletions using rainfall and evaporation measurements) and Delta export data (from the CVP [Central Valley Project] Tracy facility [Tracy], Contra Costa Water District [CCWD], SWP Banks facility, and North Delta). DAYFLOW files are now available from water year 1955 to present at the California Data Exchange Center (CDEC) website at:

http://www.cdec.water.ca.gov/.

Less accurate estimates (because of fewer flow records) are available beginning with water year 1929.

Delta Channel Geometry Measurements

DWR, Reclamation, the U.S. Geological Survey (USGS), and the U.S. Army Corps of Engineers (Corps) have collected many channel cross sections and channel sounding surveys throughout the Delta channels. A great deal of effort is required to organize and summarize these data for Delta channel descriptions in Delta models. The current version of the geometry data is located in a program database called Cross Section Development Program (CSDP). With the advent of global positioning system (GPS) boat survey methods, many Delta channels with outdated cross sections have been resurveyed. The most accurate channel geometry data are now updated and available through the CSDP database of the DSM2 system. DSM2 and the CSDP are both using the common datum of sea level (National Geodetic Vertical Datum 1929). The use of this datum is an improvement because previous models have used mean-low-low-water (MLLW), which varies by station throughout the Bay and Delta.

Tidal Stage and Velocity Measurements

Tidal stage measurements have been collected by USGS, DWR, and Reclamation for many years. Recent instrumentation improvements have allowed many of these stations to electronically record 15-minute stage elevations. Several of these stations are now available on a real-time basis through the CDEC.

A joint investigation was started in 1978 by the USGS, DWR, Reclamation, State Water Board and the Corps to determine the most appropriate method for direct measurements of Delta outflow. Acoustic velocity meters (AVMs) (24-megahertz [MHz] and 100-kilohertz [KHz] versions) manufactured by Ocean Research Equipment (ORE) were installed for testing at Chipps Island in August 1978. The major challenge was to obtain a reliable signal across the 4,000-foot-wide channel. Based on this initial testing, a 30-MHz AVM device was constructed by ORE for Chipps Island and tested in 1979. Analysis of the resulting data suggested that the signal strength across the entire channel was not great enough. Breaking the beam into three segments with two pilings in the middle of the channel was recommended but found to be infeasible because of navigation hazards. This program was discontinued in 1980. An AVM device has still not yet been installed at Chipps Island because of the technical challenges at this station.

The first progress report (1979) indicated that an ultrasonic (i.e., acoustic) velocity meter (UVM) station was being installed at Freeport by the USGS for Sacramento County to regulate its regional wastewater treatment plant discharge (no discharge allowed when tidal flow was less than a specified value). This UVM began operating in October 1979 and was the first continuous tidal flow meter installed the Delta.

The USGS has successfully operated UVM stations at several other locations in the Delta. A summary of this important program of tidal flow measurements in the Delta can be found in a USGS report (Simpson and Oltmann 1993) and a web poster presentation (Oltmann and Simpson 1997). UVM stations were established in January 1987 on Old River at Bacon Island (just downstream of Rock Slough) and on Middle River at Bacon Island (southeast corner). These two stations measure the entire flow entering the south Delta channels (except for the Head of Old River diversions from the San Joaquin River). The next UVM stations began operating upstream of the Delta Cross Channel (DCC) and downstream of Georgiana Slough in January 1993. These stations allow the combined diversions into the DCC and Georgiana Slough to be calculated by difference. These stations also allow the diversions into Steamboat and Sutter Sloughs to be estimated by difference with the Freeport UVM station.

Four additional UVM stations (installed at Rio Vista [April 1995], Threemile Slough [February 1994], Jersey Point [May 1994], and Dutch Slough [February 1996]) allow the Delta outflow to be calculated by combination. Another UVM station was established on the San Joaquin River at the discharge of the Stockton Regional Wastewater Control Facility in August 1995. The Head of Old River diversions can be estimated by difference with the San Joaquin River at the

Vernalis flow measurement station. Figure D-1 shows the location of these USGS UVM stations. A 15-minute-interval UVM tidal flow record is computed by multiplying channel cross-sectional area by average channel cross-sectional velocity. Water-surface elevation is measured at the UVM station and converted to channel cross-sectional area by a relation defined from channel geometry surveys. Average channel cross-sectional velocities are determined from acoustic-Doppler current profiling system (ADCPS) measurements and are used to define a UVM index-velocity and average channel cross-sectional velocity relation. Figures D-2 and D-3 illustrate these velocity measurement techniques. The ADCPS measurements provide the rating curve for the UVM velocity station, just like periodic channel velocity profiles are needed for a stage-discharge rating curve at a river flow measurement station. An example of the resulting tidal flow record for the San Joaquin River at Jersey Point is shown in Figure D-4.

A UVM station transmits acoustic pulses back and forth across a channel and precisely measures the travel time of each pulse. The difference in travel time between a pair of back and forth pulses provides an average velocity (*Vp*) across the channel at the depth of the transducers. The measured velocity (*Vp*) is not an average cross-sectional velocity and is referred to as an *index velocity* (*Vi*), which is used when processing the data to determine an average cross-sectional velocity. An ADCPS-based boat-mounted flow measuring system is used to make fast and accurate flow measurements of a channel for use in calibrating a UVM. Velocity and depth are measured, and the flow is computed as the ADCPS traverses the channel. Flow measurements of 600-foot-wide channels can be made in 2–3 minutes with an accuracy of 2% (Simpson and Oltmann 1993), using only a two-man crew.

Figure D-5 shows an example of the UVM stage and flow records for mid-May–October 1994 for the Jersey Point station. The daily range of stage is about 3 feet during neap tide and about 4 feet during spring tide. The tidally averaged water surface elevation fluctuates with spring tides (higher) and neap tides (lower), as well as other factors. The maximum tidal flow is more than 100,000 cubic feet per second (cfs) and can be as high as 150,000 cfs on some days. The tidally averaged (net) daily flows ranged from –2,000 cfs to about 8,000 cfs during this period from mid-May to October 1994. These data illustrate the highly dynamic nature of tidal flows in the Delta and demonstrate the remarkable technology that allows direct tidal flow measurements to be made in several Delta channels.

Delta outflow can now be indirectly measured as the sum of four of the UVM stations (Rio Vista, Threemile Slough, Jersey Point, and Dutch Slough) (Oltmann 1998). The tidal flow measurements indicate more variation caused by the spring-neap tidal cycle, as well as by atmospheric presure fluctuations and variations in the consumptive use (i.e., diversions and drainage flows) in the Delta. The mass-balance approach (i.e., DAYFLOW estimates) are similar during higher flow conditions, but the tidal flow measurements are perhaps more accurate during lower flows. Figure D-6 illustrates the Delta outflow measurements and mass-balance estimates for 1996.

The USGS tidal stage, velocity, and flow measurements from these continuous UVM stations and several short-term stations are now available from the USGS Bay Delta website at:

http://baydelta.wr.usgs.gov/database.html.

Delta Salinity Measurements

DWR and Reclamation measurements of tidal salinity had already begun during the 1960s using electronic instruments to measure Delta salinity (as EC) to support the ongoing water management operations of the CVP Tracy and planned SWP Banks facilities in the Delta. The Interagency Ecological Program (IEP) was established in 1970 as a joint investigation program for Delta water and fish management agencies. Many of the Delta EC measurements were collected to support these IEP efforts. The IEP database is extensive and can be accessed at the IEP website at:

http://www.iep.water.ca.gov.

Several EC measurement devices have been added to the network of Bay and Delta stations, generally at existing tidal stage and flow measurements stations. A general database of Delta monitoring records from 1968 to 1982 was prepared for STORET format in 1984. DWR and Reclamation had collected salinity measurements in previous years, but digital files were created starting with 1968. These data included the historical daily Delta flows that are compiled in the DAYFLOW files prepared by DWR (for water years 1956–present), and the EC data measured by Reclamation and DWR. These daily flow and EC records are needed to calibrate and validate the Delta flow and salinity models.

Much of the Delta tidal data were organized by the DWR Delta Modeling Section as a Delta database that was developed beginning in 1991 to provide necessary tidal data for specifying inputs and calibrating the Delta tidal models. This Delta database and the graphics/analysis package (called VISTA) are still available from Delta Modeling Section, although the IEP database is now generally used to support the Delta modeling efforts.

Delta salinity models have often used total dissolved solids as the salinity unit, although tidal salinity measurements have almost always been EC. The Contra Costa Canal (CCC) Pumping Plant #1 and the Los Vaqueros intake are the only Delta locations measuring daily chloride. DSM2 now uses EC as the basic salinity model variable, making calibration of the model with EC measurements a more direct process.

Many of the Delta tidal stations are now included in the CDEC database, which allows near real-time access to these hydraulic and water quality measurements.

Delta Hydrodynamic and Salinity Models

A tidal hydraulic and salinity model can be described as a combination of some mathematical equations and the numerical calculations that are used to solve the equations within a specified channel network for some specified inflow hydrology and tidal boundary conditions. A variety of tidal models have been developed and used to describe the Delta tidal flow and salinity conditions. These models have often been called hydrodynamic models, but the actual equations solved are usually empirical momentum-force balance (i.e., Manning's equations for channels with weir or orifice equations for tidal gates and barriers) and are more accurately called tidal hydraulic (i.e., bulk flow parameter) models. USGS, University of California (UC) Davis, and Stanford researchers have developed several two-dimensional and three-dimensional models of the Bay and Delta, but most of the Delta tidal models use a network of one-dimensional channels.

A tidal hydraulic model of the Delta channels was first developed by DWR in 1969 (based on the Water Resources Engineers "Dynamic Estuary" link-node model) to calculate 15-minute stage and tidal flow (repeating tide) in a grid of Delta channels (DYNFLO). The salinity calculations were done in a second model (TVRK, time-varying Runga-Kutta solution technique) using the tidal flow and stage values calculated by DYNFLO for a month-long period. DWR was continuing to develop and attempting to calibrate the TVRK (version 6) results in 1979 when the first methodology progress report was written. Dr. Hugo B. Fischer (UC Berkeley) was independently retained by the State Water Board in 1979 to review the DYNFLO/TVRK Delta model and report on its accuracy and reliability. Consultants (i.e., HydroQual, which later became HydroScience) were contracted by DWR in 1981 to improve and verify these Delta flow and salinity models. A new Delta salinity model, called TVSALT, was developed based on the U.S. Environmental Protection Agency (EPA) Water Quality Analysis Simulation Program model (also known as WASP) that had been developed in 1970 by these same consultants (i.e., HydroScience). These Delta models were used in 1981 and 1982 to investigate flow and salinity effects from various Peripheral Canal alternatives and for studies of the expanded SWP Banks capacity that was being planned (i.e., four additional pumping units).

FINEFLOW (a link-node model) was developed in 1984 to provide a more detailed simulation of south Delta channel tidal stages and flows. The Clifton Court Forebay (CCF) intake gates and various tidal gates and weirs in Old River and Middle River were simulated during 1985. Tom Paine Slough siphons were included in these simulations.

The FINEFLOW detailed grid was expanded to include the entire Delta in the improved DWR/Resource Management Associates (RMA) Delta hydrodynamic and water quality model that was developed in 1988. Both the DWR/RMA model and the Fischer Delta Models (FDMs) (see below) were available for use in the early 1990s.

Fischer Delta Model

Reclamation funded the development of a Suisun Marsh tidal flow and salinity model by Dr. Hugo B. Fischer, beginning in 1976. DWR obtained a version of these models in 1981 to apply to the Suisun Marsh facilities planning and the required environmental impact report (EIR) documentation of alternatives. The models (MFLOW and MQUAL) were soon modified by Dr. Fischer for DWR to simulate the entire Delta (Fischer 1982). The hydrodynamic portion uses the method of characteristics, while the salinity portion uses the Lagrangian (moves with the water) approach. This Delta model has been commonly called the *Fischer Delta Model* (FDM), and newer versions of this model are still used by CCWD, the East Bay Municipal Utility District, and Flow Science (i.e., consultants) for Delta simulations. The FDM model was installed on an IBM PC computer in 1985 by the Operations and Modeling unit of Central District.

Flow Science developed an integrated and improved FDM model (version 7) that included the Suisun Marsh channels for DWR in 1986. This version had about 150 channels and 120 junctions. To calculate the hydrodynamics for a single “repeating” tidal cycle (requiring three tidal periods to “stabilize”) took about 45 minutes on the best available PC-AT. Generally, a year of Delta tidal flows and salinity would be simulated using about 15–20 periods of constant inflows, exports, and outflow. A 1-year simulation of salinity with a 15-minute time step required about 6 hours. This Delta modeling was still a time-consuming process. The FDM salinity calculations were verified with 5 years of data (1968, 1972, 1976, 1977, and 1978) at 17 locations. Comparisons of measured EC with simulated total dissolved solids required empirical conversion equations. Nevertheless, the match of the FDM results with these seasonal EC patterns was generally good.

Department of Water Resources Delta Simulation Model Development

The DWR modeling section of the Central District made extensive changes in the FDM and renamed the model subroutines to be DWRFLO and DWRSAL in 1989. Simulation of the CCF with the intake gate flows from West Canal and hourly pumping at the SWP Banks facility was incorporated. The rectangular channels assumed in FDM were modified to trapezoidal channels for more accurate tidal flow simulations. This new Delta hydrodynamic and water quality model became known as DWRDSM (DWR Delta Salinity Model) in 1990. The DSM was used with 1988 historical flow and salinity data to simulate the planned operations of the Suisun Marsh salinity control gates.

A new subroutine for Delta modeling was a dynamic agricultural diversion and drainage subroutine called DICU (Delta Island Consumptive Use), which allowed the drainage salinity from each Delta island to be simulated as a function of the channel salinity and assumed soil salinity, for assumed diversion and drainage conditions that were dependent on cropping and Delta soil properties.

This dynamic salinity subroutine was never fully developed, and the current version of DSM2 uses assumed fixed monthly drainage EC values. DICU monthly flow values (seepage, diversion, and drainage) that vary somewhat for each year are specified as DSM2 boundary conditions.

The 12th annual report (April 1991) indicated that the Delta Modeling Section (formed in 1989 in the Division of Planning) was looking for a more efficient modeling code and solution engine for the DSM model. All input and output data would use the Corps' Hydrologic Engineering Center data storage system (HEC-DSS) FORTRAN routines for input and output of time variable modeling data. All available Delta data from calendar year 1988 were being digitized and converted to DSS format for modeling calibration and verification purposes.

The 14th annual report (June 1993) reported that the DWRDSM simulations of the south Delta temporary barriers were verified with field measurements with the Old River Delta-Mendota Canal (DMC) temporary barrier installed in July and August 1992 and without the temporary barrier during April 1993. The simulation of the CCF stage and the intake gate flows were verified with field measurements during the SWP Banks facility high pumping tests in January 1993. The report also described the particle-tracking model (PTM) that was being incorporated into the DSM package. The possibility of extending the downstream boundary to the Golden Gate Bridge was being investigated, although this would increase the computational time because of the increased number of channels and nodes. New solution techniques (model codes) for the hydrodynamic and water quality models were described that would allow the DSM to become a public-domain model (DWRDSM still relied on parts of the proprietary FDM program code).

Department of Water Resources Planning Models

The CVP and SWP reservoir operations control the Delta inflows and allowable exports during low-runoff periods. The Delta models are often used to simulate the Delta tidal conditions that correspond to future inflow and export conditions as simulated with a planning model. A planning model and a Delta tidal flow and salinity model are therefore often used sequentially to provide an understanding of the effects of CVP and SWP operations on Delta hydraulics and salinity.

A Delta operations model, called PCLEVEL, that calculated net flows in Delta channels as a function of river inflows and export pumping (with or without the Peripheral Canal) was used with SALDIF (a steady-state flow-salinity gradient model) by DWR during the 1970s and early 1980s to estimate the monthly net flows and salinities in the Delta. Minimum Delta outflow requirements to satisfy the D-1485 salinity objectives were programmed and added to PCLEVEL in 1983. A Delta operations model, called DELOP, was developed with a shorter time-step to allow the variations in Delta flow and salinity within a month to be considered.

The DWR Planning Simulation Model (soon to be called DWRSIM and later CALSIM) was developed from the HEC-3 reservoir system analysis model to provide a monthly planning model for the SWP and CVP reservoirs and Delta facilities. This model was documented in 1985 (California Department of Water Resources 1985a) in preparation for the State Water Board hearings on the Delta water quality control plan (WQCP) (i.e., D-1485). The Delta outflow-salinity relationships were investigated for better estimation of the required minimum outflows to specify for the 57-year planning model sequence. A subroutine, called MDO, was developed to estimate the required minimum Delta outflow that would satisfy the D-1485 salinity objectives.

The estimation of the minimum Delta outflow required to satisfy the Delta salinity objectives has always been a weak link in these monthly water management planning models. The current version of CALSIM II uses either the CCWD-developed “G-model” estimates of required outflow or an artificial neural network (ANN) algorithm to estimate the necessary Delta inflow that would allow the simulated exports and still satisfy the D-1641 salinity objectives. The ANN algorithm has been “trained” (i.e., calibrated) to match DSM2 simulations of salinity for a range of Delta inflows and exports. The monthly CALSIM II planning model is therefore indirectly linked with the DSM2 results (through the ANN subroutine) if this option is used, as it was for the CALSIM II simulations for the SDIP alternatives.

DSM2 Development

The 15th annual report (June 1994) described the initial development of DSM2, which includes the USGS four-point flow model (FOURPT) and the USGS branch Lagrangian transport model (BLTM). The 16th annual report (June 1995) described DSM2 in more detail. The use of ANNs to estimate the required Delta outflow to maintain salinity standards was first investigated in 1995. Calibration and verification of DSM2 has continued and resulted in many modifications and improvements that have increased the model accuracy.

DSM2 formulations, as well as the procedures for specifying input data and displaying results, have been modified and improved in many important ways during the 10 years since it was first developed. The existing version of DSM2 is the result of many individuals’ efforts and has been improved by the application to many DWR and CALFED Bay-Delta Program (CALFED) projects. The application of DSM2 to the SDIP alternatives is described in the following sections of this appendix. DSM2 is the best available tool for Delta tidal hydraulic and salinity modeling and is appropriate for describing the existing conditions in the Delta, as well as performing simulations for the assessment of environmental impacts (i.e., incremental changes caused by facilities and operations).

Delta Modeling Staff

The earlier annual progress reports do not give the names of Reclamation and DWR field collection and modeling staff, but quite a number of dedicated and conscientious staff have contributed to the excellent historical monitoring, special studies, and real-time data that are now available for understanding and evaluating Delta tidal flow and salinity conditions.

Beginning in 1993, the annual progress reports (now prepared by the Bay-Delta Office) list the authors of the individual chapters. Many of the staff that contributed to the modeling development and applications are still contributing their talents and energy in DWR or other California water agencies. In 1993, Francis Chung was continuing as the program manager. Shawn Mayr prepared the annual report. Mohammed Rayej, Hari Rajbhandari and Ali Ghorbonzadeh were working on the DWRDSM. Tara Smith (now Delta Modeling Section head) was working on a PTM. Art Hinojosa and Ralph Finch were working on data compilation and a graphical users' interface (VISTA). Andy Chu was working with Brad Tom on the channel geometry database (CSDP). Parvis Nader-Tehrani was working on the new DSM2 code. Paul Hutton (now with the Metropolitan Water District of Southern California) was working on trihalomethane (THM) modeling in the Delta. Nirmala Mahadevan and Chris Enright (now with the Suisun Marsh section) helped with sections of the 1994 progress report. Nicky Sandhu helped with sections of the 1995 report.

The IEP has produced several dedicated interagency teams that have maintained routine as well as special field data and analysis projects since it was formed in 1970. A San Francisco Bay/Sacramento–San Joaquin River Delta (Bay-Delta) team to conduct two-dimensional and three-dimensional modeling was formed in 1984. Mike Ford represented DWR on this 2-year model development effort under the direction of Ralph Cheng at USGS in Palo Alto. The recent contributions of the IEP project work teams on hydrodynamics and DSM2 calibration are two good examples of the collaborative nature of these IEP efforts. The quarterly IEP newsletters that are published by DWR Central District can be found on the IEP website, for issues since 1995.

The Delta Modeling Section was formed in the DWR Division of SWP Planning in 1989. George Barnes and Francis Chung were early key staff members that provided vision and innovation for the CALSIM and DWRDSM modeling teams. Central District staff assigned to the Suisun Marsh Section have been very active in Delta modeling improvements. Kamyar Guivetchi and Dwight Russell (now DWR Northern District Chief) have made many excellent contributions to Delta tidal models and evaluations. Chris Enright headed the IEP DSM2 calibration and validation team.

California Water and Environmental Modeling Forum

The Bay-Delta Modeling Forum (Forum) was formed in 1994 in an effort to organize a network of modeling expertise and provide for an exchange of modeling ideas and modeling applications for the Bay-Delta system. DWR and Reclamation staff have participated and actively contributed many presentations at the annual meetings and workshops that have been sponsored by the Forum since 1994. The current activities of the renamed California Water and Environmental Modeling Forum can be found on their website at:

http://www.cwemf.org.

The modeling forum presents an award for excellent model development or model application in honor of Dr. Fischer. Many of the 12 award recipients have participated in Delta modeling:

- Dr. Alan Jassby (UC Davis) analyzed ecological data from the Delta and the relationships between X2 and organism abundance.
- Richard Denton (CCWD) developed the G-model approximation of the salinity-outflow relationship for western delta locations.
- Ralph Cheng (USGS) continues work on three-dimensional Bay models.
- Greg Gartrell (CCWD) applied and improved the FDM.
- Francis Chung directed the development of DSM2.
- Jack Rowell (Reclamation) developed the water temperature model that is used with CALSIM to protect river temperatures below Reclamation and DWR reservoirs.
- Walter Bourez (SWRI) applied and improved the PROSIM monthly planning model.
- Dwight Russell (DWR) and Kamyar Guivetchi (DWR) applied and improved the Suisun Marsh model.
- Armin Munevar (DWR) helped develop and improve the CALSIM planning model.
- Gerald Orlob (UC Davis) was involved in early Delta modeling and continues to direct graduate student research in water quality modeling throughout California.
- Emin Dogrul (DWR) developed and improved the IGSM2 groundwater-surface modeling tools.

Delta Modeling Section Annual Progress Reports

Although the SWP and CVP water rights are now governed by D-1641, rather than by D-1485, the Delta Modeling Section continues to publish annual progress reports. The recent documents are available from the DWR Delta Modeling website. The chapters that directly describe the DSM2 modeling system are listed below to facilitate further study:

- **1994 (15th) Annual Report—**Chapter 2, "New Model Development (DSM2-HYDRO and DSM2-QUAL);"
- **1995 (16th) Annual Report—**Chapter 3, "Water Quality (DSM2-QUAL)," and Chapter 4, "Particle Tracking (DSM2-PTM);"
- **1997 (18th) Annual Report—**Chapter 2, "DSM2 Model Development" (html format for website);
- **1998 (19th) Annual Report—**Chapter 5, "DSM2 Input and Output," and Chapter 6, "Cross-Section Development Program (CSDP);"
- **1999 (20th) Annual Report—**Chapter 4, "Modeling of 1998 Hydrodynamics in the Delta (comparison to UVM stations);"
- **2000 (21st) Annual Report—**Chapter 8, "Filling In and forecasting DSM2 Tidal Boundary Level;"
- **2001 (22nd) Annual Report—**Chapter 2, "DSM2 Calibration and Validation" (also see www.iep.water.ca.gov/dsm2pwt/dsm2pwt.html), Chapter 7, "Integration of CALSIM and ANN models for Delta Flow-Salinity Relationships," Chapter 10, "Planning Tide at the Martinez Boundary," Chapter 11, "Improving Salinity Estimates at the Martinez Boundary," and Chapter 12, "DSM2 Real-Time Forecasting System;"
- **2002 (23rd) Annual Report—**Chapter 12, "DSM2 Documentation," Chapter 13, "DSM2 Input Database and Data Management System," and Chapter 14, "DSM2 Fingerprinting Methodology;"
- **2003 (24th) Annual Report—**Chapter 6, "New Behaviors and Control switches in DSM2-PTM," and Chapter 7, "Implementation of a new DOC growth (source) algorithm in DSM2-QUAL;" and
- **2004 (25th) Annual Report—**Chapter 3, "DSM2 Geometry Investigations," Chapter 6, "Net Delta Outflow Computations for DSM2 Steady State Simulations," Chapter 7, "Extensions and Improvements to DSM2," and Chapter 12, "Calculating Clifton Court Forebay Inflow."

Most of these individual modeling topics are described in this appendix on the DSM2 simulations for the SDIP alternatives impact assessment.

DSM2 Documentation

There is not a printed users manual or model documentation report. There is, however, considerable information about DSM2 available on the DWR Delta Modeling website at:

http://baydeltaoffice.water.ca.gov/modeling/deltamodeling/deltaevaluation.cfm.

This website (shown in Figure D-7) has links to information about:

- the main modules of DSM2, hydrology (HYDRO), and water quality (QUAL);
- the PTM, which uses output from the hydrology module of DSM2;
- the DICU model, which can be used to develop inputs to DSM2;
- the Cross Section Development Program, which can be used to develop channel geometry inputs to DSM2;
- the ANN model of Delta flow-salinity relationships, an alternative to using DSM2 for estimating Delta salinity;
- Martinez boundary EC generator, which can be used to estimate inputs to DSM2;
- a trihalomethanes simulation model; and
- the DSM2 Users Group.

The link to DSM2 takes the viewer to the DSM2 web page. The DSM2 web page (also shown in Figure D-7) has links to information on model use, including a DSM2 tutorial. Other links lead to model code, executable files, and model inputs. This web page also has a link to information about Vista, a program developed by DWR to view data that are stored in the HEC-DSS format. Many of the model inputs are in this format. Data in the HEC-DSS format can also be imported and viewed in Excel using a DSS add-in for Excel that is available from the HEC website at:

http://www.hec.usace.army.mil/software/hec-dss/hecdss_msexcel_addin.htm.

This add-in also allows for the creation of DSS files from Excel tables. This add-in greatly facilitates the editing and creation of input data files and the viewing of model results.

Methods Used for Tidal Hydraulic and Water Quality Modeling

DSM2 Modules

DSM2 is a one-dimensional mathematical model for dynamic simulation of tidal hydraulics, water quality, and particle tracking in a network of riverine or estuarine channels. DSM2 can calculate stages, flows, velocities, transport of individual particles, and mass transport processes for conservative and nonconservative constituents, including salts, water temperature, dissolved oxygen (DO), and dissolved organic carbon (DOC). The hydrodynamic (HYDRO), water quality (QUAL), and PTM modules of DSM2 are briefly described below:

- The HYDRO module is a one-dimensional, implicit, unsteady, open channel flow model that DWR developed from FOURPT, a four-point finite-difference model originally developed by the USGS in Reston, Virginia. DWR adapted the model to the Delta by revising the input-output system, including open water elements, and incorporating water project facilities, such as gates, barriers, and the CCF.
- The QUAL module is a one-dimensional water quality transport model that DWR adapted from the Branched Lagrangian Transport Model originally developed by the USGS in Reston, Virginia. DWR added many enhancements to the QUAL module, such as open water areas and gates. A Lagrangian feature in the formulation eliminates the numerical dispersion that is inherently in other segmented formulations, although the tidal dispersion coefficients must still be specified.
- The PTM module simulates the transport and fate of individual particles traveling throughout the Delta. The model uses velocity, flow, and stage output from the HYDRO module to monitor the location of each individual particle using assumed vertical and lateral velocity profiles and specified random movement to simulate mixing.

HYDRO Module

The HYDRO module is a tool to study the complex tidal hydraulic system found in the Delta. This module is adapted from FOURPT, a finite-difference, one-dimensional, unsteady, open channel hydrodynamic model (Delong et al. 1993).

Some of the main characteristics of the HYDRO module are described below:

- The method of solving the hydrodynamic equations is fully implicit and unconditionally stable. Larger time steps can be used compared to an explicit model, which requires smaller time steps for numerical stability.
- The model is capable of handling trapezoidal and irregular shaped channels.
- The model includes the baroclinic momentum equation term (i.e., density-driven flow) in the mathematical formulation. If the density of the water is allowed to vary, its effect can be included in the analysis with the $g\,dp/dx$ term in the momentum equation. The baroclinic effects on the 1-D tidal hydraulics are very small, however.
- FOURPT is capable of enforcing continuity both at a junction and within a channel because of its implicit nature.
- The HYDRO module solves the momentum and continuity equations. These differential equations are solved using a finite difference scheme requiring four points of computation, thus the name FOURPT. The equations are integrated in time and space, which leads to a solution of a set of nonlinear equations, with the incremental changes in stage and flow at the computational points as the unknowns.

Open Water Areas

A few open water areas, including the CCF, are modeled in the DSM2 grid. These areas are bodies of water that are too big to be modeled as channels. Open water areas are treated like tanks, with a known surface area and bottom elevation. An open water area can be connected to one or more channels. The flow interaction between the open water area and each of the connecting channels is determined using the general orifice formula:

$$q = CA\sqrt{\Delta h}$$

where q is the flow from the open water area to the channel, C is the flow coefficient, A is the flow area, and Δh is the head difference between the open water area and the channel. The variable gate opening of the CCF intake gates cannot be simulated, but the overall flows into the CCF are reasonably represented with this orifice equation.

Hydraulic Gates

The flow through hydraulic gates is also calculated using the orifice flow equation.

Gates can be placed either at the upstream or downstream end of a channel. Two values of gate flow coefficients are assigned for every gate, one for seaward flow and the other for landward flow. For a one-way gate, the flow coefficient assigned to the obstructed direction is set to zero. For a complete barrier, the gate flow coefficients for both directions are set to zero.

FOURPT enforces an “equal stage” boundary condition for all the channels connected to a junction with no gates. Once the location of a gate is defined, the boundary condition for the gated channel is modified from “equal stage” to “known flow,” with the calculated flow.

Using the current version of DSM2, the gates are allowed to open and close multiple times during a single model run using a predetermined schedule. This schedule must be determined as part of the model input, using a previous simulation to determine the appropriate times to change the gate opening.

QUAL Module

The QUAL module is a one-dimensional transport model that predicts the fate of various water quality constituents, such as salinity (EC), temperature, DO, and DOC. As water moves tidally within the Delta channels, the constituents tend to disperse in the longitudinal direction. Other processes include growth and decay, which may be caused by interactions among various constituents.

Simulation of these processes is accomplished with the conservation of mass equation, using the tidal flows and volumes calculated by the HYDRO module. Two main techniques are available for solving this equation:

- Eulerian (fixed coordinate system)—With this approach, the processes are easier to conceptualize as inflows and outflow from a "box." As it turns out, however, the computations are fairly difficult, and the results can be inaccurate and unstable. A byproduct of this approach is an error term called the numerical dispersion, which can be significant, especially in areas with a sharp gradient in the constituent concentrations.
- Lagrangian (moving coordinate system)—With this approach, each river segment is modeled as several fixed volume water parcels, each moving with the same speed as the river flow. Using this approach, the complex convective terms are eliminated. At the junctions, parcels from neighboring channels are blended to create new parcels. The dispersive term is simulated as exchange between each neighboring parcel. The growth/decay terms are computed within each individual parcel. Tracking of each individual parcel requires massive amounts of bookkeeping.

DSM2 Fingerprinting

The transport of several conservative source tracers can be simulated to determine volume contributions from each source. These volume contributions can then be used to estimate concentrations of any conservative constituent coming from these sources. Volume fingerprinting can be used to determine the relative flow contribution of each source at a specified location. For example, the fraction of the flow at CCF that originated from the Sacramento River, the San Joaquin River, eastside streams, the ocean, and agricultural return flows can be calculated. Volume fingerprinting can be used to estimate the concentrations of conservative water quality constituents at specified locations using a single DSM2 simulation, by multiplying the inflow concentrations by the fraction of water from each source.

Particle-Tracking Model Module

The PTM module simulates the transport and fate of "virtual" particles traveling in the Delta channels. The model uses velocity, flow, and stage output from the HYDRO module. The transfer file (TIDE) containing these hydrodynamic values has a 1-hour time step. The PTM module uses the geometry files that describe the model segments simulated by the HYDRO module. The particles move throughout the network under the influence of flows and random mixing effects.

The location of a particle in a channel is determined as the distance from the downstream end of the channel segment (x), the distance from the centerline of the channel (y), and the distance above the channel bottom (z).

In June 1992, the DWR hired Dr. Gilbert Bogle (Water Engineering and Modeling) to develop a nonproprietary PTM module. The PTM was originally written in FORTRAN. The code was later partially rewritten in C++ and Java to use an object-oriented input approach.

Particle Movement

The longitudinal distance traveled by a particle is determined from a combination of the lateral and vertical velocity profiles in each channel. The transverse velocity profile simulates the effects of channel shear that occurs along the sides of a channel. The result is varying velocities across the width of the channel. The average cross-sectional velocity is multiplied by a factor based on the particle's transverse location in the channel. The model uses a fourth order polynomial to represent the velocity profile (Figure D-8a). The vertical velocity profile shows that particles located near the bottom of the channel move more slowly than particles located near the surface. The model uses the Von Karman logarithmic profile to create the velocity profile (Figure D-8b). Particles also move because of random mixing. The mixing rates (i.e., distances) are a function of the water depth and the velocity in the channel. High velocities and deeper water result in greater mixing.

PTM Module Capabilities

The capabilities of the PTM module are described below:

- Particles can be inserted at any node location in the Delta.
- History of each particle's movement is available. In the model, the path each particle takes through the Delta is recorded. Output for determining the particle's movement includes:
    - ☐ animation—particles are shown moving through the Delta channels, and the effects of tides, inflows, barriers, and diversions on particles are seen at hourly time steps;
    - ☐ number of particles passing locations—the number of particles that pass specified locations are counted at each time step; and
    - ☐ number of particles within a specified group of channels and reservoirs—the number of particles left in the channels at the end of the time step.
- Each particle has a unique identity, and characteristics can change over time. Because each particle is individually tracked, characteristics (behavior) can be assigned to the particle. Examples of characteristics are additional velocities that represent behavior (self-induced velocities) and the state of the particle, such as age.
- Particles can have a settling (or buoyancy) velocity. Therefore, if particles are heavy and tend to sink toward the bottom, they will move more slowly

than if they were neutrally buoyant or floating. As a result, the travel time of heavy particles through the channels will be longer.

Particle Behaviors

PTM simulations have primarily been made using neutrally buoyant particles. The work of biologists in the IEP Estuary Ecological and Resident Fish Studies Project Work Teams has enabled some behaviors to be incorporated into the model. Some studies have been conducted in which settling velocities and mortality rates were included. These studies concentrated on striped bass eggs and larvae. Additional behaviors have been added to restrict a particle's movement within a given volume to simulate tidal "surfing" of Chinook salmon, which move on ebb tides at the surface and drop toward the bottom during flood tides.

A *fall velocity* can be added to a particle. This velocity adds an additional downward (+) or upward (–) velocity component to a particle. This addition can be useful when simulating suspended sediment or striped bass eggs, which have a slightly higher density and tend to fall and move along the bottom.

Vertical positioning allows for defining a restriction on the particle's vertical movement in the channel. Typically, a particle is allowed to roam 100% of the channel depth. Figure D-9a shows particles distributed throughout the water column. These particles can potentially be subjected to any portion of the velocity profile. With *vertical positioning,* the particles are restricted to a defined range. In Figure D-9b, the particles are restricted to the lower portion of the channel. The range can be restricted to any part of the channel and can even be defined for a given time. With the restriction, the particles are subjected only to the lower portion of the velocity profile.

DSM2 Calibration and Validation

The DSM2-modeled tidal hydraulic and salinity (EC) results were initially calibrated in 1997 by the DWR Delta modeling staff. The IEP PWT for DSM2 calibration and validation provided additional calibration during 1999. The recent network of USGS tidal flow meters as well as these more extensive geometry measurements provided the motivation for the PWT calibration and validation efforts for the newest version of the Delta tidal hydraulic and water quality model, DSM2.

The HYDRO module was calibrated using data from four different time periods:

- May 1988,
- April 1997,
- April 1998, and

- September and October 1998.

For the HYDRO module, the Manning's roughness coefficient *n* was chosen as the calibration parameter. With each subsequent run, these coefficient values were modified to try to achieve a better match. Phase and tidal amplitude error indexes were introduced to quantify the exactness of fit for tidal stage. The magnitude of the error indexes was calculated for each period separately, and these values were added to the calibration figures. Showing the error indexes directly on the figures made it easier to improve the calibrated match. Fifty-six iterations were run. Overall, model predictions for the final iteration of the calibration are noticeably closer to the field data than the original 1997 calibration.

The QUAL module was calibrated in one continuous interval because QUAL results can be affected by the initial conditions (salinity) for several months. QUAL was calibrated using EC data because EC data are plentiful, and EC is assumed to behave like a conservative substance. The most suitable periods for calibration of salinity are dry periods during which saline Bay water enters the Delta. The IEP Project Work Team (PWT) selected the 3-year period from October 1991 to September 1994 for calibration. Dispersion coefficients were used as the calibration parameter. After 16 iterations, the PWT decided that the EC calibration was complete. Overall, QUAL results and the actual EC data agree quite well. Salt intrusion into the western Delta was simulated fairly well. However, in the San Joaquin River between Antioch and Jersey Point and continuing up Old River to Bacon Island, the model overpredicts the salt intrusion.

Validation of DSM2-Simulated Tidal Stage and Flow

Delta tidal hydraulic simulations of stage and flow (velocity) and salinity (EC) with DSM2 are important for many proposed projects, such as the DWR SDIP, wastewater treatment plant discharge, fish protection efforts such as the Vernalis Adaptive Management Plan (VAMP), and flood control and levee maintenance efforts. The accurate simulation of project effects depends on reliable model calibration and application. This section of the appendix demonstrates that DSM2 has been accurately calibrated by showing the comparison of measurements and simulations of tidal hydraulic stage and flow and salinity conditions from several recent years. The simulations of the SDIP baseline and project alternatives are therefore considered to be a very reliable basis for impact evaluations.

A 6-year historical simulation of the January 1994–September 1999 period was used for a validation period. The historical tides at Martinez were used along with the daily average inflows and export pumping to produce this 6-year continuous simulation. The previous results (1997 calibration) are shown together with the most recent calibration results and the field data. The results of this interagency calibration effort are documented in a series of graphs on the website at:

http://modeling.water.ca.gov/delta/studies/validation2000.

The draft calibration and validation report is available at:

http://www.iep.ca.gov/dsm2pwt/dsm2pwt.html

A considerable effort has been made to improve the channel geometry specified for the DSM2 grid. Channel geometry is perhaps the major factor influencing the tidal hydraulics in the Delta. Modern methods of boat-mounted depth sounder connected with a GPS for location have been used to collect more accurate bathymetry data in several portions of the Delta by DWR Central District staff. All the bathymetry data are contained in the geometry database and user-interface called the “Cross Section Development Program.”

More than 50 separate model runs were performed to adjust the flow friction coefficient (Manning’s roughness coefficient *n*) values to match the stage and velocity and phase lag throughout the Delta. Salinity (EC) was calibrated by adjusting the salinity dispersion coefficient.

The results of this extensive calibration effort are demonstrated in the selected validation results shown in this section. The validation simulation used historical daily inflows and export pumping with historical tidal stage at Martinez to simulate the January 1994–September 1999 period, using the calibrated geometry and model coefficients. This period includes a wide range of flow and export pumping, with temporary barriers installed during the spring and summer months. The tidal stage comparisons for the higher flow periods are reviewed below to illustrate the accuracy of the DSM2 simulations during major flood events. Several major floods, including the January 1997 events, are simulated in these historical DSM2 results. Tidal stage comparisons in the lower flow periods illustrate the ability of DSM2 to match the normal tidal fluctuations in the Delta.

Figure D-10 shows the Delta stations with field data (tidal stage, tidal flow, or EC) that were compared during the DSM2 validation efforts. Two periods are selected to illustrate the validation of DSM2 for selected stations throughout the Delta. The daily average tidal stages and flows are shown for a 3-year period of January 1997–September 1999. The 15-minute tidal stage and flow results are compared to measured stage and flow variations for the 2-week period of February 17–March 2, 1996.

Validation at Sacramento River Locations

For the Sacramento River at Freeport, Figure D-11 shows the simulated and measured tidal stage and Figure D-12 shows the simulated and measured tidal flows. The initial calibration (green) did not match the tidal stage at higher flows. The tidal stage was about 4 feet too low when the flow was greater than 50,000 cfs, but was about 1 foot too low during lower flows of about 10,000 cfs. The revised calibration provides a very good match with the high tidal stages resulting from large flows in the Sacramento River. There is a USGS tidal flow meter at Freeport, but the daily average flows that are used as input at the upstream model boundary near downtown Sacramento are shown in the flow graph.

For the Sacramento River at Walnut Grove, just upstream of the DCC gates, Figure D-13 shows the simulated and measured tidal stage and Figure D-14 shows the simulated and measured tidal flows. The maximum tidal stage at higher flows are considerably lower than at Freeport, with the simulated maximum tidal stage in February 1996 of about 11 feet matching the measured tidal stage very well at the peak flow of about 45,000 cfs. The simulated tidal stage variations and flow variations during the February high inflow period were quite good. The tidal variations in stage and flow at lower flow are also very close to the measured variations.

For the DCC and Georgiana Slough, Figure D-15 shows both the daily average combined flows for the 1997–1999 period and the tidal flows simulated in Georgiana Slough during the February 1996 high-flow event, when the DCC was closed because the Freeport flows were above 25,000 cfs. The new calibration appears to give an accurate flow split for periods with the DCC gates either open or closed (February–June and during high flows). The tidal variation in Georgiana Slough stage and flow during the February 1996 high-flow event (when DCC was closed) are quite close to the measured data.

For the Sacramento River at Rio Vista, Figure D-16 shows the simulated and measured tidal stage and Figure D-17 shows the simulated and measured tidal flows. Flows at Rio Vista can be quite high because the Yolo Bypass joins the Sacramento River channel just upstream. The simulated daily average tidal stages at higher flows are only 4–6 feet above mean sea level (msl). The tidal stage variation during February 1996 high-flow event when the flows were between 50,000 cfs and 150,000 cfs were well matched, with a 4-foot tidal variation (i.e., high tide minus low tide) during moderate flows of 50,000 cfs, and a 2.5-foot tidal stage variation even during the peak flow of 150,000 cfs. This indicates that the tidal variations dominate the tidal flows at Rio Vista, even when the inflows are 150,000 cfs. The simulated tidal variation is about 0.5 foot greater than measured.

For Threemile Slough, which connects the Sacramento River and the San Joaquin River downstream of Rio Vista, Figure D-18 shows the daily average flow for 1997–1999 and the tidal flow for February 1996. The tidal stage is about the same as at Rio Vista. The daily net flow is about 1,000 cfs toward the San Joaquin River (negative direction). The tidal flows during the February 1996 high-flow event fluctuated from about 30,000 cfs toward the Sacramento River to about –30,000 cfs toward the San Joaquin River. The simulated tidal flows through Threemile Slough matched fairly well (about 10% too high).

For the Sacramento River at Mallard Slough (across from Chipps Island), Figure D-19 shows the simulated and measured tidal stage and Figure D-20 shows the simulated and measured tidal flows. The simulated daily average tidal stages at higher flows are only 3 feet msl. The tidal stage variation during February 1996 when the Delta outflows were between 50,000 and 150,000 cfs were well matched, with a 4.5-foot tidal variation (i.e., high tide minus low tide) during moderate flows of 50,000 cfs, and a 3.5-foot tidal stage variation even during the peak flow of 150,000 cfs. The simulated tidal variation is about 0.5 foot greater than measured during the beginning of the event and is almost exactly the same during the period of highest flows.

For the Sacramento River at Martinez, which is the downstream boundary for DSM2, Figure D-21 shows the measured tidal stage. The measured daily average tidal stage varied from about 0.25 to 2.75 feet msl during the high outflow periods, and averages about 1 feet msl. The tidal stage variation at Martinez can be quite large (i.e., more than 6 feet), and was reduced to a variation of about 4 feet during the peak outflow of 150,000 cfs during the February 1996 high-flow event. DSM2 does a good job of propagating this measured tidal stage variation into the Sacramento River channel all the way to Freeport.

Validation at San Joaquin River Locations

For the San Joaquin River at Vernalis, Figure D-22 shows the DSM2-simulated and measured daily average tidal stage and flow for the 1997–1999 period. This location is the upstream boundary for DSM2 on the San Joaquin River. The calibrated tidal stage is now reasonably well matched with the data, whereas the initial calibration had a stage during high flows that was 5 feet lower than measured.

For the San Joaquin River at the Stockton UVM station, Figure D-23 shows the simulated and measured tidal stage and Figure D- 24 shows the simulated and measured tidal flows. The simulated tidal stage is about 0.5 foot below the measured tidal stage. The simulated tidal stage variations are not well-matched with the data. The simulated minimum tidal stage is about 1 foot lower than measured during the peak flows of the February 1996 high-flow event. The simulated tidal flow is also lower than the measured tidal flow during the highest flows of the February 1996 high-flow event. The simulated tidal flows matched better during the beginning of the February 1996 high-flow event, but the simulated minimum tidal flows were too high (i.e., simulated tidal flow variation is too small).

For the San Joaquin River at Jersey Island, Figure D-25 shows the simulated and measured tidal stage and Figure D-26 shows the simulated and measured tidal flows. The simulated tidal stage is about 1.0 foot below the measured tidal stage, although the measured tidal stage appears to be too high compared to surrounding stations (i.e., Antioch and Rio Vista). The range of net flows at Jersey Point was about 0–75,000 cfs during the 1997–1999 period, although the simulated peak net flows were only 50,000 cfs. The simulated tidal flow is close to the measured tidal flows at the Rio Vista USGS tidal flow station. The tidal flows generally range from –150,000 cfs during the moderate flows at the beginning of the February 17–March 2 period. The simulated and measured tidal flows are dampened slightly by the higher net flows at the end of this period, with flood tide maximum flows of –100,000 cfs and maximum ebb tides flows of 125,000 cfs.

For the San Joaquin River at Antioch, Figure D-27 shows the simulated and measured tidal stage and Figure D-28 shows the simulated and measured tidal flows. The simulated daily average tidal stage is about the same as the measured tidal stage (suggesting the Jersey Point stage data are 1.0 foot higher than actual). The tidal range during the February 1996 high-flow event was about 4 feet at the beginning and about 3 feet during the peak flow, although some of this variation is caused by the spring-neap cycle, as well as the tidal stage damping from the higher flow. The range of simulated net flows at Antioch was about 0 cfs to 50,000 cfs during the 1997–1999 period, although the measured net flows at Jersey Pint suggest the peak flows AT Antioch should be higher (same as Jersey Point net flows). The simulated tidal flows generally range from –175,000 cfs (flood) to 175,000 cfs (ebb) during the moderate flows at the beginning of the February 17-March 2 period. The simulated tidal flows are damped out a little by the higher net flows at the end of this period, with flood tide maximum flows of –100,000 cfs and maximum ebb tides flows of 150,000 cfs. The initial calibration (green line) indicated higher tidal flows than the current calibration that matched the measured Jersey Point tidal flows.

These validation results for the San Joaquin River suggest that DSM2 is very well calibrated for the San Joaquin River channel upstream to Jersey Point. There is some indication that the tidal stage and flows upstream of the Stockton are a little lower than measured. Overall, the tidal stage and flow fluctuations within the San Joaquin River, which forms the boundary for the south Delta channels, are accurately simulated by DSM2. The simulated tidal effects of the SDIP alternatives on tidal hydraulic conditions in these Delta channels are therefore assumed to be reliable.

Validation at South Delta Locations

For Old River at Tracy Boulevard Bridge, Figure D-29 shows the simulated and measured tidal stage and Figure D-30 shows the simulated and measured tidal flows. The simulated daily average tidal stage with the new calibration now matches the measured tidal stage at higher flows of 5,000 cfs. The tidal stage variations during the February 1996 high-flow event match the measured tidal stage data reasonably well, although the simulated high tides are about 0.5 foot higher than measured. The range of simulated net flows in Old River at the Tracy Boulevard Bridge is only about 0–5,000 cfs. The simulated tidal flows (there are no measured tidal flows) are very irregular, with a pulse flood tide flow and a more steady ebb tide flow. Most of the flow entering the Old River channel from the head of Old River diversion from the San Joaquin River flows down the Grant Line Canal and does not flow past the Tracy Boulevard Bridge.

For Old River upstream of the CVP DMC intake channel and Tracy Fish Facility, Figure D-31 shows the simulated and measured tidal stage and Figure D-32 shows the simulated and measured tidal flows. This is the location of the temporary barrier location and the proposed tidal gate. The simulated daily average tidal stage with the new calibration now matches the measured tidal stage of 5 feet msl at high flows of 5,000 cfs. The effects of the temporary barriers in the summer can be seen from the difference between the old calibration (green line) and the new calibration (blue line) results. The tidal stage variations during the February 1996 high-flow event match the tidal stage data well, although the simulated high tides are about 0.5 foot higher than measured. The range of simulated net flows in Old River at the DMC is only about 0–5,000 cfs. Some measurements from spring 1998 confirm the simulated net flows of about 1,500 cfs. The simulated tidal flows are irregular, with a pulse flood tide flow and a pulse ebb tide flow that varied from –2,000 to 3,000 cfs during the February 1996 high-flow event.

For Old River at Clifton Court Ferry, located just upstream of the CCF intake gates and just downstream of the CVP DMC intake channel, Figures D-33 and D-34 show the simulated and measured tidal stage. This station has the lowest measured tidal stage in the Delta and is most directly affected by the CVP Tracy and SWP Banks pumping. The simulated daily average tidal stage with the new calibration now matches the measured tidal stage of about 4 feet at a flow of about 10,000 cfs. The simulated daily average tidal stage matches the measured tidal stage, with a minimum value of about 0 feet msl. The tidal stage variations during the February 1996 high-flow event match the measured tidal stage data (range from 1 to 5 feet msl) reasonably well, although the simulated high tides are about 1.0 foot higher than measured and the simulated minimum tides are slightly lower than measured. Figure D-34 shows two additional periods with tidal stage variations from the validation graphs. During the November 1997 period, the tidal stage ranged from about –1 to 4 feet msl. During the April 1999 period, the tidal stage ranged from about –1 to 3 feet msl. The simulated tidal stage variations during these two periods generally confirm that DSM2 matches the observed tidal stage variations quite well. The minimum tidal stage at the CCF station is about –1 foot msl.

For Old River at Bacon Island, at the USGS UVM tidal flow station, Figure D-35 shows the simulated and measured tidal stage and Figure D-36 shows the simulated and measured tidal flows. The simulated daily average tidal stage matches the measured tidal stage of between 1 and 4 feet msl. The simulated tidal stage variations during the February 1996 high-flow event match the measured tidal stage data very well, although the simulated high tides are about 0.5 foot higher than measured. The range of simulated net flows in Old River at Bacon Island is about –5,000 cfs (net upstream flow) to about 10,000 cfs. The simulated tidal flow variations during the February 1996 high-flow event match the measured tidal flows well, with a range of –15,000 to 10,000 cfs before the high flow and –10,000 to 10,000 cfs during the peak flow.

For Middle River at Bacon Island, at the USGS UVM tidal flow station, Figure D-37 shows the simulated and measured tidal stage and Figure D-38 shows the simulated and measured tidal flows. The simulated daily average tidal stage matches the measured tidal stage of between 1 and 4 feet msl. The simulated tidal stage variations during the February 1996 high-flow event match the measured stage data very well, although the simulated high tides are about 0.5 foot higher than measured. The range of simulated net flows in Middle River at Bacon Island is about –5,000 cfs (net upstream flow) to about 10,000 cfs. The simulated tidal flow variations during the February 1996 high-flow event match the measured tidal flows well, with a range of –15,000 to 10,000 cfs before the high flow and –10,000 to 10,000 cfs during the peak flow. The similarity of the tidal flows in Old and Middle River is remarkable. The calibrated DSM2 is properly simulating this nearly equal division of net and tidal flows between Old River and Middle River channels.

For Grant Line Canal at Tracy Boulevard Bridge, Figure D-39 shows the simulated and measured tidal stage and Figure D-40 shows the simulated and measured tidal flows. The simulated daily average tidal stage with the new calibration now matches the measured tidal stage of 6 feet at a flow of 15,000 cfs. The tidal stage variations during the February 1996 high-flow event match the measured tidal stage data reasonably well. The range of simulated net flows in Old River at the Tracy Boulevard Bridge is about 0–20,000 cfs. Most of the flow entering the south Delta from the head of Old River diversion from the San Joaquin River flows down the Grant Line Canal. The simulated tidal flows are somewhat irregular, with a pulse flood tide flow and a more steady ebb tide flow. During the February 1996 high-flow event, the tidal flows varied from 2,500 to 7,500 cfs.

The calibrated DSM2 appears to provide accurate simulations of tidal stage and tidal flow variations within the south Delta channels. The potential effects from the SDIP alternatives can be reliably evaluated by comparing the results from DSM2 simulations of the alternatives and the baseline conditions.

Tidal Hydraulics in the Delta

This section provides:

- a basic understanding of tidal dynamics (i.e., how tides work in the Delta),
- a general review of the simulated tidal hydraulics at selected sites throughout the Delta,
- a detailed review of simulated tidal hydraulics of the south Delta channels, and
- the simulated tidal effects of CVP Tracy and SWP Banks pumping as well as of the Vernalis Adaptive Management Plan.

Introduction to Tidal Dynamics

Differential gravitational forces between the earth and the moon create tides in the earth's oceans. Because estuaries have open connections to oceans, tidal flows propagate into estuaries. The location and morphology of an estuary influence the type of tide. Figure D-41 illustrates the three general types of tides:

- A *diurnal tide* has one high and one low tide per lunar day (24 hours 50 minutes). This type of tide occurs in the Gulf of Mexico and along the coast of Southeast Asia.
- A *semidiurnal tide* has two high and two low tides of similar amplitude per lunar day. This type of tide occurs along the Atlantic Coast of the United States.
- A *mixed tide* has two high and low tides per lunar day, but the amplitude of the high and low tides differ from one another. Mixed tides are typical of tides that occur on the Pacific Coast of the United States. The Delta has a mixed tide.

Although the gravitational effects of the moon are the main source of tidal amplitude, the gravitational effect of the sun also affects the amplitude (Figure D-42). The maximum tidal range, known as a spring tide, occurs during new and full moons (Figure D-43). The minimum tidal range, known as a neap tide, occurs during the quarter phases of the moon. Though the moon has a greater effect than the sun on tides, the magnitudes of the spring and neap tides vary throughout the year because of the changing distance between the earth and the sun. The tilting of the earth relative to the sun also influences the amplitude of tides. For example, in the Bay, the maximum tidal amplitudes occur during May and June, when the Northern Hemisphere is tilted toward the sun, and the minimum tidal amplitudes occur during November and December, when the Northern Hemisphere is tilted farthest away from the sun.

Tides at Martinez

The Bay system includes the Suisun, San Pablo, and South Bays. The Bay has a surface area of about 400 square miles at mean tidal stage. Most of its shoreline has a mild slope, which creates a relatively large intertidal zone. The volume of water in the Bay changes by about 21% from mean higher-high tide to mean lower-low tide. The overall average depth of the Bay is only about 20 feet, with the central Bay averaging 43 feet and the south Bay averaging 15 feet. The Bay is surrounded by about 130 square miles of tidal flats and marshes. The outlet of the Bay at Golden Gate Bridge is located approximately 46 miles from Chipps Island, the assumed boundary between the Delta and Suisun Bay.

Average net Delta outflow into Suisun Bay, as measured at Chipps Island, is about 20,000 cfs, or about 15 million acre-feet per year. Average natural freshwater inflow to the Delta varies by a factor of more than 10 between the highest flow month in winter or spring and the lowest flow month in fall. During summer months of critically dry years, net Delta outflow is regulated to remain at about 3,000 cfs. Stream flow is highly seasonal, with more than 90% of the annual runoff occurring during November–April.

Upstream of the central Bay is San Pablo Bay and the Carquinez Strait. The Carquinez Strait separates San Pablo Bay from Suisun Bay and the Delta. Martinez, at the upstream end of Carquinez Strait, is used as the DSM2 tidal boundary for the Delta. North of Suisun Bay lies the Suisun Marsh, an extensive mosaic of 80,000 acres of tidal channels and partially controlled tidal marshlands. Suisun Bay is the area where the salinity gradient, caused by the tidal mixing of fresh water and salt water, is typically most pronounced.

Adjusted Astronomical Tide

In past modeling studies, a monthly time-step for inflows and a repeating 25-hour tidal fluctuation pattern was used to represent the general tidal flows in the Delta channels.

In the 16-year DSM2 modeling studies of October 1975–September 1991 for SDIP impact assessment, historically-based tidal stage data were specified every 15-minutes at Martinez in order to represent both the diurnal mixed tidal pattern and the 14-day spring-neap tidal fluctuations. Since there are gaps in the observed tidal stage at Martinez, a technique was used to fill in these gaps using the astronomical tide and observed data from nearby locations. Missing historical Martinez stage data were filled using an astronomical stage forecast at Martinez, which was then modified or “adjusted” using observed historical stage from San Francisco and Mallard Island. The resulting 15-minute continuous time series of primarily historical Martinez stage data with missing data filled with adjusted astronomical data is referred to as an Adjusted Astronomical Tide. Since the Adjusted Astronomical Tide is based on historical data, it represents the diurnal, spring-neap, and seasonal variations in the tidal stage at Martinez. The Adjusted Astronomical Tide was specified as the downstream stage boundary condition at Martinez for all of the DSM2 simulations conducted for SDIP impact analysis.

Tidal Flows

Tidal flows are a major component of the hydrodynamics of an estuary. As the incoming, or flood, tide propagates upstream, the water surface elevation rises. The amplitude of the flood tide and thus the amount of rise in the water surface elevation decreases as the tide propagates upstream. Because tidal flows are a dynamic propagation of a wave, high and low tides do not occur at all locations in the estuary at the same time. When high tide is reached at a particular location, the flow slows and the tide begins to ebb or recede toward the ocean. During the ebb tide, the water surface elevations fall as the tidal flows recede. Near the time of slack tides, as the tidal flows shift between a flood tide and an ebb tide, parts of the estuary can be experiencing rising water of a flood tide while water surface elevations at other locations are still falling on an ebb tide.

Tidal Stage–Velocity Relationship

In an estuary, there is a direct relationship between tidal-induced changes in stage (water surface elevation) and water velocities (Figure D-44). As the tide enters an estuary on a rising or flood tide, the water velocity and stage increase. About halfway through the flood tide, the rate of tidal stage change is greatest, so the tidal flow and velocity are also at maximum values. As the rate of tidal stage change decreases, the tidal flow and velocity also decrease. At high tide, the tidal stage reaches its maximum height, and shortly after the tidal stage reaches its maximum value, the tidal flow and velocity decrease to zero (slack tide) and reverse direction as the ebb tide begins. The tidal flow and velocity increases as the tidal water level decreases on the ebb tide. About halfway through the ebb tide, the water velocity reaches a maximum and begins to decrease. The tidal water level continues to decline until low tide. At low tide, the flow again reverses, and the velocity again passes through zero at slack tide.

Summary of DSM2 Delta Tidal Hydraulics

The tidal stage fluctuations in the Pacific Ocean at the Golden Gate Bridge propagate upstream to the boundary for DSM2 at Martinez, located at the downstream end of Suisun Bay. Figure D-45 shows the tidal stage fluctuations at Martinez for August 1997, which is considered to be representative of the normal range of monthly tidal variations at Martinez.

Figure D-46 shows the corresponding simulated tidal flows at Martinez for August 1997. As the tidal stage rises at Martinez, the small water surface slope produces a large tidal flow into the Delta. This flood-tide flow begins to move upstream into all of the Delta channels. The tidal flow moves upstream into all the Delta channels and generally fills them until the high-tide slack water. There is a delay of several hours in the timing of high tides (and low tides) at upstream locations because the tidal flow acts like a slowly propagating wave.

The tidal volume upstream of a location is defined as the channel volume at high tide minus the channel volume at low tide. This volume is also called the *tidal prism volume*. It can be generally estimated as the upstream surface area times the tidal stage difference between the high tide and low tide. Because the Delta tides are mixed (i.e., of unequal magnitude), the tidal prism should be averaged between the two flood periods each day. The tidal volume varies each day as the tides vary but can be approximated from the average low tide and the average high tide.

The Delta surface area upstream of the Martinez model boundary at the average low-tide elevation (about –1 foot msl) is about 80,000 acres, and the surface area at average high-tide elevation (about 3 feet msl) is about 84,000 acres. The actual tidal prism volume can be calculated as the sum of the simulated flood-tide flow moving past a location during each flood-tide period. For example, the sum of the simulated floodflows moving upstream at Martinez during August 1997 was 349,000 acre-feet per day. The sum of the simulated ebb-tide flows moving downstream during August 1997 was 361,000 acre-feet per day. These flows would be identical except for the river outflow of about 12,000 acre-feet per day (equivalent to about 6,000 cfs) during August 1997. The average tidal exchange flow of 355,000 acre-feet per day indicates that a large volume of water fills the Delta channels twice each day, representing an average tidal prism depth of 2.2 feet covering the 82,000 acres of Delta channels and bays upstream of the Martinez boundary.

Calculation of Tidal Flows

The tidal flows are simulated in DSM2 just like river flows or canal flows using the Manning's equation, which relates the water velocity to the water surface slope and the hydraulic radius of the channel:

$$\text{Velocity}(\text{fps}) = \frac{1.49}{n} \times \sqrt{slope} \times R^{\frac{2}{3}}$$

$$\text{Flow (cfs)} = \frac{1.49}{n} \times flow\, area \times \sqrt{slope} \times R^{\frac{2}{3}}$$

where *n* is the Manning's friction factor (generally about 0.03 in the Delta channels), *slope* is the water surface slope, and *R* is the hydraulic radius (i.e., flow area/channel perimeter). The hydraulic radius is slightly less than the average channel depth.

Only very small slopes are needed for the gravitational force acting on the water volume to produce very large flows. To illustrate this fact, the Manning's equation can be used to estimate the flow capacity for the California Aqueduct from the Bethany Forebay above the SWP Banks facility to the O'Neil Forebay below the San Luis Reservoir.

The California Aqueduct is a trapezoid that is about 40 feet wide at the bottom with side slopes of 1.5:1 and a design depth of about 30 feet. The top width is 130 feet, the conveyance area of the canal is 2,550 square feet when full, and the hydraulic radius is about 17.2 feet (i.e., 2,550-square-foot area/148-foot perimeter), so $R^{2/3}$ is about 6.7. The aqueduct elevation drops from 244 feet msl at the Bethany Forebay to about 225 feet msl at the O'Neil Forebay over a distance of about 63 miles, so the water surface slope is just 4 inches per mile (0.00006). The Manning's *n* coefficient for smooth concrete is about 0.018, so the aqueduct is calculated to convey a flow of about 10,000 cfs when full. Similar calculations reveal that 7,500 cfs could be conveyed with a canal depth of 25 feet, and 5,000 cfs could be conveyed with a canal depth of 20 feet. A series of 12 check dams (i.e., radial gates) along the canal is used to regulate the flow independently of the water depth in the canal, as well as control the aqueduct flows during periods when the pumping rate at the SWP Banks facility is changing. The design velocity in the canal is about 4 feet per second (feet/sec).

The DMC between the CVP Tracy facility and the Mendota Pool along the San Joaquin River (115 miles long) was built with a similar hydraulic design. The DMC begins at an elevation of 195 feet msl and ends at an elevation of 155 feet msl, so the slope is only 4.2 inches per mile. The average slope is therefore 0.000066, and the Manning's *n* coefficient is estimated to be slightly higher than for concrete (0.025) because the canal is unlined in sections. The DMC has a bottom width of 100 feet, with side slopes of 3:1 and a design depth of 14.3 feet. The conveyance area is about 2,045 square feet, the hydraulic radius is 10.75 feet, and $R^{2/3}$ is 4.9. The average capacity of the DMC is therefore calculated to be about 4,850 cfs at a velocity of 2.4 feet/sec. At the downstream end of the DMC, the canal dimensions are smaller, and the capacity is about 3,200 cfs at the Mendota Pool.

Simulated Tidal Hydraulics of the Delta

Results from DSM2 for the 16-year planning period of 1976–1991 at key locations throughout the Delta will be described in the following sections to illustrate the range of tidal hydraulic conditions in the Delta. Two graphs will show the monthly range of tidal stage and tidal flows at each selected station for the 16-year period that is used to represent the full range of expected hydrologic conditions in the Delta. The 16-year period simulated with DSM2 is water year 1976 (October 1975) through water year 1991 (September 1991). The 15-minute results for each month are sorted as cumulative values for each month and summarized as the average tidal stage or flow and the percentiles of tidal stage or flow (i.e., 0 [minimum], 10th, 20th, 30th, 40th, 50th [median], 60th, 70th, 80th, 90th, and 100th [maximum] percentile tidal stage or flow). The first two days of each month are ignored to allow the hydraulic modeling to stabilize following the monthly changes in Delta inflow and exports obtained from the CALSIM modeling results.

The minimum, 10th percentile, average, 90th percentile, and maximum stage values at Martinez are shown in Figure D-47. Only in a few months are the minimum and maximum tidal stages influenced by high flows through the Delta. The highest tidal stage is generally between 4 and 5 feet msl. The 90th percentile tidal stage values are about 3 feet, suggesting that the Martinez tidal stage is at or above 3 feet msl for about 2–3 hours each day (during the higher-high tide). The average tidal stage is about 1 foot msl. The 10th percentile tidal stage is usually between –2 feet msl and –1 foot msl. This range represents the normal low tides that occur once each day (for about 2–3 hours). The minimum tides each month are generally between –3 and –2 feet msl. The lowest tides simulated during the 16-year period were in December and January 1988. The possible causes of these exceptionally low tides of –3.75 feet msl have not been investigated. Tidal Stage and Flows at Martinez

Figure D-48 shows the tidal flows at Martinez as simulated by DSM2 for the 16-year period. The average tidal flow (net Delta outflow) is very close to 0 cfs on this tidal flow graph, except during exceptionally high outflow months in a few years. The 90th percentile downstream (ebb tide) flows are generally about

500,000 cfs, and the maximum downstream tidal flows in almost all months are between 600,000 and 750,000 cfs. The 10th percentile upstream (flood-tide) flows are generally about –500,000 cfs, and the minimum (highest upstream) tidal flows at Martinez are between –600,000 and –700,000 cfs. These flows are very large tidal flows moving into and out of the Delta channels twice each day.

Figure D-49 shows the simulated tidal velocity at Martinez for the 16-year period. The tidal velocity is what the model estimates as a function of the water surface slope. The 90th percentile tidal velocity (i.e., during ebb tide) is about 2.75 feet/sec, and the 10th percentile tidal velocity is –2.25 feet/sec (i.e., during flood tide). The tidal velocity is therefore generally less than 3.0 feet/sec at the Martinez tidal boundary.

Because the tidal flow moves into and out of the Delta channels twice each day, the average tidal excursion between low tide and high tide can be estimated from these tidal velocities. The 10th percentile and 90th percentile tidal velocities represent estimates of the average flood and ebb tide velocities that will be sustained for about 4 hours during each tidal cycle (with 1–2 hours of slack tide). The average tidal excursion can therefore be estimated as the average tidal velocity of about 2.5 feet/sec (1.7 mph) times the 4 hours of sustained flow, or about 6.8 miles. The tidal excursions are somewhat variable, with a typical range of 6–8 miles. The upstream tidal excursion is less because the cross- section in Suisun Bay is larger than the cross-section at Martinez, so the tidal velocity is slower in Suisun Bay. This range represents the distance that an orange (or fish larvae) would move between a high tide and a low tide.

The water surface slope that is required to drive these tidal velocities (and flows) can be quickly estimated from the Manning's equation. The hydraulic radius for this channel is calculated from the cross section to be about 46 feet, and $R^{2/3}$ is 12.8. The channel width is about 1 mile, and the Manning's *n* coefficient has been calibrated to be 0.022. The required slope for a tidal velocity of 3 feet/sec is therefore 0.000012 feet/feet $[(3*(0.022/1.49)*(12.8)^2]$, which is just 0.75 inch per mile. A water surface slope of less than 1 inch per mile is therefore all that is required in this very wide and deep section of the Delta to produce the observed tidal velocity of 3 feet/sec with a corresponding tidal flow of 700,000 cfs.

Tidal Stage and Flows at Chipps Island

Chipps Island is the traditional location for estimating Delta outflow because it is located downstream of the confluence of the Sacramento and San Joaquin Rivers. Chipps Island is located along the north side of the channel just west of Van Sickle Island and is part of the Suisun Marsh complex of islands and tidal channels. The monitoring for salinity and tidal stage has now moved across the channel to Mallard Slough because this location provides much more convenient access, but the location is still generally referred to as Chipps Island. Mallard Slough is one of the primary salinity monitoring locations for the X2 Delta salinity criteria. Chipps Island is located 47 miles upstream of the Golden Gate Bridge and 12 miles upstream of the Martinez DSM2 boundary.

Figure D-50 shows the monthly tidal stage range at Chipps Island for the 16-year period. The tidal stage ranges from about –2.5 to 4.5 feet msl during most months. The high tides are similar to those at Martinez. During periods of high outflow, there is a slight increase between Martinez and Chipps Island. The high tides are only about 0.1 foot lower at Chipps Island than at Martinez in most months. The 90th percentile monthly tide elevations are similar at Chipps Island and Martinez. The low-tide values are about 1 foot higher at Chipps Island than at Martinez. The 10th percentile monthly tides are about 0.5 foot higher, with a 10th percentile tidal stage of about –1 foot during most months. The 10th percentile monthly tide elevation will be used to represent the average low-tide elevation during the month. The extreme lowest-tide elevation will generally be about 1 foot below the 10th percentile monthly tide elevation in the western portion of the Delta.

Figure D-51 shows that the tidal flows at Chipps Island are about 300,000 cfs during the flood tide (10th percentile monthly flows of –300,000 cfs) and about 300,000 cfs during the ebb tide (90th percentile monthly flows of 300,000 cfs). These tidal flows at Chipps Island are less than the tidal flows at Martinez because some of the tidal flow at Martinez must fill the Suisun Bay and Suisun Marsh channels. The average (net flow) at Chipps Island is usually very small relative to the tidal flows.

The tidal flows at Chipps Island split and move upstream past Collinsville into the Sacramento River channels or move upstream past Antioch into the San Joaquin River channels. In the discussion below, the tidal flows in the Sacramento River channels are shown first, and then the tidal flows in the San Joaquin River channels and the south Delta channels are described.

Tidal Stage and Flows at Rio Vista

Rio Vista is located on the Sacramento River at the confluence of Cache Slough and the Yolo Bypass and Sacramento Deep Water Ship Channel. Steamboat and Sutter Sloughs also join Cache Slough, so the entire flow of the Sacramento River (except the flow diverted into Georgiana Slough and the DCC) passes Rio Vista. Rio Vista is located about 28 miles upstream of Martinez and 16 miles upstream of Chipps Island, so the tidal range is slightly less and the tidal flows are much less than at Martinez.

Figure D-52 shows the monthly tidal stage range at Rio Vista for the 16-year period. The tidal stage ranges from about –2.5 to 4.5 feet msl during most months. The high tides are similar to those at Martinez. During periods of high outflow, there is about a 1-foot increase between Martinez and Rio Vista high-tide elevations. The tidal stage does not increase by much during high outflows (including Yolo Bypass flows) because the Sacramento River channel at Rio Vista is about 0.5 mile wide. The high tides are about 0.5 foot higher at Rio Vista than at Martinez in most months, indicating that there is a downstream water surface gradient between Rio Vista and Martinez. The 90th percentile monthly tide elevations are usually about 3 feet msl at Rio Vista and at Martinez.

The low-tide values are –2 feet msl, which is about 1 foot higher than at Martinez. The 10th percentile monthly tides are about 0.5 foot higher than at Martinez, with a 10th percentile monthly tidal stage of about –1 foot during most months. The monthly lowest-tide elevation is generally about 1 foot below the 10th percentile monthly tide elevation.

Figure D-53 shows that the tidal flows at Rio Vista are about 70,000 cfs during the flood tide (10th percentile monthly flows of –75,000 cfs) and about 75,000 cfs during the ebb tide (90th percentile monthly flows of 75,000 cfs). These tidal flows in the Sacramento River at Rio Vista are much less than at Chipps Island because there is a much smaller surface area upstream of Rio Vista. The average (net flow) at Rio Vista is usually less than 10,000 cfs and is small relative to the tidal flows.

Tidal Stage and Flows at Freeport

The Sacramento River is tidally influenced all the way upstream to Sacramento. The tidal variation at Freeport, located 34 miles upstream of Rio Vista (62 miles above Martinez and 97 miles upstream from the Golden Gate Bridge), is still about 3 feet. The tidal flows are only about 1,000 cfs and are relatively small compared to the net river flow of 5,000–25,000 cfs.

Figure D-54 shows the monthly tidal stage range at Freeport for the 16-year period. The tidal stage during months with low net river flow ranges from about 1 foot msl to 4 feet msl during most months. The Freeport tidal stage increases to almost 18 feet as the river flow increases to 80,000 cfs. The tidal stage variation is greatly reduced during these months with higher river inflow. The high tides are about 1 foot higher than at Rio Vista during low river flow months. The 90th percentile monthly tide elevations are usually between 3 and 4 feet msl at Freeport. The maximum monthly tide is about 1 foot higher than the 90th percentile monthly tide. The low-tide values are between 0 and 2 feet msl, which is 3–4 feet higher than at Rio Vista. The 10th percentile monthly tides are about 0.5 foot higher than the minimum tide in most months.

Figure D-55 shows that the tidal flows at Freeport are only about 5,000 cfs less than the river flow during flood tide and only about 5,000 cfs more than the net river flow during ebb tide. These tidal flows in the Sacramento River at Freeport are even less when the net river flow increases to more than 10,000 cfs. A USGS tidal flow station was installed at Freeport in 1980 and has been used to calibrate DSM2 in this portion of the Sacramento River.

Figure D-56 shows the tidal stage–discharge "rating" curve for the Sacramento River at Freeport. As the Sacramento River flow increases to the flood channel capacity of 80,000 cfs (the remainder of the Sacramento River flow is diverted into the Yolo Bypass), the tidal stage increases steadily to about 18 feet msl. This increase is a very unusual rating curve for a river station and indicates the trapezoidal shape of the Sacramento River levees downstream of Sacramento. Most river stations have a decreasing slope in the tidal stage discharge curve as the river width increases more rapidly at higher tidal stages. Figure D-56 also shows the tidal stage at Walnut Grove, located between the DCC and the head (beginning) of Georgiana Slough, and indicates that the river stage has decreased to about half of the stage at Freeport during higher flow periods. This reduced river stage is caused in part by the diversions of some of the flow into Sutter and Steamboat Sloughs and because Walnut Grove is 20 miles downstream. The corresponding stage at Rio Vista is almost always controlled by tidal stages, except for the highest flows, when the average stage is 2–3 feet msl instead of the average tidal stage of 1 foot msl stage during low-flow periods.

Sacramento River Diversions into Sutter Slough and Steamboat Slough

The net river flows that enter the Delta are distributed into the many sloughs and side channels that make the Delta channel network so interesting. These net channel flows and channel flow splits are almost independent of the tidal flows and can be thought of as a net flow pattern that is superimposed on the basic tidal flows in the Delta. From the Sacramento River side of the Delta, the first possible diversion from the Sacramento River channel occurs at Sacramento, where the flow from the Sacramento and American Rivers is diverted into the Yolo Bypass channel through the Sacramento Weir.

The Sacramento Weir is a gated low dam along the west bank of the Sacramento River about 3 miles upstream from its confluence with the American River. When flood stages in the Sacramento River at the I Street Bridge reach 27.5 feet msl (corresponding to a flow of about 96,000 cfs), the weir gates are manually opened and flows are diverted into the Sacramento Bypass, which joins the Yolo Bypass. The Sacramento Weir is a 1,850-foot-wide weir (48 gates) with a crest elevation of 17.2 feet msl (corresponding to a river flow of 56,000 cfs). The diversion flow fraction depends on the Sacramento River stage and the number of gates that are opened. The Sacramento Weir diversion limits the Sacramento River flow at Freeport to a maximum of about 100,000 cfs, with the highest monthly average during the 16-year DSM2 simulation period being about 80,000 cfs.

Within the Delta, the first Sacramento River diversion is on the right bank (looking downstream) into Sutter Slough, opposite Courtland. Steamboat Slough, the favorite route for steamboats between San Francisco and Sacramento, is also a right-bank diversion and is located 1.25 miles downstream from Sutter Slough. All of the diverted water and fish are transported through Sutter and Steamboat Sloughs or Miner Slough to Cache Slough, which rejoins the Sacramento River at Rio Vista. These are well-shaded channels with excellent aquatic habitat conditions.

Figure D-57 shows the diversion of flow into Sutter and Steamboat Sloughs. The top figure shows the diversion of flow as a function of the Freeport flow. The bottom figure shows the diversion of flow as a fraction of the Freeport flow. As the Freeport flow increases, the diversion flow entering these sloughs increases, and the fraction of the flow diverted also increases as the Freeport flow increases to about 25,000 cfs. Sutter Slough diverts about 25% of the Freeport flow, and Steamboat Slough diverts about 20% of the Freeport flow at these higher flows. When the DCC gates are closed (always closed at Freeport flows of more than 25,000 cfs), about 10% more of the Sacramento River flow is diverted into these sloughs because the river stages at these slough diversions are slightly higher.

The Sutter Slough diversion fraction increases from about 20% at a river flow of 7,500 cfs to 25% at a flow of 20,000 cfs if the DCC is closed and from about 15% at a river flow of 7,500 cfs to 20% at a flow of 20,000 cfs if the DCC is open. Steamboat Slough diverts about 12.5% at a Sacramento River flow of 7,500 cfs and about 17.5% at a river flow of 20,000 cfs if the DCC is closed and about 5% less if the DCC is open.

Migrating fish (i.e., Chinook salmon, steelhead, American shad, striped bass) moving downstream in the 25–45% of the Sacramento River flow that is diverted into Sutter and Steamboat Sloughs have a relatively safe route through the Delta to Suisun Bay. These fish are much less likely to be diverted into the central Delta channels through the DCC and Georgiana Slough. Fish that enter the central Delta may have a lower survival because of increased predation losses and entrainment losses in agricultural diversions and the export pumping plants in the south Delta. DSM2 accurately simulates these channel diversions along the Sacramento River.

Sacramento River Diversions into Delta Cross Channel and Georgiana Slough

The DCC was constructed by Reclamation in 1951 as part of the CVP to allow more Sacramento River flow to move across the Delta toward the CVP Tracy facility for the DMC. The DCC was designed to increase the net flow in the San Joaquin River channel at Antioch, so that less salinity intrusion of Suisun Bay water would move upstream toward the Rock Slough intake to the Contra Costa Canal (CCC) and the CVP Tracy facility. The DCC was assumed to thereby reduce salinity intrusion during periods of low Delta outflow.

The DCC design capacity (at low Sacramento River flows) was 3,500 cfs. The DCC is a 1.25-mile-long channel that connects the Sacramento River to the Mokelumne River channel through Snodgrass Slough. The DCC has a bottom width of 210 feet, a top width of 366 feet, and a water depth of 26 feet, so that the cross-sectional area is about 7,500 square feet. There are two manually operated radial gates near the opening to the Sacramento River, just upstream of Walnut Grove. The two DCC gates are each 60 feet wide and 30 feet tall. The conveyance area is therefore about 3,000 square feet (assuming a water depth of 25 feet). The DCC gates are normally closed to prevent scouring around the gates when the Sacramento River flow is above 25,000 cfs, indicating a DCC diversion of about 6,000 cfs, with a velocity of about 2 feet/sec.

Georgiana Slough is located just downstream of the DCC and connects to the Mokelumne River channel near its mouth at the San Joaquin River.

Figure D-58 shows the diversions into the DCC and Georgiana Slough. The top figure shows the diversions as a function of the Freeport flow. The bottom figure shows the diversions as a fraction of the Freeport flow. As the Freeport flow increases, the diversion flows entering the DCC and Georgiana Slough increase, but the fraction of the flow diverted decreases as the Freeport flow increases to about 25,000 cfs. At Freeport flows above 25,000 cfs, the DCC is assumed to be closed to prevent localized scour at the gate structure, which was designed to operate safely only at lower Sacramento River flows.

The DCC diverts about 25% of the Freeport flow, and Georgiana Slough diverts about 15% of the Freeport flow at a Sacramento River flow of 20,000 cfs (with the DCC open). The diversion fractions increase at lower flows, and the DCC diverts about 33% and Georgiana Slough diverts about 22% at a Freeport flow of 7,500 cfs when the DCC gates remain open. A total of 50% of the Freeport flow is diverted into the Mokelumne River and central Delta channels at Sacramento River flows of less than 10,000 cfs with the DCC gates open. The DCC gates are closed during some months (February–May) for fish protection to reduce the fraction of migrating fish that enter the Mokelumne River and central Delta channels, where survival is assumed to be less. The Georgiana Slough diversions increase by about 5% of the Sacramento flow, but the net Sacramento River diversions are reduced by at least 25% when the DCC is closed at low river flows. This reduction is considered to result in substantial fish survival benefits for striped bass larvae and migrating juvenile fish (e.g., Chinook salmon).

The DSM2 simulation of the DCC gates includes partial closure and full closure in some months for fish protection. The DCC gates are assumed to be closed for the entire month if Freeport flow is greater than 25,000 cfs. The DCC gates are assumed to be closed 10 days in November, 15 days in December, and 20 days in January. The DCC is closed every day in February–May for fish protection and is closed 4 days in June. These closure requirements are part of the 1995 Bay-Delta WQCP and are specified in State Water Board D-1641 that regulates the CVP Tracy and SWP Banks facilities.

Figure D-59a shows the tidal flows in the DCC. The 10th percentile tidal flow in the DCC increases as the average flow into the DCC increases, but only at low Freeport flows (below 10,000 cfs) will the tidal flow during flood-tide periods leave the DCC channel and flow into the Sacramento River. The average tidal flow is about 3,000 cfs higher than the 10th percentile tidal flow, and the 90th percentile tidal flows are about 3,000 cfs higher than the average flow, suggesting that the normal tidal fluctuation in the DCC is about 3,000 cfs (above and below the net flow moving into the DCC).

Figure D-59b shows the tidal flows in Georgiana Slough. The tidal flows are about 500 cfs lower in Georgiana Slough when the DCC is open. The 10th percentile tidal flows are about 1,500 cfs lower than the average flow, and the 90th percentile tidal flows are about 1,500 cfs higher than the average flow when the Sacramento River flow is less than 20,000 cfs. As the Sacramento flow increases, the tidal variation in Georgiana Slough becomes less because the stage is higher and the tidal influence on stage and flow lessens. Nevertheless, there is still a tidal fluctuation of 500 cfs above and below the average Georgiana flow of 11,000 cfs when the Sacramento River flow is 80,000 cfs.

Tidal Flow and Net Flow in Threemile Slough

Figure D-60a shows the tidal flows in Threemile Slough, which is the final connecting channel between the Sacramento River and the San Joaquin River prior to their confluence near Collinsville. The tidal flows are very large through this relatively small channel, which winds between Sherman Island on the west and Twitchell Island and Brandon Island on the east. The 10th percentile tidal flows are about –31,000 cfs (from the Sacramento River to the San Joaquin River). The 90th percentile tidal flows are about 26,000 cfs. The net flow is generally only about –1,000 to –2,000 cfs (from the Sacramento River to the San Joaquin River). The corresponding 10th percentile and 90th percentile tidal velocities are about 3 feet/sec.

Figure D-60b indicates that the net flow in Threemile Slough from the Sacramento River to the San Joaquin River can be estimated as:

> Threemile Slough Flow = 3% Rio Vista Flow – 16% San Joaquin Flow + 1,250 cfs

where San Joaquin River flow is the flow moving past Threemile Slough (i.e., Delta outflow minus the Rio Vista flow).

For example, if the Rio Vista flow was 10,000 cfs and the San Joaquin River flow at Threemile Slough was 2,500 cfs (i.e., Delta outflow of 12,500 cfs), the Threemile Slough flow would be about 1,150 cfs. The Threemile Slough net flow increases slowly with increased Sacramento River flow and is reduced by higher San Joaquin River flow. The net flow will become zero only when the San Joaquin River flow is at least 10,000 cfs and the Rio Vista flow is less than 12,500 cfs (a very rare condition).

Tidal Flow and Net Flow in Montezuma Slough

Montezuma Slough is the main channel of the Suisun Marsh that connects with the Sacramento River just downstream of Collinsville. Collinsville is another important salinity monitoring station located about 16 miles upstream of Martinez. There is usually a tidal flow in Montezuma Slough that moves into the Sacramento River during flood-tide periods and moves into Suisun Marsh channels during ebb-tide periods. The Montezuma Slough salinity control gates (MSSCG) were constructed by DWR in 1989 to control (reduce) the flood-tide flows and shift the net flows into the Suisun Marsh when salinity in the Suisun Marsh channels was relatively high during the fall months. DSM2 assumes that the gates operate (close) just after low tide as the flood-tide flow begins to move Suisun Marsh water into the Sacramento River. The gates then open on high tide and allow the ebb-tide flows to move Sacramento River water into the Suisun Marsh channels. These tidal gate operations are scheduled to provide a net inflow of Sacramento River water for Suisun Marsh salinity control. DSM2 assumes that the gates operate during October–May.

Figure D-61 shows the tidal flow into Montezuma Slough for the 16-year DSM2 simulation period. The tidal flows when the gates are open range from a 10th percentile tidal flow of –5,000 cfs (flood-tide flow from Suisun Marsh) to a 90th percentile tidal flow of about 4,000 cfs (ebb-tide flow from Sacramento River). The net flow when the gates are open is very small. When the gates are operated, the ebb-tide flows remain about the same, but the flood-tide flows are reduced to almost zero. The tidal gate operation provides an average inflow of about 1,750 cfs from the Sacramento River to the Suisun Marsh tidal channels.

This 1,750-cfs net flow diversion from the Sacramento River into Suisun Marsh channels can be about half of the total Delta outflow during the late summer and fall in low-flow years. The possible effects of these MSSCG operations on salinity at Collinsville and other upstream locations in the Delta have not been directly evaluated.

Tidal and Net Flow at Antioch

Antioch is located 4 miles above the mouth of the San Joaquin River (near Collinsville) and about 19 miles upstream of Martinez. The tidal stage variations at Antioch are slightly reduced compared to the tidal variations at Martinez. The small surface water slope between Martinez and Antioch (of less than 1 foot) is the driving force producing the tidal flows at this location.

Figure D-62 shows the monthly tidal stage range at Antioch for the 16-year period. The tidal stage ranges from about –2 to 4 feet msl during most months. The high tides are similar to those at Martinez. During periods of high outflow, there is a slight increase between Martinez and Antioch. The high tides are about 0.25 foot lower at Antioch than at Martinez in most months. The 90th percentile monthly tide elevations are similar at Antioch and Martinez. The low-tide values are about 1 foot higher at Antioch than at Martinez. The 10th percentile monthly tides are about 0.5 foot higher, with a 10th percentile tidal stage of about –1 foot during most months.

Figure D-63 shows that the tidal flows at Antioch are about 150,000 cfs during the flood tide (10th percentile monthly flows of –150,000 cfs) and about 150,000 cfs during the ebb tide (90th percentile monthly flows of 150,000 cfs). These tidal flows in the San Joaquin River at Antioch are about half of the tidal flow passing Chipps Island because about half of the Delta channel surface area is located upstream of Antioch on the San Joaquin River and connecting channels. The average (net flow) at Antioch is usually very small relative to the tidal flows. The net flow at Antioch can be negative during periods when the DCC is closed and export pumping is high.

Tidal and Net Flows in Dutch Slough

Dutch Slough connects the San Joaquin River channel upstream of Antioch through Big Break to Franks Tract and Old River. Dutch Slough is on the south side of Jersey and Bethel Islands. Dutch Slough is the most downstream channel connecting the San Joaquin River channel with the south Delta channels (channels located south of the San Joaquin River).

Sand Mound Slough connects Dutch Slough with Rock Slough on the west side of Holland Tract. Sand Mound Slough has flap gates to prevent upstream movement of water from Dutch Slough to Rock Slough. These gates were installed to reduce Rock Slough salinity when the CCC and pumping plants, with a diversion capacity of 350 cfs, were constructed by the CVP in 1948.

Figure D-64 shows that the tidal flows in Dutch Slough are about 8,000 cfs during flood tide and about 8,000 cfs during ebb tide. These tidal flows in Dutch Slough correspond to channel velocities of about 2 feet/sec. The net flows in Dutch Slough are usually slightly negative, indicating that some (generally less than 200 cfs) of the San Joaquin River water from upstream of Antioch moves upstream toward Franks Tract and Old River.

Tidal and Net Flows in False River and Fisherman’s Cut

False River and Fisherman’s Cut connect the San Joaquin River with Franks Tract. False River is a wide channel between Jersey and Bradford Islands. Fisherman’s Cut is a narrow channel between Bradford Island and Webb Tract.

Figure D-65 shows the tidal flows in False River. The tidal flows in False River are about 45,000 cfs during ebb tide and about –45,000 cfs during flood tide. The net flows are generally less than 1,000 cfs and are usually positive, indicating a net flow from Franks Tract to the San Joaquin River. Even during periods of high pumping at the CVP Tracy and SWP Banks facilities, False River net flows do not reverse direction but continue to be positive from Franks Tract to the San Joaquin River. This lack of reversal suggests that there is a net circulation pattern of about 1,000–2,500 cfs around Webb Tract. Some net tidal flow apparently moves into Franks Tract from the mouth of Old River but leaves Franks Tract through the False River channel.

Figure D-66 shows the tidal flows in Fisherman’s Cut. Fisherman’s Cut is a relatively small channel with tidal flows of about 4,000 cfs (10th percentile flow of –4,000 and 90th percentile flow of 4,000 cfs). The net flow of less than 500 cfs is positive, indicating a net flow from the San Joaquin River to False River, so the Fisherman's Cut flow returns to the San Joaquin River through the False River.

Tidal Stage and Flows in San Joaquin River at San Andreas Landing

Figure D-67 shows the range of tidal stage in the San Joaquin River just downstream of the Mokelumne River mouth (at San Andreas Landing) for the 16-year period. The tidal stage (10–90th percentile stage) ranges from about –0.5 to 2.5 feet msl during most months. During periods of high San Joaquin River flow, tidal stage values increase slightly. The maximum high tides are about 0.5 foot lower at San Andreas Landing than at Antioch in most months. The 90th percentile monthly tide elevations are about 0.5 foot lower than at Antioch, but the average tide elevation of 1 foot msl is the same as at Antioch. The minimum low-tide values of about –1.5 feet msl are about 0.5 foot higher than at Antioch. The 10th percentile monthly tides of about 0.5 foot msl are about 0.5 foot higher than at Antioch. The simulated tidal fluctuations are therefore reduced as the tide propagates upstream from Antioch to San Andreas Landing.

Figure D-68 shows that the tidal flows at San Andreas Landing are about 100,000 cfs during flood tide (10th percentile monthly flows of –150,000 cfs and 90th percentile monthly flows of 100,000 cfs). These tidal flows in the San Joaquin River at San Andreas Landing are less than the tidal flow passing Antioch because about one-third of the San Joaquin River channel surface area is between these two stations. The average (net flow) at San Andreas Landing is usually about 0 cfs because most of the Mokelumne River outflow (from the DCC and Georgiana Slough) moves across the San Joaquin River into the Old River channel. The net flow at San Andreas Landing can be negative (maximum monthly reverse flow of –4,000 cfs simulated) during periods when the DCC is closed and export pumping is high.

Tidal and Net Flows in Mokelumne River Channels

Figure D-69 shows the tidal flows at the Mokelumne River mouth, located just upstream of San Andreas Landing. The tidal flows range from –15,000 to 20,000 cfs, with a net flow of about 3,000–6,000 cfs in most months. Most of this flow is diversions from the Sacramento River that have moved through the DCC and Georgiana Slough. Most of this Mokelumne River outflow moves across the San Joaquin River and enters the Old River.

Some of the Mokelumne River flow (including Georgiana Slough and DCC flow) moves through the adjoining channels north of the San Joaquin River upstream (i.e., Potato, Little Potato, Disappointment, and Fourteenmile Sloughs) and enters the San Joaquin River upstream of the mouth of the Mokelumne River. Analysis of the simulated net flows indicates that about 75% of the total Mokelumne River flow enters the San Joaquin River channel at the mouth of the

Mokelumne River. About 20% of the total Mokelumne River flow moves through Little Potato Slough and joins the San Joaquin River channel at Medford Island, opposite the Middle River Mouth and Columbia Cut. Only small net flows move through Potato, Disappointment, and Fourteenmile Sloughs.

Figure D-70 shows the tidal flows at the mouth of Potato Slough and the mouth of Little Potato Slough. Potato Slough joins the San Joaquin River just 1 mile upstream of the Mokelumne River mouth. Potato Slough flows along the north side of Venice Island and connects to Little Potato Slough. Little Potato Slough flows along the east side of Venice and Bouldin Islands and connects with the South Fork Mokelumne River channel at the northeast corner of Bouldin Island.

The range of tidal flows in Potato Slough is constant. Regardless of the San Joaquin River flow or the Mokelumne River flow, the Potato Slough tidal flows fluctuate between about 12,000 cfs during the flood tide (10th percentile tidal flow of –12,000 cfs) and 11,000 cfs on the ebb tide (90th percentile tidal flow of 11,000 cfs). The mean flow is almost always about 0 cfs, unless the San Joaquin River flow is high. When the San Joaquin River flow is high, Potato Slough (as well as Little Potato Slough) acts like a branch of the San Joaquin River flowing around Venice Island.

The range of tidal flows in Little Potato Slough is much more variable. The average tidal flow is about 1,000 cfs toward the San Joaquin River from the Mokelumne River channels, but the magnitude of the average tidal flow varies from about 500 to 1,500 cfs. Only during 1983, with very high San Joaquin River flows, did the average tidal flow become negative. The tidal range is about 3,000 cfs, with ebb-tide flows of 2,000–3,000 cfs flowing into the San Joaquin River channel and flood-tide flows of 0–1,000 cfs flowing from the San Joaquin River into the Mokelumne River channels.

The tidal flow at the mouth of Disappointment Slough ranges from about -5,000 cfs during flood tide and 5,000 cfs during ebb tide, with a net flow of just 500 cfs (5% of the total Mokelumne River flow). The tidal flow at the mouth of Fourteenmile Slough is only about –500 cfs during flood tide and 500 cfs during ebb tide. The net flow in Fourteenmile Slough is about 0 cfs.

Tidal and Net Flows at the Mouth of Old River

Figure D-71 shows the tidal and net flows at the mouth of the Old River channel, located upstream of San Andreas Landing and the mouth of the Mokelumne River. The mouth of Old River is the major connection into the south Delta channels. The tidal flows range from about –20,000 cfs (10th percentile flows) during flood tide to about 10,000 cfs (90th percentile flows) during ebb tide, with a net flow of between –3,000 and –5,000 cfs. Some of this negative net flow is caused by the tidal circulation pattern that apparently moves into Franks Tract from the Old River mouth and exists from Franks Tract through False River. Net flows at the mouth of Old River never become positive, even during high San Joaquin River flows.

The remainder of the net flow at the Old River mouth is determined by the total exports and the net agricultural diversions in the south Delta (assumed in DSM2 [DICU module] to be about 40% of total net Delta depletions). If the head of Old River flow from the San Joaquin River is less than the combined pumping and south Delta net diversions, the net flow into Old and Middle River channels must be negative to make up the difference. The remaining south Delta exports and diversions must move through the Old River mouth, the Middle River mouth (including Columbia Cut), Turner Cut, or Dutch Slough.

The simulated Dutch Slough net flows are usually negative (toward Franks tract) but are generally less than 500 cfs and supply only about 5% of the net south Delta exports and diversions. Analysis of the DSM2 results indicates that about 45% of the net south Delta exports and diversions enter through the Old River mouth. About 40% of the net south Delta exports and diversions enter through the Middle River mouth, and about 10% of the net flows enter through Turner Cut. These fractions remain about the same for the full range of net exports and diversions, which can be more than 10,000 cfs during periods of high pumping.

Tidal and Net Flows in Middle River

Figure D-72 shows the tidal and net flows in Middle River just upstream of the confluence with Columbia Cut, which connects with the San Joaquin River on the south side of Medford Island. The tidal flows range from –20,000 cfs (10th percentile flow) during flood tide to about 15,000 cfs (90th percentile flow) during ebb tide, with a net flow that varies from 0 to about –5,000 cfs. About 40% of the net south Delta exports and diversions move through Middle River. The net flow at the Middle River mouth can become slightly positive during high San Joaquin River flows.

Figure D-73 shows the tidal and net flows in Turner Cut. Turner Cut joins Empire Cut, which connects with the Middle River channel just south of flooded Mildred Island. The mouth of Turner Cut is located on the San Joaquin River at river mile (RM) 32.5, about 10 miles upstream of the Mokelumne River mouth and about 7 miles downstream of the upstream end of the Stockton Deep Water Ship Channel. The tidal flows in Turner Cut range from about –4,500 cfs (10th percentile flow) during flood tide to about 2,500 cfs (90th percentile flow) during ebb tide. The net flow is usually negative but can be positive during high San Joaquin River flows (i.e., 1983 only). About 10% of the net south Delta exports and diversions move through Turner Cut. The net tidal flows into Turner Cut range from –200 cfs to about –1,000 cfs. These net flows in Turner Cut join with Middle River net flows to supply the net south Delta exports and diversions.

Tidal and Net Flows in the Stockton Deep Water Ship Channel at Rough & Ready Island

Figure D-74 shows the range of tidal stage at Rough & Ready Island, located at the Port of Stockton. DWR operates a tidal stage and water quality monitor at this station. The minimum monthly tidal stage ranges from about –2 feet msl to -1 foot msl, except when the San Joaquin River flows are high. The 10th percentile tidal stage values are generally between –1 and –0.5 foot msl. The median tidal stage is about 1 foot msl, and the 90th percentile tidal stage values are generally between 2.5 and 3.0 feet msl. The maximum tidal stage is usually between 3.5 and 4.5 feet msl. This range of tidal fluctuation at Rough & Ready Island is surprising because this location is about 39 miles upstream of the San Joaquin River confluence near Antioch. Comparison with the simulated Antioch tidal stage variation indicates that the minimum and 10th percentile tidal stage are about 0.5 foot higher at Rough & Ready Island, and the 90th percentile and maximum tidal stage are about 0.5 foot less at Rough & Ready Island. The median tidal stage of about 1 foot msl is similar at Rough & Ready Island and Antioch, except during periods of high San Joaquin River flow, when the stage at Rough & Ready Island is raised to 2–3 feet msl.

Figure D-75 shows the tidal flows at Rough & Ready Island. The range of tidal flow in the San Joaquin River at Rough & Ready Island is between about -5,000 cfs during flood tide (10th percentile tidal flow) and about 5,000 cfs during ebb tide (90th percentile tidal flow). The net flow is often less than 500 cfs when San Joaquin River at Vernalis flow is less than 2,000 cfs but increases to about 40% of the Vernalis flow during periods of higher San Joaquin River flow. DSM2 indicates a few periods of negative net flow, although the USGS tidal flow station at the discharge of the City of Stockton wastewater treatment plant (about 3 miles upstream) has not measured any negative net daily flows since it was installed in 1995.

Tidal and Net Flows in the Head of Old River

Figure D-76 shows the range of tidal stages in the head of Old River just downstream of Mossdale. These tidal stages have been simulated without any temporary rock weirs, which have often been installed by DWR during the fall (September–December) to increase the San Joaquin River flows past Stockton to improve the DO concentrations for migrating Chinook salmon. The tidal stage range is higher at the head of Old River than at other Delta locations because upstream San Joaquin River hydraulic conditions have a strong influence. The minimum tidal stage is about 0 feet msl, and the 10th percentile tidal stage is about 0.5 foot. The median tidal stage is between about 1 and 2 feet msl, and the 90th percentile tidal stage is about 2.5 feet msl. The low tide elevations are about 1–2 feet above the corresponding tidal stage at Rough & Ready Island. The higher tide elevations are about 0.5 foot lower than at Rough & Ready Island.

Figure D-77 shows the tidal flows at the head of Old River. The mean tidal flow is always positive and is about 60% of the Vernalis flow when the Vernalis flow is more than 2,000 cfs. At lower river flow, the head of Old River flow is influenced by the south Delta exports and diversions. The tidal flows are about 500 cfs more than the net flow during ebb tide (90th percentile tidal flow) and about 500 cfs less than the net flow during flood tide (10th percentile tidal flow). The minimum tidal flow is negative only if the net head of Old River flow is less than 1000 cfs.

Figure D-78 shows how the head of Old River tidal flows are influenced by the San Joaquin River flow at Vernalis. When the Vernalis flow is more than 10,000 cfs, there is no tidal flow variation (because the tidal stage is higher than the high tide) and the head of Old River diversion is about 50% of the Vernalis flow. The tidal variation is about 1,000 cfs above and below the average diversion flow when the Vernalis flow is less than 5,000 cfs. When the Vernalis flow is less than 2,500 cfs, the tidal variation is reduced and the net flow is increased by higher pumping. Analysis of the DSM2 results indicates that the diversion flow is about 50% of the Vernalis flow and is increased by about 5% of the export pumping flow. Pumping of 10,000 cfs would increase the diversion flow by about 500 cfs and would result in most of the San Joaquin River being diverted when Vernalis flow was less than 1,000 cfs.

The head of Old River diversion from the San Joaquin River is similar to the DCC diversion from the Sacramento River. The head of Old River diversion is about 50% of the San Joaquin River flow at higher flows and is increased by about 5% of the combined south Delta exports and diversions.

Stage and Velocity in the San Joaquin River at Vernalis

Vernalis is located on the San Joaquin River at RM 72 and is just upstream of the tidal influence from the Delta. Vernalis is the upstream boundary for the DSM2 tidal flow and water quality model.

Figure D-79 shows the monthly flows at Vernalis for the 16-year period simulated with DSM2 for the 2020 baseline conditions. Simulated Vernalis flows are almost always between 1,000 and 2,500 cfs. Only a few high flows are simulated for the winter months of wet years. The highest monthly average flow during the 16-year period was just above 35,000 cfs in March and June of 1983.

Figure D-80 shows the stage and velocity at Vernalis as a function of flow (i.e., stage-discharge curve). The river stage and velocity increase with flow in a manner typical of river cross sections with levees. The stage and velocity continue to increase even at higher flows because the river width is confined by levees. The flood warning level at Vernalis is about 29 feet, which corresponds to a flow of about 32,500 cfs. DSM2 stage is slightly lower than the actual rating curve for Vernalis, but there is not any large effect from this difference. The top of the levee is about 37 feet msl, and the peak stage was recorded on January 5, 1997, at 35 feet msl.

There is a flood control diversion weir downstream of Vernalis at Paradise Cut. The weir notch in the left-hand levee is at elevation 12.5 feet and is 235 feet long. The DSM2-simulated flood diversions begin at a Vernalis flow of about 15,000 cfs (Vernalis stage of 20 feet). DSM2 indicates that the Paradise Cut flow will be half of the Vernalis flow in excess of 15,00 cfs. Paradise Cut therefore diverts 5,000 cfs when the Vernalis flow is 25,000 cfs and diverts 10,000 cfs when the Vernalis flow is 35,000 cfs.

The simulated tidal stage and tidal flows at additional south Delta locations are shown in the next section, where the specific effects of export pumping on south Delta tidal stage and flows are described and summarized.

Introduction to Tidal Hydraulics of South Delta Channels

The SDIP components are located in the south Delta channels of Old River, Middle River, and Grant Line Canal. The tidal hydraulics in these channels must be accurately described and understood to allow the proper evaluation of the existing conditions (i.e., water supply and water quality difficulties) and the assessment of the expected improvements and potential impacts from the proposed project alternatives.

Figure D-81 shows the San Joaquin River and south Delta channels, as well as the existing CVP Tracy facility and Tracy Fish Facility for the DMC, CCF, Skinner Fish Facility, and SWP Banks facility. The boundaries of the South Delta Water Agency are outlined on the map. This section introduces the south Delta channel geometry and illustrates some simple simulations of south Delta tidal hydraulics. The south Delta can generally be defined as all Delta channels and flooded islands located south and west of the San Joaquin River. The total south Delta surface area is therefore about 16,600 acres, with a volume of 183,500 acre-feet (including the CCF). Table D-1 summarizes the south Delta channel geometry data (obtained from DSM2 geometry files), as well as the geometry for the remainder of the Delta.

Table D-1. Summary of Delta Channel Geometry

	Length (Miles)	Total Surface Area (acres) at Elevation (feet msl)				Total Volume (acre-feet) at Elevation (feet msl)			
		-2	0	2	4	-2	0	2	4
Vernalis to Head of Old River	19.8	275	342	475	592	952	1,573	2,372	3,447
HOR to Stockton DWSC	14.5	326	346	365	384	2,097	2,769	3,480	4,229
DWSC to Turner Cut	13.5	743	757	770	783	12,276	13,776	15,303	16,855
SJR Turner to Old River Mouth	17.8	1,644	1,684	1,720	1,753	30,788	34,117	37,521	40,995
Mouth of Old River to Jersey Point	21.5	4,644	4,754	4,834	4,884	98,870	108,272	117,865	127,587
Jersey Point to Confluence	33.3	8,542	8,680	8,771	8,839	156,280	173,166	190,276	207,543
HOR to Grant Line Canal	8.2	173	187	199	212	935	1,296	1,683	2,094
Old River at Grant Line to DMC	16.2	313	359	393	419	1,569	2,242	2,995	3,808
OR from DMC to Vict & West Canal	3.1	192	202	211	222	1,676	2,069	2,482	2,914
Old River Victoria to Rock Slough	25.9	1,539	1,578	1,614	1,645	17,688	20,805	23,997	27,257
Old River Rock Slough to Mouth	17.2	1,228	1,280	1,312	1,340	16,941	19,449	22,043	24,696
Middle River Head to Victoria	12.3	126	167	204	230	363	656	1,028	1,462
Middle River Victoria to Mouth	46.0	3,575	3,697	3,801	3,892	46,929	54,201	61,701	69,395
Sugar Cut and Tom Paine	4.6	111	115	119	122	312	538	772	1,013
Paradise Cut and Drainage Canal	6.2	148	165	171	177	522	840	1,177	1,525
Grant Line Canal	8.9	335	366	388	412	2,131	2,835	3,588	4,388
Victoria Canal (North Canal)	4.8	229	246	261	276	1,863	2,340	2,847	3,384
Franks Tract and Big Break	35.7	6,275	6,385	6,437	6,483	46,742	59,407	72,230	85,150
Mokelumne River Channels	461.0	4,398	4,639	4,868	5,075	46,615	55,656	65,165	75,109
Sutter and Steamboat Sloughs	36.2	951	1,023	1,070	1,111	7,477	9,452	11,547	13,728
Sacramento Ship Channel	29.7	1,900	1,960	2,016	2,074	34,901	38,761	42,738	46,828
Cache Slough	21.7	1,235	1,273	1,309	1,339	14,547	17,056	19,639	22,288
Sacramento River to Emmaton	56.5	5,423	5,562	5,682	5,783	82,952	93,938	105,187	116,653
Suisun Bay	48.3	22,282	22,958	23,357	23,603	320,309	365,577	411,919	458,891
Suisun Marsh	110.7	12,390	12,624	12,775	12,881	42,281	66,932	91,976	117,264
Total Delta	1073.6	78,996	81,349	83,123	84,530	988,018	1,147,722	1,311,528	1,478,503
Upstream of Chipps Island	914.7	44,324	45,766	46,991	48,046	625,428	715,213	807,634	902,348
South Delta Channels	178.4	16,124	16,616	16,980	17,301	150,743	183,499	217,108	251,397
Upstream of South Delta Gates	45.7	947	1,078	1,184	1,273	4,999	7,029	9,293	11,751
Clifton Court Forebay	2.0	2,140	2,150	2,160	2,170	13,905	18,200	22,515	26,850

South Delta Channel Geometry

The geometry of the south Delta channels are summarized below to provide an accurate understanding of the water volumes and the tidal and net flows in these channels. There are only three pathways for water to enter the south Delta channels as it moves toward the DMC and CCF. It can flow from the:

- San Joaquin River through the upstream end of Old River, called the head of Old River, west toward Tracy;
- Central Delta through Middle River along the eastern edge of Bacon Island and Woodward Tract, and then southwest in Victoria Canal along the southeast edge of Victoria Island; or
- Central Delta through Old River along the western edge of Bacon Island, Woodward Tract, and Victoria Island.

San Joaquin River flow (measured at the Vernalis Bridge at RM 72) enters the upstream end of the Old River channel at the head of Old River, located downstream of Mossdale at RM 53.5. In the absence of CVP Tracy and SWP Banks pumping, about 50% of the San Joaquin River flow enters the Old River channel, and the other 50% continues down the San Joaquin River channel toward Stockton. During storm flows of greater than about 15,000 cfs at Vernalis, the Paradise Cut Weir (elevation 12.5 feet) diverts some of the San Joaquin River flow at RM 60 into Paradise Cut toward Grant Line Canal, reducing the San Joaquin River flow at Mossdale and the head of Old River.

The San Joaquin River fish protection tidal gate will be located at the head of Old River (fish control barrier at head of Old River) and can be used to control the flow split from the San Joaquin River.

South Delta Channels within the Proposed Tidal Gates

This section describes the location, surface area, and volume of south Delta channels and the locations of the proposed tidal gates.

Old River

Old River flows west from the head of Old River. Middle River is approximately 4 miles downstream of the head of Old River, and Doughty Cut (which connects Old River with the eastern end of Grant Line Canal), Paradise Cut, and Tom Paine Slough/Sugar Cut are about 8 miles downstream from the head of Old River. The Old River channel in the vicinity of Tracy is the southernmost Delta channel influenced by tides.

The length of Old River between the head of Old River and Grant Line Canal is about 8 miles, with a surface area of about 187 acres and a volume of 1,296 acre-feet. The length of Old River between Grant Line Canal and the DMC is about 16 miles, with a surface area of about 359 acres and a volume of 2,242 acre-feet.

One of the proposed tidal gates will be constructed on Old River just upstream of the DMC. Most of the water in Old River flows through Doughty Cut to Grant Line Canal. These south Delta channel geometry values are given in Table D-1.

Middle River

Middle River is a relatively narrow and shallow channel that extends 12 miles from Old River to Victoria Canal. The channel has been dredged wider and deeper in the lower 4 miles from Victoria Canal to between the Tracy Boulevard Bridge and the Howard Road Bridge. The surface area of Middle River is about 167 acres, with a volume of 656 acre-feet. One of the proposed tidal gates will be constructed near the confluence with Victoria Canal to protect this reach of Middle River.

Grant Line Canal

Grant Line Canal is the common name for what are actually two parallel canals. Grant Line Canal is about 9 miles long and begins at the Doughty Cut on the east and continues to its mouth at Old River just north of the DMC. Fabian and Bell Canal begins near the Tracy Boulevard Bridge and continues for about 6 miles parallel to Grant Line Canal, rejoining the downstream end of Grant Line Canal near where the canal rejoins Old River. The two canals are interconnected at numerous points between the remaining channel islands. The surface area of Grant Line Canal is about 366 acres, with a volume of about 2,835 acre-feet. One of the proposed tidal gates will be constructed at the downstream end of Grant Line Canal near the confluence with Old River near the DMC and CCF.

Paradise Cut

Paradise Cut is essentially a dead-end tidal slough connected to Old River. It is about 6 miles long, with a surface area of 165 acres and a volume of 840 acre-feet. Water level changes are expected to be similar to those in Old River. Old River at Tracy Boulevard Bridge is used as the reference station.

Tom Paine Slough

Tom Paine Slough is about 5 miles long and has been isolated from tidal influence with siphons. It is operated as a lake to supply several irrigation diversions. DWR and the South Delta Water Agency dredged portions of the channel in 1986 and installed new siphons in 1989. The CCF operations (i.e., schedule) were modified to reduce SWP Banks diversions during the flood-tide period of the higher-high tide to increase the water level maintained in Tom Paine Slough. Tom Paine Slough has a surface area of 64 acres and a volume of 168 acre-feet. Sugar Cut extends about 2 miles south of the siphons to Tom Paine Slough, with a surface area of 36 acres and a volume of 268 acre-feet.

Old River, Middle River, and Grant Line Canal between the Four Proposed Tidal Gates

The total surface area in the main channels of Old River, Middle River, and Grant Line Canal between the four proposed south Delta tidal gates is about 1,100 acres, with a volume of 7,300 acre-feet. As the tidal elevation fluctuates, the surface area and volume will change, as indicated in Table D-1. For the average tidal fluctuation of 3 feet (i.e., from –1.0 to 2 feet msl), the surface area will increase from 1,000 to 1,200 acres, and the volume will increase from about 6,000 to 9,500 acre-feet, a change of about 3,500 acre-feet. This change between the low tide and the high tide will occur in the south Delta channels twice each day. It represents an average tidal flow of about 3,500 cfs flowing into these channels during the flood tides (for about 12 hours each day) and about 3,500 cfs flowing out of these channels during the ebb tides.

South Delta Channels Downstream of the Proposed Barriers

This section describes the channels that convey the tidal flows into and out of the south Delta.

Clifton Court Forebay

The CCF was completed in 1969 to provide a short-term storage forebay to reduce the tidal fluctuations at the SWP Banks facility and allow off-peak power (i.e., nighttime) to be used to pump water into the California Aqueduct. The CCF has a surface area of 2,180 acres and a volume of 31,260 acre-feet at a maximum water surface elevation of 6 feet msl. However, the CCF operates at an average water surface elevation of only about 0 feet msl. Table D-1 indicates that the surface area of the CCF at 0 feet msl is about 2,150 acres and the volume is about 18,200 acre-feet. The CCF intake structure is located on Old River just north of the mouth of Grant Line Canal. The intake channel is about 300 feet wide, and there are five radial gates with widths of 20 feet each. The water depth in the channel is about 15 feet at a water surface elevation of 0 feet msl. The CCF intake was designed for a maximum flow of 16,000 cfs, at a water velocity of about 10 feet/sec, with a water surface difference (i.e., head) of 1 foot. The maximum design flow is maintained by closing the gates to limit the flow when the water elevation difference between Old River and the CCF is greater than 1 foot.

West Canal

West Canal forms the eastern boundary of the CCF along the western edge of Coney Island. Old River flows around the eastern edge of Coney Island. Old

River and West Canal between the DMC and Victoria Canal have a surface area of 202 acres and a volume of 2,069 acre-feet.

Victoria Canal

Victoria Canal connects Middle River to Old River just north of Coney Island. Victoria Canal is the common name for the Victoria Canal along the southeastern edge of Victoria Island and the parallel North Canal along the northwestern edge of Union Island. Victoria Canal (including North Canal) is about 5 miles long and has a surface area of 246 acres and a volume of 2,340 acre-feet.

Old River

Old River continues north past Victoria Island, Woodward Island, Bacon Island, Holland Tract, and Franks Tract, which is a flooded island, to its mouth (i.e., downstream end) at the San Joaquin River. About half of the water entering the south Delta on its way to the CVP Tracy and SWP Banks facilities flows in this portion of the Old River channel. Old River from Victoria Canal to its mouth at the San Joaquin River is about 20 miles long, with several bends and meanders in the channel. The surface area is about 1,600 acres from Victoria Canal to Rock Slough and 1,280 acres from Rock Slough to the mouth. The Old River volume is about 20,000 acre-feet from Victoria Canal to Rock Slough (including Rock, Indian, and Italian Sloughs and Discovery Bay) and another 20,000 acre-feet from Rock Slough to the mouth (not including Franks Tract).

Franks Tract

Franks Tract connects with the San Joaquin River through False River, Fisherman’s Cut, and Dutch Slough to Big Break. The surface area of these channels and flooded islands is about 6,400 acres, with a volume of about 60,000 acre-feet.

Middle River

Middle River channel extends north from Victoria Canal along Victoria Island, Woodward Island, and Bacon Island. Turner Cut and Empire Cut connect the San Joaquin River to Middle River near the middle of Bacon Island. Mildred Island, which is flooded, is located just downstream (north) of Empire Cut. Middle River continues north along Mandeville Island and splits around both the eastern side of Medford Island in Columbia Cut and around the western side of Medford Island to its mouth at the San Joaquin River. The mouth of Middle River is located only about 3 miles upstream of the mouth of the Old River. The Middle River channels north of Victoria Canal have a surface area of 3,700 acres, with a volume of 54,200 acre-feet. The channels include Turner/Empire and

Columbia Cuts, which connect with the San Joaquin River; three channels that connect to Old River; and flooded Mildred Island. About half of the water flowing through the Delta is drawn from the Sacramento River into the Mokelumne River. The water then flows into the central Delta and down Middle River to Victoria Canal and toward the CVP Tracy and SWP Banks facilities.

Simulated Effects of Pumping on Tidal Hydraulics of the South Delta

This section presents DSM2 results for August 1997 with the San Joaquin River flow at Vernalis set to 1,500 cfs, measured Martinez tides and Sacramento River daily inflows, and no south Delta channel barriers or tidal gates. Three pumping scenarios were simulated and compared to the no-pumping conditions:

- CVP Tracy pumping at a constant 4,600 cfs,
- SWP Banks pumping at 6,680 cfs added to the CVP Tracy pumping, and
- SWP Banks pumping at 8,500 cfs added to the CVP Tracy pumping.

These comparisons identify the maximum tidal effects of the CVP Tracy and SWP Banks pumping with no temporary barriers or tidal gates. These model results are considered typical of the maximum potential effects of the CVP Tracy facility and the maximum allowed SWP Banks pumping with associated CCF gate operations. Results for SWP Banks pumping of 6,680 and 8,500 cfs, in addition to CVP Tracy pumping of 4,600 cfs, are used to demonstrate the maximum likely effects of increased SWP Banks pumping during the summer without temporary barriers. Table D-2 gives a summary of these tidal flows and stage simulation results. Simulated tidal stage and flow results are presented for the following nine channel locations:

- Old River at Bacon Island,
- Middle River at Bacon Island,
- head of Old River,
- Old River at Clifton Court Ferry,
- CCF intake gates,
- Old River at Tracy Boulevard Bridge,
- Grant Line Canal at Tracy Boulevard Bridge,
- Middle River at Mowry Bridge, and
- Middle River at Tracy Boulevard Bridge.

Table D-2. Simulated August 1997 Net Channel Flow in South Delta Channels for a Range of Central Valley Project and State Water Project Exports

A. Net Channel Flows (cubic feet per second)

State Water Project	**0**	**0**	**6,680**	**8,500**	**10,300** [a]
Central Valley Project	**0**	**4,600**	**4,600**	**4,600**	**4,600**
Delta Outflow	5,000	5,000	5,000	5,000	5,000
Sacramento River at Freeport	5,864	10,464	17,144	18,964	20,764
San Joaquin River	1,500	1,500	1,500	1,500	1,500
Head of Old River	895	1,078	1,342	1,393	1,452
San Joaquin River at Stockton	605	422	158	107	48
Turner Cut	-130	-473	-957	-1,098	-1,236
Middle River at Mouth	-94	-1,918	-4,524	-5,241	-5,944
Mouth of Old River	-2,260	-3,632	-5,518	-6,024	-6,514
False River at Franks Tract	1,770	1,239	353	103	-148
Dutch Slough	0	-250	-550	-650	-750
Old River at Bacon Island	382	-1,510	-4,355	-5,142	-5,901
Middle River at Bacon	-177	-2,428	-5,626	-6,518	-7,406
Grant Line Canal at Tracy Blvd Bridge	552	692	980	1,042	1,118
Old River at Tracy Boulevard Bridge	102	164	176	173	168
Middle River at Tracy Boulevard Bridge	-17	-36	-72	-79	-87
Total Inflow to South Delta	**1,607**	**6,111**	**12,538**	**14,304**	**16,044**
Total Exports (CVP and SWP)	**0**	**4,600**	**11,280**	**13,100**	**14,900**

B. Flow Entering South Delta That Does Not Come from Head of Old River (cubic feet per second)

Total Flow Not from Head of Old River	**713**	**5,034**	**11,196**	**12,910**	**14,592**
Percent from Turner Cut	18	9	9	9	8
Percent from Middle River	13	38	40	41	41
Percent from Old/False River	69	48	46	46	46
Percent from Dutch Slough	0	5	5	5	5

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[a] Shown for comparison purposes only.

Review of the DSM2 results indicates that the effects of both constant CVP Tracy pumping at 4,600 cfs and the tidal diversion of water into CCF for SWP Banks pumping will cause an increase in the flows moving from the San Joaquin River toward the pumping plants. The increased flow will move along three main pathways from the San Joaquin River. These pathways are from the:

- head of Old River to Grant Line Canal and then down Old River and Grant Line Canal to the DMC;
- mouth of Middle River, and also Columbia and Turner Cuts, up Middle River to Victoria Canal and then to Old River; and

- mouth of Old River up past Franks Tract to the CCF intake gates and the DMC.

The effects of the CVP Tracy and SWP Banks pumping on tidal stage elevations in the south Delta can be detected at head of Old River but cannot be detected at the mouth of Middle River or the mouth of Old River. Details of how pumping changes tidal stages and flows in the south Delta channels will be described in the following sections.

Old River at Bacon Island

Figure D-82 shows the simulated tidal stage at the Bacon Island station on Old River, which is just upstream (i.e., south) of Rock Slough. The USGS-operated UVM tidal flow station has measured 15-minute tidal stage and flow data since 1987. This station is located about 10 miles north of the DMC.

Maximum CVP Tracy and SWP Banks pumping has almost no effect on the tidal stage at this location. With no pumping, the high tides reach 4.1 feet msl, and the low tides drop to about –0.5 foot msl. The maximum CVP Tracy and SWP Banks pumping reduces the high-tide stages by only about 1 inch and reduces the low-tide stages by about 2 inches. The average tidal variation remains about 3 feet at this station.

Figure D-83 shows the effects of 4,600 cfs of CVP Tracy pumping on Old River flows at Bacon Island: the tidal flows are reduced (more negative or in upstream direction) by about 2,000 cfs during all tidal periods. This reduction in tidal flow suggests that the water surface slope in the vicinity of Old River at Bacon increases slightly throughout the tidal cycle. The tidal flows are relatively high in Old River, with maximum downstream (ebb-tide) flows of about 10,000 cfs and maximum upstream (flood-tide) flows of about 12,500 cfs. The maximum CVP Tracy pumping shifts all of the tidal flows by about 2,000 cfs in the upstream direction. The CVP Tracy pumping flow is superimposed onto the tidal flows in Old River.

Figure D-84 shows the effects of adding SWP Banks pumping at 6,680 and 8,500 cfs to 4,600 cfs of CVP Tracy pumping. CCF intake gates were assumed to remain open unless the CCF stage was higher than the Old River stage. The CCF gate flow will increase as the tidal stage increases and was assumed to be about 7,500 cfs at a stage difference of 1.0 foot. The effects of the SWP Banks tidal diversions, which generally increase at higher tides, are more complex than the effects from the constant CVP Tracy pumping. The tidal flows are reduced by about 3,000 cfs at the lowest values (stronger upstream flow) and by as much as 8,000 cfs during periods of highest flow (reduced downstream flow). The tidal flows in Old River are almost “captured” by the 8,500-cfs SWP Banks pumping, with only a few hours of downstream flow each day.

Table D-2 indicates that the net flow in Old River at Bacon Island is reduced from –177 cfs to –2,428 cfs by the 4,600 cfs of CVP Tracy pumping. The Old

River net flow is reduced to –5,626 cfs with 6,680 cfs of SWP Banks pumping and to –6,518 cfs with 8,500 cfs of SWP Banks pumping. This reduction suggests that about 48% of the flow moving toward the CVP Tracy and SWP Banks facilities from the San Joaquin River will flow through the Old River pathway. Therefore, about half of the export pumping flow change (i.e., 892 cfs more upstream flow if the SWP Banks pumping is increased from 6,680 to 8,500 cfs) will be observed at the Bacon Island station on Old River. The tidal stage changes will be very difficult to measure because the average tidal variation of 3 feet is so much greater than the 2-inch maximum difference at low tides.

Middle River at Bacon Island

Figure D-85 shows the simulated tidal stage at the Bacon Island station on Middle River, which is just downstream (i.e., north) of Woodward Canal, connecting Old River and Middle River between Bacon and Woodward Islands. Turner Cut and Columbia Cut join Middle River downstream of this station, so all of the flow from the San Joaquin River moving through Middle River passes this station. Another USGS UVM tidal flow station has measured 15-minute tidal stage and flow data in Middle River since 1987. This station is located about 15 miles north of the DMC (along Victoria Canal and Middle River).

There is almost no effect of maximum CVP Tracy (4,600 cfs) and maximum SWP Banks pumping (8,500 cfs) on the tidal stage at this location. With no pumping, the high tides reach 4.1 feet msl, and the low tides drop to about -0.5 foot msl. The maximum CVP Tracy and SWP Banks pumping reduces the high-tide stages by about 1 inch and reduces the low-tide stages by about 2 inches. The tidal variation remains about 3 feet at this station. The tidal stage variation in Middle River is similar to the tidal stage variation in Old River because they are both controlled by San Joaquin River tidal variation.

Figure D-86 shows the effects on flows caused by CVP Tracy pumping of 4,600 cfs at the Bacon Island station on Middle River: the flows are reduced by about 2,500 cfs during the entire tidal cycle. This reduction suggests that the water surface slope in the vicinity of Middle River at Bacon Island increases slightly throughout the tidal cycle. The tidal flows without any pumping are slightly higher than in Old River, with maximum downstream (ebb-tide) flows of about 12,500 cfs and maximum upstream (flood-tide) flows of about 15,000 cfs.

Figure D-87 shows the effects from 6,680 and 8,500 cfs of SWP Banks pumping in addition to 4,600 cfs of CVP Tracy pumping on tidal flows in Middle River at Bacon Island. The effects of the SWP Banks tidal diversions into the CCF, which generally increase at higher tides, are more complex than the effects from the constant CVP Tracy pumping. The tidal flows are reduced by about 5,000 cfs at the lowest values (upstream flow) and are reduced by as much as 10,000 cfs during periods of highest flow (downstream flow). The reductions caused by 6,680 cfs of SWP Banks pumping are more variable than the changes caused by 8,500 cfs of SWP Banks pumping because the higher pumping causes the diversions into the CCF to be more sustained throughout the tidal cycle.

Table D-2 indicates that the net flow in Middle River at Bacon Island is reduced from 381 cfs (downstream) to –1,510 cfs by the 4,600 cfs of CVP Tracy pumping. The Middle River net flow is reduced to –4,355 cfs with 6,680 cfs of SWP Banks pumping and to –5,142 cfs with 8,500 cfs of SWP Banks pumping. This reduction suggests that about 42% of the net flow moving toward the CVP Tracy and SWP Banks facilities from the San Joaquin River will use the Middle River pathway. For the maximum change in SWP Banks pumping from 6,680 to 8,500 cfs, about 787 cfs more flow will move upstream past the Middle River at Bacon Island station.

In summary, the tidal stage variations are similar at Old River and Middle River. Tidal flow variations are slightly stronger in Middle River than in Old River, yet the net flow is simulated to be slightly higher in Old River. Although the USGS UVM stations indicate that Middle River net flow is generally higher than Old River net flow, the DSM2 channel geometry and Manning's *n* coefficients have not been adjusted to match the measured flow split between Old River and Middle River.

Head of Old River

Figure D-88 shows the simulated tidal stage at the head of Old River. The head of Old River is located about 24 miles upstream of the DMC. Without any CVP Tracy or SWP Banks pumping, tidal variations at the head of Old River range from a high tide of about 4.0 feet msl during the spring-tide period to a low tide of about 1.0 foot msl. Additionally, Figure D-88 shows that the 4,600-cfs constant pumping at the CVP Tracy facility reduces the tidal stage by about 2 inches at low tide and about 4 inches at high tide.

Figure D-89 shows the effects of SWP Banks pumping on the tidal elevations at the head of Old River. The tidal variations at the head of Old River station are reduced by the SWP Banks pumping and tidal diversions into CCF. The high-tide values are reduced by about 12 inches compared to the no-pumping conditions, while the low-tide values are reduced by only about 6 inches.

The reduced tidal stage increases the flow from the San Joaquin River at Mossdale into Old River and produces a higher net flow into the head of Old River. CVP Tracy and SWP Banks pumping does not lower the San Joaquin River stage at Mossdale sufficiently to produce a net upstream flow from Stockton, unless the total pumping is more than 10 times the San Joaquin River flow at Vernalis. Higher pumping will cause a greater fraction of the San Joaquin River flow to be diverted into Old River.

Figure D-90 shows the simulated tidal flows and stages at the head of Old River for no-pumping and CVP Tracy 4,600-cfs pumping conditions for a 7-day period. The highest tidal flows from the San Joaquin River into Old River occur at the beginning of the flood tide as the tide begins to rise and tidal flow moves upstream from Stockton toward Mossdale. A portion of this flood-tide flow turns down into Old River at the same time that downstream flow from Mossdale moves into Old River. During most of the ebb tide, approximately 1,000 cfs flows from the San Joaquin River into Old River, with the Vernalis flow at 1,500 cfs. However, there is a short period at the end of each flood tide (i.e., during high “slack” water) when the tidal stage in Old River can be slightly higher than the tidal stage in the San Joaquin River, and the tidal flow in Old River moves upstream into the San Joaquin River for about an hour. This brief period of upstream flow is almost eliminated by the maximum CVP Tracy pumping of 4,600 cfs because of the reduction in Old River.

Table D-2 indicates that flow from the San Joaquin River in Old River is about 895 cfs with no CVP Tracy or SWP Banks pumping and south Delta agricultural diversions of about 1,000 cfs and CCWD diversions of 207 cfs. This flow is equal to approximately 60% of the Vernalis flow. This flow is increased to 1,078 cfs with CVP Tracy pumping of 4,600 cfs and is increased to 1,342 cfs with the SWP Banks pumping of 6,680 cfs. The head of Old River diversion is 1,393 cfs with SWP Banks pumping of 8,500 cfs. These increases in flows into Old River are equal to about 4% of the export pumping.

Old River at Clifton Court Ferry

The Old River at Clifton Court Ferry station is just downstream of the mouth of Grant Line Canal and about 1 mile north of the DMC. The tidal stages at this station are directly influenced by CVP Tracy and SWP Banks pumping.

Figure D-91 shows the simulated tidal stages at Clifton Court Ferry for CVP Tracy pumping of 4,600 cfs. The constant pumping at CVP reduces the stage in Old River about 6 inches uniformly at all tidal stages. This drawdown of 6 inches provides the required change in water surface slope along Old River to help supply 4,600 cfs to the CVP Tracy intake.

Figure D-92 shows the effects of SWP Banks pumping of 6,680 and 8,500 cfs on the Clifton Court Ferry stages. The low tides are not lowered by as much as the higher stages because the diversions into CCF are generally much less during periods of low tide. The 8,500-cfs SWP Banks pumping reduces the high-tide stages by 18–24 inches, depending on the CCF gate diversions, while the low tides at Clifton Court Ferry are reduced by only about 6 inches. The low-tide reductions at all other south Delta locations will be less than the 6 inches that was simulated at both Clifton Court Ferry and at the head of Old River. The difference in low-tide reduction between SWP Banks pumping of 6,680 and 8,500 cfs is simulated to be less than 2 inches at both the Clifton Court Ferry and head of Old River stations.

Figure D-93 shows the corresponding changes in tidal flows in Old River at Clifton Court Ferry. The CVP Tracy pumping reduces the flow by about 4,000 cfs throughout the tidal cycle. All of the CVP Tracy pumping flow not supplied through the head of Old River must come south from Middle River or Old River and flow past the Clifton Court Ferry station. The general effect of the SWP Banks pumping of either 6,680 or 8,500 cfs is to reduce the tidal fluctuations in the south Delta upstream of the CCF intake gates and thereby reduce the tidal flows moving past Clifton Court Ferry into either Grant Line Canal or Old River upstream of the DMC. The tidal flows at Clifton Court Ferry without CVP Tracy or SWP Banks pumping ranged from 7,000 cfs (downstream) to –7,000 cfs (upstream). SWP Banks pumping and diversions into CCF reduce the tidal flows to a range from about 2,000 cfs (downstream) to about –8,000 cfs (upstream).

Clifton Court Forebay Intake Gates

Figure D-94 shows the simulated diversions into CCF for the last 7 days of August 1997 with SWP Banks pumping of 6,680 and 8,500 cfs. The diversions follow the tide and are reduced to 0 cfs for portions of the tidal cycle each day for the 6,680 cfs pumping simulations because the Old River stage becomes less than the CCF stage during the lowest tide each day. The diversions with 8,500-cfs pumping are generally higher because the CCF stage is reduced by the higher pumping rate (simulated as constant SWP Banks pumping). When pumping 8,500 cfs, the CCF stage is reduced enough to remain lower than the Old River throughout the tidal cycle, so diversions are not stopped during the day. The 8,500 cfs pumping will reduce the CCF stage by about 6 inches, but the effect on Old River stage will be less than 2 inches.

Figure D-95 shows that the simulated diversion flow is proportional to the square root of the stage difference. The actual diversion flow capacity of the CCF intake gates may be higher than the value used in these simulations. This higher capacity would allow the diversions to increase more rapidly as the Old River elevation rises and allow CCF stage to remain higher. However, the peak diversion into CCF is limited to a maximum of about 15,000 cfs to prevent localized scouring. The higher SWP Banks pumping of 8,500 cfs will increase the duration of the higher diversion flows but will not actually produce any higher diversion flows because they are already limited to the maximum design capacity of about 15,000 cfs.

Old River at Tracy Boulevard Bridge

Figure D-96 shows the simulated tidal stage in Old River at the Tracy Boulevard Bridge station. The Tracy Boulevard Bridge is located about 9 miles upstream of the DMC and about 2 miles downstream of the Doughty Cut. The tidal stage variation at this location without CVP Tracy or SWP Banks pumping is almost the same as the tidal stage variation at Old River at Bacon Island (Figure D-82). The high tide is about 4.0 feet, and the low tide is about 0 foot msl. The low tide at Tracy Boulevard Bridge is apparently influenced by the higher-tide elevation at the head of Old River that is caused by the San Joaquin River flows. The effect of the maximum CVP Tracy pumping of 4,600 cfs is to reduce the stage at Tracy Boulevard Bridge by about 6 inches throughout the tidal range. The rising tides are reduced a little more than the falling tides because the rising-tide flow moves past the DMC and is diverted, whereas the falling-tide flow moves from upstream past the Tracy Boulevard Bridge and is less affected by the CVP Tracy pumping.

Figure D-97 shows the simulated tidal variation at the Tracy Boulevard Bridge station on Old River with CVP Tracy pumping of 4,600 cfs and SWP Banks pumping of 6,680 cfs, compared with SWP Banks pumping of 8,500 cfs. The SWP Banks pumping reduces the Tracy Boulevard Bridge stage by an additional 3–6 inches at the low tide, resulting in a low tide of about –1.0 foot msl. The SWP Banks pumping has a larger effect on the high tides at Tracy Boulevard because more of the flood-tide flows moving upstream in Old River are diverted into CCF, so Old River and Grant Line Canal do not fill as high as when there is no pumping. The high tides at Tracy Boulevard are reduced by 18–24 inches from the no-pumping conditions. The additional effects of the 8,500-cfs SWP Banks pumping compared with the 6,680-cfs SWP Banks pumping are very small, generally about 2 inches throughout the tidal range.

The highest tides are reduced from 4.0 feet msl to only about 2.5 feet msl. This reduction may have an effect on the water level that can be maintained in Tom Paine Slough, which is connected to Old River with siphons and tidal gates.

Figure D-98 shows the tidal flows at Tracy Boulevard Bridge. Without any CVP Tracy or SWP Banks pumping, the tidal flows range from about 600 cfs during ebb tide (downstream) to about –400 cfs during flood tide (upstream). During maximum CVP Tracy pumping, the ebb-tide flows do not changed, but the flood-tide flows are reduced by about 200 cfs. With SWP Banks pumping of 6,680 or 8,500 cfs, the tidal flows range from about 500 cfs during the ebb tide to about -200 cfs during the flood tide.

Table D-2 indicates that the net flow in Old River is about 102 cfs when there is no pumping. Net flow is increased to about 164 cfs with 4,600 cfs of CVP Tracy pumping. This increase indicates that most of the flow from the head of Old River is moving down Grant Line Canal to the DMC. SWP Banks pumping of 6,680 or 8,500 cfs does not increase the net flow at Tracy Boulevard Bridge by more than 10 cfs. The SWP Banks pumping only increases the head of Old River flow by about 300 cfs, and almost all of this water moves down Grant Line Canal to the CCF intake gates. CVP Tracy and SWP Banks pumping will lower the tidal stage in Old River at Tracy Boulevard Bridge and will reduce the flood-tide flows but will have only a slight effect on the net flow in Old River between Doughty Cut and the DMC.

Grant Line Canal at Tracy Boulevard Bridge

Figure D-99 compares the no-pumping tidal stage variation in Grant Line Canal at Tracy Boulevard Bridge station with CVP Tracy pumping of 4,600 cfs. The Tracy Boulevard Bridge is located near the upstream end of Grant Line Canal, about 5.5 miles upstream of the mouth of Grant Line Canal near the DMC and CCF intake gates. The Grant Line temporary barrier is installed each year at this location. The tidal stage variation at this location without CVP Tracy or SWP

Banks pumping is almost the same as the tidal stage variation at Old River at Bacon Island (Figure D-82). The high tide is about 4.0 feet, and the low tide is about –0.25 foot. The low tide is apparently influenced by the higher-tide elevation at the head of Old River that is caused by San Joaquin River flows. The effect of the maximum CVP Tracy pumping of 4,600 cfs is to reduce the tidal stage in Grant Line by about 6 inches throughout the tidal range. The rising tides are reduced a little more than the falling tides because the rising-tide flow from Old River is diverted into the DMC, whereas the falling tide flow is moving from upstream past the Tracy Boulevard Bridge and is less affected by the CVP Tracy pumping.

Figure D-100 shows the tidal variation in Grant Line Canal at Tracy Boulevard Bridge station with CVP Tracy pumping of 4,600 cfs and SWP Banks pumping of 6,680 cfs, compared with SWP Banks pumping of 8,500 cfs. The SWP Banks pumping reduces the Tracy Boulevard Bridge stage by an additional 3–6 inches at the low tide, resulting in a low tide of about –1.0 foot msl. The SWP Banks pumping has a larger effect on the high tides in Grant Line Canal because more of the flood-tide flows moving upstream in Old River are diverted into CCF. The higher tides in Grant Line Canal are reduced by 18–24 inches from the no-pumping conditions. The additional effects of the 8,500-cfs SWP Banks pumping compared with the 6,680-cfs SWP Banks pumping are very small, generally about 2 inches throughout the tidal range. The highest tides in Grant Line Canal are reduced from 4.0 feet msl to only about 2.5 feet msl.

Figure D-101 shows the tidal flows in Grant Line Canal at Tracy Boulevard Bridge. Without any CVP Tracy or SWP Banks pumping, the tidal flows range from about 4,000 cfs during ebb tide (downstream) to about –3,000 cfs during flood tide (upstream). With maximum CVP Tracy pumping, the ebb-tide flows do not changed, but the flood-tide flows are reduced by about 500 cfs. With SWP Banks pumping of 6,680 or 8,500 cfs, the tidal flows in Grant Line range from about 3,500 cfs during the ebb tide to about –2,000 cfs during the flood tide.

Table D-2 indicates that the net flow in Grant Line Canal is about 552 cfs with no pumping and increases to about 692 cfs with 4,600 cfs of CVP Tracy pumping. This increase indicates that most of the head of Old River flow from the San Joaquin River is moving down Grant Line Canal to the CVP Tracy intake. SWP Banks pumping of 6,680 or 8,500 cfs increases the net flow in Grant Line Canal at Tracy Boulevard Bridge to 980 and 1,042 cfs, respectively. The SWP Banks pumping only increases the head of Old River flow by about 300 cfs, and almost all of this water moves down Grant Line Canal to the CCF intake gates. The CVP Tracy and SWP Banks pumping will lower the tidal stage in Grant Line at Tracy Boulevard Bridge, reduce the tidal flows, and increase the net flow in Grant Line Canal as the head of Old River diversion from the San Joaquin River is increased.

Middle River at Mowry Bridge

Figure D-102 shows the tidal variation in Middle River at Mowry Bridge, located about 1.5 miles downstream from the head of Middle River at Old River. The tidal stage variation without any CVP Tracy or SWP Banks pumping ranges from a high tide of about 4.1 feet msl to a low tide of about 0.25 foot msl. The low-tide stage in this upstream portion of Middle River is maintained by the relatively high head of the Old River stage that is sustained by San Joaquin River flow. The effects of the maximum CVP Tracy pumping of 4,600 cfs are similar to the drawdown effects at Old River at Tracy Boulevard Bridge and Grant Line Canal at Tracy Boulevard Bridge. The effects of SWP Banks pumping of 6,680 and 8,500 cfs are similar, reducing the low tide by about 6 inches from the no-pumping condition and reducing the higher-tide values by about 12–18 inches. The high tide with 8,500-cfs SWP Banks pumping and 4,600-cfs CVP Tracy pumping is about 2.75 feet msl. The tidal stage difference at Mowry Bridge between 6,680 and 8,500 cfs of SWP Banks pumping is less than 2 inches.

Figure D-103 shows the tidal flows in Middle River at Mowry Bridge. Even with no CVP Tracy or SWP Banks pumping, the tidal flows into Middle River from Old River are small, producing peak flows during rising tides of about 150–200 cfs. There is a slight positive flow into Middle River even during falling tide. With SWP Banks pumping, there is a short period of reverse flow during the high slack water because the net flow toward the CVP Tracy and SWP Banks pumps is strong enough to draw about 50–100 cfs from Middle River.

Table D-2 indicates that the net flow in Middle River is 89 cfs with no pumping and is actually reduced to 71 cfs by CVP Tracy pumping of 4,600 cfs. The SWP Banks pumping of 6,680 and 8,500 cfs reduces the Middle River net flow to 34 and 28 cfs but does not reverse the net flow in Middle River. The SWP Banks pumping of 8,500 cfs has only a slight effect on the tidal stage and no effect on tidal flows in Middle River, compared with 6,680 cfs of SWP Banks pumping.

Middle River at Tracy Boulevard Bridge

Figure D-104 shows the tidal variation in Middle River at Tracy Boulevard Bridge. This station is located about 1.75 miles upstream from the junction with Victoria Canal. Each year, the Middle River temporary barrier is installed downstream of this location near the junction with Victoria Canal. The tidal stage variation without any CVP Tracy or SWP Banks pumping ranges from a high tide of about 4.0 feet msl to a low tide of about –0.5 foot msl. This range is similar to the tidal range for the Middle River at Bacon Island station (Figure D-85). The effects of the maximum CVP Tracy pumping of 4,600 cfs are small, with a reduction of about 4 inches throughout the tidal range. The effects of SWP Banks pumping of 6,680 and 8,500 cfs are similar, reducing the tidal stage by about 6 inches evenly over the tidal range. The tidal stage difference between 6,680 and 8,500 cfs of SWP Banks pumping is less than 1 inch.

Figure D-105 shows the tidal flows in Middle River at Tracy Boulevard Bridge. With no CVP Tracy or SWP Banks pumping, the tidal flows into Middle River from Old River are small, producing peak flows during flood tides of about 500–750 cfs. The tidal flow during ebb tide is about 750–1,000 cfs. The net flow into this portion of Middle River is slightly negative because of supplies to the agricultural diversions along Middle River. SWP Banks pumping of 6,680 and 8,500 cfs reduces the tidal flow into Middle River because the tidal stage range is reduced by about 1 foot. The flood-tide and ebb-tide flows are reduced by about 250 cfs with SWP Banks pumping of 6,680 or 8,500 cfs. The changes in tidal stage, tidal flow, or net flow by 8,500-cfs pumping compared to 6,680-cfs pumping are very small in Middle River.

Table D-2 indicates that the net flow in Middle River at the Tracy Boulevard Bridge is –17 cfs (upstream) with no pumping and is –35 cfs with CVP Tracy pumping of 4,600 cfs. The SWP Banks pumping of 6,680 and 8,500 cfs further reduces the Middle River net flow to –72 and –79 cfs, respectively.

Summary of South Delta Tidal Effects from CVP Tracy and SWP Banks Pumping

This section summarizes the tidal tour of the south Delta channels and the initial assessment of the effects of SWP Banks pumping on the tidal stage, tidal flows, and net flows in these channels, as described above. Historical August 1997 conditions were used to simulate and compare tidal conditions in the south Delta. Relatively minor changes in low-tide elevation, which produced a maximum of 12 inches below the no-pumping conditions, were simulated with 8,500 cfs of SWP Banks pumping upstream of the temporary barrier locations in Old River, Grant Line Canal, and Middle River.

Figure D-106 provides a summary of these monthly tidal stage variations for Old River at Tracy Boulevard Bridge and Grant Line Canal at Tracy Boulevard Bridge. For each month of 15-minute values (2,976 values for a 31-day month), the values were sorted from minimum to maximum. The percentiles (i.e., 0 [minimum], 10th, 20th, 30th, 40th, 50th [median]… 90th, and 100th [maximum]) values were recorded. These percentile values were plotted as a function of the export pumping to indicate the shift in the tidal stage range that was caused by the different assumed pumping flows. The maximum SWP Banks pumping of 10,300 cfs was included in these figures to indicate the potential for the next increment of SWP Banks export pumping, which influences the tidal stage range in the south Delta.

Grant Line Canal maximum stage decreases from about 2.75 to 2.5 feet (3 inches) as the SWP Banks pumping increases from 6,680 to 8,500 cfs. The minimum stage decreases from –0.5 to –0.75 foot (3 inches) without any tidal barriers or tidal gates. Old River at Tracy Boulevard Bridge maximum stage decreases from 2.75 to 2.5 feet with the increased SWP Banks pumping from 6,680 to 8,500 cfs. Minimum tide decreases from –0.75 to –1.0 foot.

Figure D-107 shows the simulated effects of the export pumping on Middle River stage at Tracy Boulevard Bridge and at Mowry Bridge. Maximum stage decreases by about 3 inches at both stations in Middle River as the SWP Banks pumping increases from 6,680 to 8,500 cfs. The minimum stage decreases from –0.75 to –1.0 foot at Tracy Boulevard Bridge and from –0.25 to –0.5 foot at Mowry Bridge as the SWP Banks pumping increases from 6,680 to 8,500 cfs with no temporary barriers or permanent tidal gates.

Figure D-108 shows the effects of pumping on tides simulated in Old River at Clifton Court Ferry and at the head of Old River. Maximum stage decreases by the most at Clifton Court Ferry because it is located near the DMC intake channel and the CCF intake gates. The maximum stage decreases by less than 3 inches at Clifton Court Ferry (to about 2.5 feet msl) and at the head of Old River (to about 3.0 feet msl) as the SWP Banks pumping increases from 6,680 to 8,500 cfs. The minimum stage decreases from –1.0 to –1.15 feet at Clifton Court Ferry and from 0.5 to 0.4 foot at the head of Old River as the SWP Banks pumping increases from 6,680 to 8,500 cfs with no temporary barriers or permanent tidal gates.

The maximum effect of increasing SWP Banks pumping from 6,680 to 8,500 cfs is very small without any temporary barriers or permanent tidal gates. The changes in tidal hydraulic conditions are considered to be less than significant because the changes in minimum tidal stages would be less than 3 inches, even without permanent tidal gates. The simulated changes in tidal flows are relatively small compared to the existing flows with 6,680 cfs of SWP Banks diversion (and pumping). The changes are simulated to be less than 5% of the existing maximum tidal flow magnitude because the maximum diversion of 15,000 cfs at the CCF intake gates already occurs during high tides with 6,680 cfs of SWP Banks pumping.

However, the SDIP facilities are intended to improve tidal stage conditions that currently exist in the south Delta channels with 4,600 cfs of CVP Tracy pumping and 6,680 cfs of SWP Banks pumping, and not simply mitigate effects from the increased pumping from 6,680 to 8,500 cfs.

Hydraulic Effects of the Vernalis Adaptive Management Plan

The VAMP involves three management actions used in combination to improve Chinook salmon survival from the San Joaquin River tributaries:

- increase the natural San Joaquin River flow during the April 15–May 15 period to one of five target flows—2,000 cfs, 3,200 cfs, 4,450 cfs, 5,700 cfs or 7,000 cfs;
- install a temporary rock barrier with culverts at the head of Old River to reduce the diversion of San Joaquin River water into Old River during the peak migration of Chinook salmon smolts; and

- reduce CVP Tracy and SWP Banks pumping to less than the 1995 WQCP-mandated level, which allows combined CVP Tracy and SWP Banks pumping to be equal to the San Joaquin River flow.

Reclamation and the San Joaquin River Group Authority jointly prepared an environmental impact statement (EIS)/EIR for meeting the flow objectives for the draft San Joaquin River Agreement from 1999 to 2010. The agreement developed as an alternative that provides a level of protection equivalent to the San Joaquin River flow objectives contained in the 1995 WQCP. Discussion over the flow objectives led to a proactive, problem-solving process for developing an adaptive fish management plan and the water supplies to support that plan. The process of developing VAMP resulted in the agreement in April 1998. The agreement identifies where the water to support the VAMP study would be obtained, specifically from the San Joaquin River Group Authority, whose members are willing sellers. The agreement provides for a maximum of 137,500 acre-feet of water to be supplied in any one year. Smaller amounts are required in dry years. The average allocation of water for VAMP flows is expected to be about 40 thousand acre-feet per year.

A temporary rock barrier placed across the head of Old River reduces the flow into Old River and thereby reduces the loss of Chinook salmon smolts at the CVP Tracy and SWP Banks facilities. The weir crest elevation has varied slightly during the period of spring placement. The 2003 weir crest elevation was 10 feet msl. The weir is higher than the normal tidal fluctuations at this location and prevents most San Joaquin River flow from entering Old River. Culverts have been included to allow a controlled portion of San Joaquin River flow to enter Old River and provide a water supply to the south Delta. The culverts are 48-inch-diameter pipes with a capacity of about 150 cfs averaged over the daily tidal stage variation. There is also some seepage of water through the rock weir structure.

A series of DSM2 simulations were made to evaluate the effects of VAMP on south Delta tidal hydraulic conditions. San Joaquin River flow was assumed to be at one of the VAMP target flows of 2,000 cfs, 3,200 cfs, 4,450 cfs, 5,700 cfs, or 7,000 cfs. The head of Old River temporary rock barrier (2002 design) was assumed to be either open or installed without culverts to provide the most complete barrier to San Joaquin River flow diversion into Old River. Exports were assumed to be equal to the San Joaquin River flow, with export pumping split between the CVP and SWP, or equal to the VAMP export target (i.e., 1,500 cfs exported when the San Joaquin River flow is 2,000 cfs, 3,200 cfs, or 4,450 cfs; 2,250 cfs exported when the San Joaquin River flow is 5,700 cfs; and 3,000 cfs exported when the San Joaquin River flow is 7,000 cfs). These assumptions result in a total of 20 modeled combinations to evaluate the five VAMP target conditions. Table D-3 summarizes the simulated flows in south Delta channels for this range of VAMP conditions.

Table D-3. Simulated Net Channel Flow in Delta Channels for the Range of San Joaquin River Flows and Exports during Vernalis Adaptive Management Plan Period (Sacramento River at Freeport Flows of 15,000 cfs)

	San Joaquin River =2,000 cfs				S an Joaquin River =3,200 cfs				San Joaquin River =4,450 cfs				San Joaquin River =5,700 cfs				San Joaquin River =7,000 cfs			
	Barrier Open		Barrier Closed		Barrier Open		Barrier Closed		Barrier Open		Barrier Closed		Barrier Open		Barrier Closed		Barrier Open		Barrier Closed	
Location	Exports = 2,000 cfs	Exports = 1,500 cfs	Exports = 2,000 cfs	Exports = 1,500 cfs	Exports = 3,200 cfs	Exports = 1,500 cfs	Exports = 3,200 cfs	Exports = 1,500 cfs	Exports = 4,450 cfs	Exports = 1,500 cfs	Exports = 4,450 cfs	Exports = 1,500 cfs	Exports = 5,700 cfs	Exports = 2,250 cfs	Exports = 5,700 cfs	Exports = 2,250 cfs	Exports = 7,000 cfs	Exports = 3,000 cfs	Exports = 7,000 cfs	Exports = 3,000 cfs
San Joaquin River at Mossdale	1,914	1,914	1,914	1,914	3,115	3,115	3,115	3,115	4,365	4,365	4,365	4,365	5,615	5,615	5,615	5,615	6,915	6,915	6,915	6,915
Old River at Head	1,225	1,207	0	0	1,780	1,727	0	0	2,358	2,287	0	0	2,996	2,931	0	0	3,679	3,620	0	0
Old River at Tracy	134	133	-14	-16	200	200	-8	-16	262	272	-1	-15	325	345	6	-12	407	420	16	-9
Old River at Clifton Court Ferry	-140	89	-1,311	-1,063	-206	583	-1,906	-1,063	-277	1,111	-2,524	-1,063	-298	1,341	-3,141	-1,435	-311	1,607	-3,784	-1,807
Old River near Byron	-733	-419	-1,523	-1,195	-1,157	-84	-2,308	-1,194	-1,603	275	-3,129	-1,192	-2,015	198	-3,951	-1,681	-2,436	149	-4,806	-2,169
Old River at Bacon Island	-350	-139	-877	-657	-627	92	-1,401	-649	-919	340	-1,951	-640	-1,191	296	-2,506	-961	-1,467	272	-3,082	-1,282
Old River at Mouth	-2,787	-2,674	-3,207	-3,087	-3,005	-2,613	-3,620	-3,207	-3,240	-2,549	-4,049	-3,330	-3,455	-2,635	-4,478	-3,631	-3,670	-2,709	-4,921	-3,937
Grant Line Canal at Tracy Boulevard Bridge*	862	843	-161	-161	1,330	1,269	-161	-161	1,822	1,726	-161	-161	2,363	2,258	-162	-161	2,917	2,824	-165	-161
Middle River at Mowry Bridge	77	80	24	26	98	107	18	26	124	139	12	26	159	177	6	23	206	226	-1	19
Middle River at Tracy Boulevard Road	-7	-4	-60	-58	14	23	-66	-58	40	55	-72	-58	75	93	-78	-61	123	142	-84	-65
Middle River at Bacon Island	-1,003	-760	-1,629	-1,378	-1,331	-503	-2,234	-1,387	-1,668	-225	-2,860	-1,397	-1,970	-282	-3,485	-1,783	-2,273	-314	-4,138	-2,168
Turner Cut	-271	-234	-420	-381	-354	-229	-562	-432	-433	-218	-714	-489	-502	-253	-872	-609	-573	-286	-1,046	-735
Middle River at Mouth	-817	-625	-1,379	-1,179	-1,116	-462	-1,932	-1,256	-1,424	-282	-2,503	-1,334	-1,705	-366	-3,068	-1,709	-1,985	-431	-3,650	-2,082
False River	1,550	1,638	1,499	1,588	1,526	1,825	1,449	1,751	1,500	2,020	1,395	1,921	1,474	2,086	1,342	1,957	1,447	2,159	1,288	2,001
San Joaquin River at Antioch	4,170	4,536	4,157	4,524	4,160	5,401	4,145	5,386	4,151	6,301	4,135	6,286	4,146	6,655	4,127	6,637	4,142	7,047	4,120	7,026

Notes:

cfs = cubic feet per second.

Open = Head of Old River barrier open.

Closed = Head of Old River barrier closed.

Grant Line Canal at Tracy Boulevard Bridge is Grant Line Canal East.

Mossdale and Head of Old River Tidal Stage

Figure D-109 shows the effects of closing the head of Old River fish control barrier with a San Joaquin River flow of 2,000 cfs and export pumping of 2,000 cfs. The San Joaquin River stage increases because the entire flow is confined in the San Joaquin River channel from Mossdale downstream to Stockton. The San Joaquin River low-tide stage at Mossdale for May 1997 increases from about 2 to 3 feet msl when the head of Old River fish control barrier is closed. The high-tide elevation at Mossdale is about 2.5–3.5 feet msl. The tidal stage variations at Mossdale are slightly reduced by closing the head of Old River fish control barrier because the San Joaquin River stage is higher.

The tidal stage in Old River downstream of the head of Old River fish control barrier is reduced when the flow from the San Joaquin River is eliminated. The low-tide stage with the head of Old River fish control barrier open is about 0.75–1.00 foot msl. The low-tide stage with the head of Old River fish control barrier closed is about –1.0 foot msl. The downstream stage is reduced by almost 2.0 feet at a San Joaquin River flow of 2,000 cfs. The stage change between Mossdale and Old River is about 1 foot when the barrier is open. The tidal stage variation in Old River is greater than at Mossdale because the low-tide elevation is only about 0.5 foot msl, allowing the high tides of 3.0 feet msl to increase the water elevation in Old River by about 2.5 feet. When the head of Old River fish control barrier is closed, the tidal variation in Old River downstream of the barrier becomes similar to other south Delta channels, with a low tide of -1.0 foot msl and a high tide of about 2.5 feet msl.

Figure D-110 shows the effects of closing the head of Old River fish control barrier with a San Joaquin River flow of 3,200 cfs and export pumping of 3,200 cfs. Upstream of the barrier, the simulated May 1997 San Joaquin River stage at Mossdale increases by about 1.5 feet, from 3–4.5 feet msl. The tidal stage variations are reduced by closing the head of Old River fish control barrier because the river stage is raised above the normal tidal range. Downstream of the barrier, the Old River stage is reduced. The low-tide stage with the head of Old River fish control barrier open is about 1.5 feet msl. The low-tide stage with the head of Old River fish control barrier closed is about –1.25 feet msl. The downstream stage is reduced by almost 2.5 feet at a San Joaquin River flow of 3,200 cfs.

Figure D-111 shows the effects of closing the head of Old River fish control barrier with a San Joaquin River flow of 4,500 cfs and exports of 4,500 cfs. The Mossdale stage increases from about 4.5 feet (head of Old River fish control barrier open) to about 6.25 feet (head of Old River fish control barrier closed). The tidal stage variations are slightly more than 0.5 foot at this flow and are reduced slightly by closing the head of Old River fish control barrier because the river stage is raised by an additional 2 feet. The stage in Old River downstream of the temporary head of Old River fish control barrier is reduced substantially when the diversion from the San Joaquin River is eliminated. The low-tide stage with the head of Old River fish control barrier open is about 2.5 feet msl. The low-tide stage with the head of Old River fish control barrier closed is about

-1.25 feet msl. The downstream stage is reduced by almost 3.75 feet at a San Joaquin River flow of 4,450 cfs.

Figure D-112 shows the effects of closing the head of Old River fish control barrier with a San Joaquin River flow of 5,700 cfs and exports of 5,700 cfs. The Mossdale stage increases from about 5.5 feet (head of Old River fish control barrier open) to about 7.75 feet (head of Old River fish control barrier closed). The tidal stage variations are less than 0.25 foot at this flow and are reduced even more by closing the head of Old River fish control barrier because the river stage is raised by an additional 2 feet. Again, the stage in Old River downstream of the temporary head of Old River fish control barrier is reduced substantially when the diversion from the San Joaquin River is eliminated. The low-tide stage with the head of Old River fish control barrier open is about 3.25 feet msl. The low-tide stage with the head of Old River fish control barrier closed is about -1.25 feet msl. The downstream stage is reduced by almost 4.5 feet at a San Joaquin River flow of 5,700 cfs because the diversion flow of about 3,000 cfs raises the tidal stage substantially in the Old River channel.

Figure D-113 shows the effects of closing the head of Old River fish control barrier with a San Joaquin River flow of 7,000 cfs and exports of 7,000 cfs. This flow is the highest VAMP target flow for Vernalis. The Mossdale stage increases from about 6.5 feet (head of Old River fish control barrier open) to about 9.0 feet (head of Old River fish control barrier closed). The tidal stage variations are less than 0.25 foot at this flow and are reduced even more by closing the head of Old River fish control barrier because the river stage is raised by an additional 2.5 feet. Meanwhile, the stage in Old River downstream of the temporary head of Old River fish control barrier is reduced substantially when the diversion from the San Joaquin River is eliminated. The low-tide stage with the head of Old River fish control barrier open is about 4.0 feet msl. The low-tide stage with the head of Old River fish control barrier closed is about –1.5 feet msl with export pumping of 7,000 cfs. The downstream stage is reduced by almost 5.5 feet at the San Joaquin River flow of 7,000 cfs because the diversion flow of about 3,678 cfs raises the tidal stage substantially in the Old River channel. The tidal stage range is only about 0.75 foot (9 inches) with the head of Old River fish control barrier open and is much greater (high tide of 3.0 feet), although not quite the full tidal range, when the head of Old River fish control barrier is closed.

Middle River at Mowry Bridge Stage

Mowry Bridge is located about 1.5 miles downstream of the head of Middle River at Old River. The head of Middle River is located about 4 miles downstream of the head of Old River fish control barrier. Tidal flows in Middle River are relatively small, and the net flow from Old River into Middle River is about 100 cfs when San Joaquin River flow is 2,000 cfs.

Figure D-114 shows the effects of closing the head of Old River fish control barrier with a San Joaquin River flow of 2,000 cfs and exports of 2,000 cfs.

Figure D-114 also shows the comparable effects of closing the head of Old River fish control barrier with a flow of 7,000 cfs and exports of 7,000 cfs. With a San Joaquin River flow of 2,000 cfs, closing the head of Old River fish control barrier has less than a 0.75-foot (9-inch) effect on the low tides and about the same effect on the high tides. Closing the head of Old River fish control barrier when the San Joaquin River flow is 7,000 cfs has a larger effect because the stage in Middle River at Mowry Bridge is considerably elevated by the San Joaquin River flow of 7,000 cfs. The tidal stage at Mowry Bridge when the head of Old River fish control barrier is closed ranges from low tides of –1.25 feet msl to high tides of about 2.0 feet msl. The tidal range is raised by about 3 feet with the head of Old River diversions (of about 3,678 cfs) at a San Joaquin River flow of 7,000 cfs. The tidal stage in Middle River ranges from a low tide of about 1.75 feet msl to a high tide of about 3.5 feet msl with the head of Old River fish control barrier open at a San Joaquin River flow of 7,000 cfs.

Old River at Tracy Boulevard Bridge Stage

The Tracy Boulevard Bridge is located about 10 miles downstream of the head of Old River. The effects of the head of Old River diversions from the San Joaquin River on tidal stage variations at the Tracy Boulevard Bridge are much less than at the head of Old River. Most of the diversions flow through Doughty Cut into Grant Line Canal.

Figure D-115 shows the effects of closing the head of Old River fish control barrier with a San Joaquin River flow of 2,000 cfs and exports of 2,000 cfs. Figure D-115 also shows the comparable effects of closing the head of Old River fish control barrier with a flow of 7,000 cfs and exports of 7,000 cfs. With a San Joaquin River flow of 2,000 cfs, closing the head of Old River fish control barrier has less than a 0.5-foot (6-inch) effect on the low tides and about the same effect on the high tides in Old River at Tracy Boulevard Bridge. Closing the head of Old River fish control barrier when the San Joaquin River flow is 7,000 cfs has a larger effect because the stage in Old River at Tracy Boulevard Bridge station is somewhat elevated by the San Joaquin River flow of 7,000 cfs. The tidal stage when the head of Old River fish control barrier is closed ranges from low tides of –1.25 feet msl to high tides of 1.75 feet msl. The tidal range is raised by about 0.75 foot with the head of Old River diversions at a San Joaquin River flow of 7,000 cfs.

Grant Line Canal at Tracy Boulevard Bridge Stage

Head of Old River diversion flows generally move into Grant Line Canal through Doughty Cut, located about 8 miles downstream of the head of Old River. The Tracy Boulevard Bridge is located about 2 miles downstream of this connection with Old River, so this station is about 10 miles downstream from the head of Old River.

Figure D-116 shows the effects in Grant Line Canal at Tracy Boulevard Bridge of closing the head of Old River fish control barrier with a San Joaquin River flow of 2,000 cfs and exports of 2,000 cfs. Figures D-117a–d also show the comparable effects of closing the head of Old River fish control barrier with a flow of 7,000 cfs and exports of 7,000 cfs. With a San Joaquin River flow of 2,000 cfs, closing the head of Old River fish control barrier has less than a 0.5-foot (6-inch) effect on the low tides and about the same effect on the high tides in Grant Line Canal at Tracy Boulevard Bridge. Closing the head of Old River fish control barrier when the San Joaquin River flow is 7,000 cfs has a larger effect because the stage at the Grant Line Canal at Tracy Boulevard Bridge station is somewhat elevated by the San Joaquin River flow of 7,000 cfs. The tidal stage when the head of Old River fish control barrier is closed ranges from low tides of –1.25 feet msl to high tides of 1.75 feet msl. The low tides are raised by about 1.0 foot, and the high tides are raised by 0.75 foot in Grant Line Canal at Tracy Boulevard Bridge with the head of Old River diversions at a San Joaquin River flow of 7,000 cfs.

Summary of South Delta Tidal Effects from the Vernalis Adaptive Management Plan

This section summarizes the tidal tour of the south Delta channels given above. The increased San Joaquin River flow at Vernalis raises the stage in the San Joaquin River at Mossdale and increases the head of Old River flow and stages in the south Delta channels. The low tide at the head of Old River increases from about 0.5 foot msl at a flow of 2,000 cfs to about 1.5 feet at a flow of 3,200 cfs. The low-tide stage increases to about 2.0 feet msl at a flow of 4,450 cfs and to about 3.25 feet msl at a flow of 5,700 cfs. The low-tide stage is about 4.0 feet at a flow of 7,000 cfs. The increase in stage in the south Delta channels that are upstream of the temporary barriers is about 0.5–1.0 foot with a San Joaquin River flow of 7,000 cfs, compared to a flow of 2,000 cfs. The stage variations in the south Delta channels are more directly controlled by the Delta tidal stage variations than by the head of Old River diversions.

Closing the head of Old River fish control barrier reduces the stage in the south Delta channels to the normal tidal variations, with low tides of about –1.0 to –1.5 feet. With the head of Old River fish control barrier closed, the effects of additional pumping (2,000–7,000 cfs) during the VAMP period do not substantially reduce the low tides at the Old River, Grant Line Canal, or Middle River stations.

Figures D-117a–d show the effects of San Joaquin River flow and export pumping on stage variations at these south Delta stations. The tidal stage ranges when the head of Old River fish control barrier is closed are only slightly reduced as pumping increases. The tidal flows are somewhat reduced as the tidal stage increases with higher head of Old River diversions.

DSM2 Simulation of SDIP Alternatives

Approach

For the analysis of the SDIP alternatives, a two-tiered modeling approach was used (Figure D-118). The California statewide operations model, CALSIM II, was used to simulate monthly impacts of alternatives on statewide water supply (e.g., reservoir operations, project deliveries) over a 73-year period using hydrology from water years 1992–1994. Details of the CALSIM II analysis can be found in Chapter 5.1, "Water Supply and Management." To assess the impacts of these alternatives on the Delta tidal hydraulics and water quality conditions, DSM2 was used to simulate 15-minute hydrodynamics and water quality over a 16-year period using hydrology provided by CALSIM II results for water years 1976–1991. The Delta tidal hydraulic impacts and water quality impacts of the SDIP alternatives were assessed for a shorter time period than the statewide water supply impacts because of the extensive computational requirements of the DSM2 tidal hydraulic model. However, because the 16-year time period from 1976 to 1991 encompasses a variety of water year types (Table D-4), including the driest and wettest time periods on record, the SDIP alternatives analysis takes into account the full range of historical hydrologic conditions.

Table D-4. Water Year Designations for the Sacramento River System

	Year															
	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
Water Year Type	C	C	AN	BN	AN	D	W	W	W	D	W	D	C	D	C	C

Note: W=Wet, AN=Above normal, BN=Below normal, D=Dry, C=Critical.

Two modules of DSM2, HYDRO and QUAL, were used to analyze SDIP alternatives for 16 years of hydrologic conditions. An additional module, PTM, was used to analyze fish movement and entrainment for selected conditions of exports and VAMP conditions.

Representation of Delta Water Quality in CALSIM II and DSM2

The assessment of flow and salinity impacts of the SDIP alternatives in the Delta requires tools that represent flow-salinity relationships in the Delta. The two numerical models CALSIM II and DSM2 both represent flow-salinity relationships in the Delta. The main difference between the salinity representations in the two models is that CALSIM II uses an average salinity-outflow representation, whereas DSM2's includes spring-neap tidal effects.

Thus, salinity extremes (both high values and low values) will be greater in the DSM2 representation than in the CALSIM II representation.

To better describe Delta flow-salinity representations in CALSIM II and DSM2, some terminology is defined below:

- *ANN*—A computer algorithm that can be "trained" to recognize complex relationships from information in a large data set. In this case, an ANN was created to determine relationships between Delta flow parameters and salinity concentrations at specified locations (California Department of Water Resources 2002).
- *25-Hour Repeating 19-Year Mean Tide*—A 25-hour time series of hourly varying tidal stage that represents the two high and two low tides (mixed tide) that occur in the Bay every tidal cycle. For simulations longer than 25 hours, the 25-hour tidal sequence is repeated for subsequent tidal cycles. For Martinez, a 25-hour hourly time series of tidal stage was computed based on 19 years of field data. This 19-year mean tide represents a typical daily tidal cycle; however, it does not include the bimonthly spring-neap tidal cycle (Nader-Tehrani 2001).
- *Adjusted Astronomical Tide*—A computed 15-minute varying tidal stage time series that approximates the observed tidal stage data. An adjusted astronomical tide is computed by modifying (adjusting) the astronomical tide at a given location to incorporate long-period wave components. For DSM2, an adjusted astronomical tide is computed at Martinez using long-period wave components from observed data at San Francisco. The adjusted astronomical tide represents both the daily tidal variations and the spring-neap tidal fluctuations expected at Martinez (Figures D-119a and b) (Ateljevich 2001a).

Although estimation of Delta salinity is important in both models, they employ different methods. DSM2 is a physically based, one-dimensional tidal hydraulic model that simulates the transport of constituents, such as salinity, throughout the Delta. This transport is represented by advection (movement with the flow) and dispersion (mixing caused by turbulence and diffusion) of salinity. To simulate this transport, salinity concentrations must be known at all of the boundaries.

In the San Francisco Bay and Delta, salinity concentrations are mainly determined by the tidal transport of salt from the ocean balanced against the Delta outflow. Thus, the downstream boundary condition for water quality simulations in DSM2 reflects the dynamic dispersion of salt into the Delta from the ocean. DSM2 uses an empirical model known as the *modified G-model* to compute a 15-minute time series of electrical conductivity (EC), a measure of salinity at Martinez, based on an adjusted astronomical tide and net delta outflow (Ateljevich 2001b). Given this downstream boundary time series and other salinity boundary conditions, DSM2 simulates the advection and dispersion of salinity throughout the Delta to determine salinity concentrations at interior Delta locations. Because an adjusted astronomical tide was used as input for the modified G-model to create the Martinez salinity boundary condition for the

SDIP alternative simulations, the representation of salt intrusion into the Delta from the ocean in these simulations considers spring-neap tidal effects.

CALSIM II uses a different approach for representing salinity in the Delta. Although the Delta salinity standards are integral for determining the upstream reservoir operations, the simple mass-balance routing and monthly time step in CALSIM II do not produce sufficiently accurate estimates of Delta salinity. Additionally, although DSM2 can compute the necessary Delta salinities, the computational requirements of DSM2 are orders of magnitude larger than those for CALSIM II, making integrated simulations using DSM2 and CALSIM II interactively unfeasible. Thus, an ANN was developed to represent Delta flow-salinity relationships based on DSM2 simulation results. The ANN provides a computationally efficient method for determining flow-salinity relationships that can be integrated into CALSIM II. The flow-salinity relationships represented by the ANN were developed by "training" the ANN on DSM2 simulation results based on a 25-hour repeating 19-year mean tide. Thus the ANN representation of salinity in CALSIM II does not take into account the spring-neap tidal cycle. The ANN estimates of salinity are used in CALSIM II to estimate required Delta outflow. The CALSIM outflow is used in DSM2 to set the Martinez salinity conditions, and the DSM2 model calculates salinity within the Delta. The CALSIM II estimates and the DSM2 results may not match exactly.

SDIP Alternatives

For the tidal hydraulic and water quality analysis of impacts of the SDIP alternatives, scenarios at both the 2001 and 2020 levels of development were examined. The baseline scenarios used temporary fish and agricultural barriers in the south Delta, whereas the SDIP alternatives used proposed permanent fish and agricultural tidal gates (Figures D-120a–c).

For analysis of the SDIP alternatives, four south Delta barriers or gates were considered:

- fish barrier at head of Old River (both temporary barrier and permanent tidal gate),
- agricultural barrier at Middle River (both temporary barrier and permanent tidal gate),
- agricultural barrier at Grant Line Canal (east temporary barrier, west permanent tidal gate), and
- agricultural barrier at Old River at Tracy Boulevard Bridge (both temporary barrier and permanent tidal gate).

Alternative 2B was used to assess the impacts of various tidal gate configurations (no gates, fish gate at head of Old River only, fish gate with two agricultural gates, and fish gate with three agricultural gates). Because the three agricultural gates were required to maintain minimum water-level requirements in the south Delta, additional alternatives were examined only with the fish gate and three agricultural gates. Detailed descriptions of the SDIP alternatives are found in Chapter 2 of the EIS/EIR. The scenarios examined using DSM2 were:

- Existing Conditions:
  - ❑ 2001 conditions with temporary south Delta fish barrier and three temporary agricultural barriers;
- Future No Action:
  - ❑ 2020 conditions with no south Delta barriers and
  - ❑ 2020 conditions with temporary fish barrier and three temporary agricultural south Delta barriers;
- Alternative 2A for 8,500 cfs:
  - ❑ 2001 conditions with permanent fish tidal gate and three permanent agricultural south Delta tidal gates and
  - ❑ 2020 conditions with permanent fish tidal gate and three permanent agricultural south Delta tidal gates;
- Alternative 2B for 8,500 cfs:
  - ❑ 2001 conditions with permanent fish tidal gate and three permanent agricultural south Delta tidal gates and
  - ❑ 2020 conditions with permanent fish tidal gate and three permanent agricultural south Delta tidal gates;
- Alternative 2C for 8,500 cfs:
  - ❑ 2001 conditions with no south Delta gates;
  - ❑ 2001 conditions with permanent fish tidal gate and three permanent agricultural south Delta tidal gates;
  - ❑ 2020 conditions with no south Delta gates;
  - ❑ 2020 conditions with permanent fish tidal gate;
  - ❑ 2020 conditions with permanent fish tidal gate and two permanent agricultural south Delta tidal gates; and
  - ❑ 2020 conditions with permanent fish tidal gate and three permanent agricultural south Delta tidal gates.

DSM2 Input Requirements

Extensive input data are required for DSM2 (Figure D-121). These input data fall into four general categories:

- physical description of the system (e.g., channel cross sections and other geometry information) (Delta Simulation Model Version 2 Project Work Team 2001),

- description of flow control structures (i.e., gates and barriers) (Anderson and Mierzwa 2002),
- initial estimates for stage and flow throughout the Delta, and
- boundary conditions (i.e., time-varying input for all inflows and exports).

Figure D-122 illustrates the hydrodynamic and water quality boundary conditions required for the SDIP studies. Inflows, exports, and DCC gate operations were provided by the 73-year CALSIM II simulations. The tidal boundary condition at Martinez was provided by an adjusted astronomical tide (Ateljevich 2001a). Delta channel depletions (i.e., diversions and drainage) were estimated using DWR's DICU model (Mahadevan 1995) for both the 2001 and 2020 levels of development. The major hydrodynamic boundary conditions and the time period for which they are specified are:

- tidal boundary condition (15 minutes):
  - ☐ tidal stage from adjusted astronomical tide at Martinez;
- inflow boundary conditions from CALSIM II (monthly, except San Joaquin River flows are specified bimonthly during VAMP):
  - ☐ Sacramento River,
  - ☐ San Joaquin River,
  - ☐ eastside streams (Mokelumne and Cosumnes Rivers),
  - ☐ Calaveras River, and
  - ☐ Yolo Bypass;
- export boundary conditions from CALSIM II (monthly, except SWP Banks and CVP Tracy exports are specified bimonthly during VAMP):
  - ☐ CCF (SWP),
  - ☐ CVP Tracy facility–DMC (CVP), and
  - ☐ CCC (combined CCC and Los Vaqueros);
- DCC gate operations and MSSCG operations from CALSIM II; and
- DICU for 2001 and 2020 from DICU model.

Water quality boundary conditions consist of specifying constituent concentrations at each inflow. The water quality boundary conditions and typical time periods for which they are specified are:

- tidal boundary condition (15 minutes):
  - ☐ constituent concentration at Martinez;
- inflow boundary conditions (monthly or constant):
  - ☐ Sacramento River (constant),
  - ☐ San Joaquin River (monthly from CALSIM II),

    - ❑ eastside streams (Mokelumne and Cosumnes Rivers),
    - ❑ Calaveras River, and
    - ❑ Yolo Bypass; and
- Delta island drainage and return flows (monthly).

Input Assumptions for SDIP Studies

Input assumptions and characteristics for the DSM2 16-year planning studies for SDIP are described below. The assumptions that changed for different operational and barrier (or gate) scenarios are summarized in Table D-5.

Vernalis Adaptive Management Plan Flows for San Joaquin River and SWP Banks and CVP Tracy Exports

VAMP modifies San Joaquin River flows and SWP Banks and CVP Tracy export rates to enhance anadromous fish migration. Components of VAMP include a 31-day flow pulse in the San Joaquin River from April 15 to May 15 and corresponding reductions in exports at the SWP Banks and CVP Tracy during this time period. CALSIM II accounts for VAMP in its computations; however, the final (cycle 5 results) monthly outputs for the San Joaquin River at Vernalis, SWP Banks, and CVP Tracy do not reflect the VAMP flows and exports. Thus, for all the SDIP alternatives, the CALSIM II results were postprocessed to produce input data for DSM2 that include the VAMP pulse flow and reduced CVP Tracy and SWP Banks exports (from cycle 2 results).

Clifton Court Forebay Operations

DSM2 can simulate the operation of the CCF intake gates in a variety of ways known as priorities (Figure D-123). For the SDIP existing condition simulation, the CCF was operated tidally using Priority 3. For the alternative scenarios, the CCF intake gates were always open (Priority 4) as long as the inside CCF stage was lower than the outside Old River stage. Thus, differences between water levels inside and just outside the CCF in West Canal determined when and how much water flowed into the CCF. To ensure that DSM2 did not allow unrealistically high flows into the CCF, the maximum flow was capped at about 15,000 cfs. The rate at which water can flow into the CCF was determined by a flow coefficient called *coeff2res*. For the SDIP studies, coeff2res was set equal to 2,400, a value appropriate for flows on the order of 15,000 cfs.

Flow through an orifice is calculated using the following equation:

$$Q = coeff\,2res \times \sqrt{2g\Delta h}$$

Table D-5. Simulation Characteristics and Assumptions for 16-Year DSM2 Simulations of SDIP Alternatives

Simulation Characteristic or Assumption	Baseline		2001 Conditions			2020 Conditions		
	2001	2020	Alternative 2A	Alternative 2B	Alternative 2C	Alternative 2A	Alternative 2B	Alternative 2C
Barrier or Gate								
Type	Temporary	Temporary	Permanent	Permanent	Permanent	Permanent	Permanent	Permanent
Fish control barrier/ gate operations	Temporary barrier operations criteria	Temporary barrier operations criteria	Closed April–May and partially Closed October–November unless SJR>10,000 cfs	Closed April–May and partially Closed October–November unless SJR>10,000 cfs	Closed April–May and partially Closed October–November unless SJR>10,000 cfs	Closed April–May and partially Closed October–November unless SJR>10,000 cfs	Closed April–May and partially Closed October–November unless SJR>10,000 cfs	Closed April–May and partially Closed October–November unless SJR>10,000 cfs
DSM2 analysis with fish gate (head of Old River) only				X			X	
DSM2 analysis with fish gate and two agricultural gates				X			X	
DSM2 analysis with fish gate and three agricultural gates	X	X	X	X	X	X	X	X
Geometry								
Dredging in Middle River			X	X	X	X	X	X
Modified Delta geometry near the Middle River temporary barrier	X	X						

Notes:

SJR = San Joaquin River.

cfs = cubic feet per second.

where Q=flow cfs, g=acceleration caused by gravity (32.2 feet^2/sec) and Δh =head difference in feet. However, because of past numerical instabilities, the DSM2 code applies a factor of 75% to the reservoir coefficient. Although the numerical instabilities are no longer an issue, the 75% factor has remained in the DSM2 code. Effectively, DSM2 calculates the equation:

$$Q = 0.75 \times coeff\,2res \times \sqrt{2g\Delta h}\ .$$

A value of *coeff2res* of 1,800 is typically used for simulations in which a flow of near 15,000 cfs into CCF is desired at a head difference of 1 foot. To adjust for the 75% factor in the SDIP simulations, the value of *coeff2res* was divided by 0.75:

$$\left(coeff\,2res_{adjusted} = \frac{coeff\,2res}{0.75} = \frac{1{,}800}{0.75} = 2{,}400 \right).$$

Temporary Barrier Operations

Historically, temporary barrier operations have changed from year to year. The temporary barrier operations and target flows used for the SDIP alternative analysis are described below:

- Head of Old River fish barrier is:
  - installed between April 16 and May 15 when San Joaquin River flows fall below 5,000 cfs;
  - installed between September 16 and November 30 when San Joaquin River flows fall below 5,000 cfs;
  - removed when San Joaquin River flows exceed 8,500 cfs;
  - installed in spring (April 16–May 15) at:
    - 10 feet msl if VAMP flow is less than or equal to 7,500 cfs (dry, below normal, normal years) or
    - 11 feet msl if VAMP flow is greater than 7,500 cfs (wet years);
  - installed in fall (September 16–November 30) with a 32-foot notch at 0.0 foot msl;
- Agricultural barriers (Middle River, Old River at Tracy Boulevard Bridge, Grant Line Canal East):
  - may be installed between April 16 and November 30;
  - are not installed when San Joaquin River flows exceed 18,200 cfs;
  - are not installed between April 16 and May 15 if head of Old River fish control barrier is not installed,
  - are not installed until the San Joaquin River flow drops below 12,000 cfs if head of Old River fish control barrier is not installed;

- ☐ have a 20-foot notch cut during the fall (September 16–November 30);
- ☐ change fall notch configuration (Old River at DMC only) when San Joaquin River flow is above 5,500 cfs; and
- ☐ are removed if the head of Old River fish control barrier is removed as a result of Vernalis flows exceeding 8,500 cfs, unless the barriers are needed to maintain 0.0-foot msl minimum water levels at three key locations.

The temporary barrier operations for the 16-year DSM2 simulations for the 2001 and 2020 baseline scenarios resulting from these operational guidelines and DSM2 parameters are presented in Tables D-6–D-13. As a result of similar flow regimes for the 2001 and 2020 levels of development, the barrier operations were identical for both the 2001 and 2020 baselines.

Table D-6. Head of Old River Temporary Fish Barrier Operations for 2001 and 2020 Baselines

Water Year	Oct	Nov	Dec	Jan	Feb	Mar	April	May	June	July	Aug	Sep
1976	▨ open	▨ open					■ open	■ open				▨ open
1977	▨ open	▨ open					■ open	■ open				▨ open
1978	▨ open	▨ open										▨ open
1979	▨ open	▨ open										▨ open
1980	▨ open	▨ open										▨ open
1981	▨ open	▨ open						■ open				▨ open
1982												▨ open
1983												
1984	▨ open	▨ open										▨ open
1985	▨ open	▨ open					■ open	■ open				▨ open
1986	▨ open	▨ open										▨ open
1987	▨ open	▨ open					■ open	■ open				▨ open
1988	▨ open	▨ open					■ open	■ open				▨ open
1989	▨ open	▨ open					■ open	■ open				▨ open
1990	▨ open	▨ open					■ open	■ open				▨ open
1991	▨ open	▨ open					■ open	■ open				▨ open

Notes:

open = Culvert open.
☐ = No barrier in place.
■ = Barrier in place.
▨ = Notched weir in barrier.

Table D-7. Summary of DSM2 Input Variables for Head of Old River Temporary Fish Barrier Operations for 2001 and 2020 Baselines

Variable	Value and Conditions
CFPIPEDOWN	0.60 when barrier is in place and culvert is tied open
CFPIPEUP	0.60 when barrier is in place and culvert is not tied open
CFWEIRDOWN	1.00 when barrier is not in place, 0.70 when barrier is in place
CFWEIRUP	1.00 when barrier is not in place, 0.70 when barrier is in place
CRESTELEV	10.0 feet msl when barrier is in place in spring, 0.0 foot msl when weir is notched in fall
NPIPES	6
PIPEELEV	-5.0 feet msl
PIPERAD	2 feet
POS	1 (operate barriers based on values of these variables) when barrier is in place, 10 (remove entire structure from channel) when barrier is not in place
WIDTHDOWN	200 feet in spring, 32 feet in fall when weir is notched
WIDTHUP	200 feet in spring, 32 feet in fall when weir is notched

Note: msl = mean sea level.

Table D-8. Middle River Temporary Agricultural Barrier Operations for 2001 and 2020 Baselines

Water Year	Oct	Nov	Dec	Jan	Feb	Mar	April	May	June	July	Aug	Sep
1976	▨	▨					□ ■	■ open	■	■	■	■ ▨
1977	▨	▨					□ ■	■ open	■	■	■	■ ▨
1978	▨	▨						□ open	■	■	■	■ ▨
1979	▨	▨						□ open	■	■	■	■ ▨
1980	▨	▨						□ open	■	■	■	■ ▨
1981	▨	▨						■ open	■	■	■	■ ▨
1982	▨	▨							■	■	■	■ ▨
1983	▨	▨									■	■ ▨
1984	▨	▨						□ open	■	■	■	■ ▨
1985	▨	▨					□ ■	■ open	■	■	■	■ ▨
1986	▨	▨						□ open	■	■	■	■ ▨
1987	▨	▨					□ ■	■ open	■	■	■	■ ▨
1988	▨	▨					□ ■	■ open	■	■	■	■ ▨
1989	▨	▨					□ ■	■ open	■	■	■	■ ▨
1990	▨	▨					□ ■	■ open	■	■	■	■ ▨
1991	▨	▨					□ ■	■ open	■	■	■	■ ▨

Notes:

open = Culvert open.
□ = No barrier in place.
■ = Barrier in place.
▨ = Notched weir in barrier.

Table D-9. Summary of DSM2 Input Variables for Middle River Temporary Agricultural Barrier Operations for 2001 and 2020 Baselines

Variable	Value and Conditions
CFPIPEDOWN	0.60 when barrier is in place and culvert is tied open, 0.0 when operated as tidal flap gate
CFPIPEUP	0.60
CFWEIRDOWN	1.00 when barrier is not in place, 0.70 when barrier is in place
CFWEIRUP	1.00 when barrier is not in place, 0.70 when barrier is in place
CRESTELEV	-6.00 feet msl when barrier is not in place, 1.00 foot msl when barrier is in place, 0.86 foot msl when weir is notched
NPIPES	6
PIPEELEV	-4.0 feet msl
PIPERAD	2 feet
POS	1 (operate barriers based on values of these variables) when barrier is in place, 10 (remove entire structure from channel) when barrier is not in place
WIDTHDOWN	140 feet
WIDTHUP	140 feet

Note: msl = mean sea level.

Table D-10. Grant Line Canal (East) Temporary Agricultural Barrier Operations for 2001 and 2020 Baselines

Water Year	Oct	Nov	Dec	Jan	Feb	Mar	April	May	June	July	Aug	Sep
1976	▨	▨						☐ ■ open	■	■	■	■ ▨
1977	▨	▨						☐ ■ open	■	■	■	■ ▨
1978	▨	▨						☐ ■ open	■	■	■	■ ▨
1979	▨	▨						☐ ■ open	■	■	■	■ ▨
1980	▨	▨						☐ ■ open	■	■	■	■ ▨
1981	▨	▨						☐ ■ open	■	■	■	■ ▨
1982	▨	▨							■	■	■	■ ▨
1983	▨	▨									■	■ ▨
1984	▨	▨						☐ ■ open	■	■	■	■ ▨
1985	▨	▨						☐ ■ open	■	■	■	■ ▨
1986	▨	▨						☐ ■ open	■	■	■	■ ▨
1987	▨	▨						☐ ■ open	■	■	■	■ ▨
1988	▨	▨						☐ ■ open	■	■	■	■ ▨
1989	▨	▨						☐ ■ open	■	■	■	■ ▨
1990	▨	▨						☐ ■ open	■	■	■	■ ▨
1991	▨	▨						☐ ■ open	■	■	■	■ ▨

Notes:

open = Culvert open.
☐ = No barrier in place.
■ = Barrier in place.
▨ = Notched weir in barrier.

Table D-11. Summary of DSM2 Input Variables for Grant Line Canal (East) Temporary Agricultural Barrier Operations for 2001 and 2020 Baselines

Variable	Value
CFPIPEDOWN	0.60 when barrier is in place and culvert is tied open, 0.0 when operated as tidal flap gate
CFPIPEUP	0.60
CFWEIRDOWN	1.00 when barrier is not in place, 0.80 when barrier is in place
CFWEIRUP	1.00 when barrier is not in place, 0.80 when barrier is in place
CRESTELEV	-11.00 feet msl when barrier is not in place, -13.10 feet msl when boat ramp is in place, 1.00 foot msl when barrier is in place, and 0.84 foot msl when weir is notched
NPIPES	6
PIPEELEV	-6.5 feet msl
PIPERAD	2 feet
POS	1 (operate barriers based on values of these variables); thus, culverts are in place year round, even when barrier is not in place
WIDTHDOWN	125 feet
WIDTHUP	125 feet

Note: msl = mean sea level.

Table D-12. Old River Temporary Agricultural Barrier Operations for 2001 and 2020 Baselines

Water Year	Oct	Nov	Dec	Jan	Feb	Mar	April	May	June	July	Aug	Sep
1976	▨	▨	⬜	⬜	⬜	⬜	⬜ ⬛	⬛ open	⬛	⬛	⬛	⬛ ▨
1977	▨	▨	⬜	⬜	⬜	⬜	⬜ ⬛	⬛ open	⬛	⬛	⬛	⬛ ▨
1978	▨	▨	⬜	⬜	⬜	⬜	⬜	⬜ open	⬛	⬛	⬛	⬛ ▨
1979	▨	▨	⬜	⬜	⬜	⬜	⬜	⬜ open	⬛	⬛	⬛	⬛ ▨
1980	▨	▨	⬜	⬜	⬜	⬜	⬜	⬜ open	⬛	⬛	⬛	⬛ ▨
1981	▨	▨	⬜	⬜	⬜	⬜	⬜	⬛ open	⬛	⬛	⬛	⬛ ▨
1982	▨	▨	⬜	⬜	⬜	⬜	⬜	⬜	⬛	⬛	⬛	⬛ ▨
1983	▨	▨	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬛	⬛ ▨
1984	▨	▨	⬜	⬜	⬜	⬜	⬜	⬜ open	⬛	⬛	⬛	⬛ ▨
1985	▨	▨	⬜	⬜	⬜	⬜	⬜ ⬛	⬛ open	⬛	⬛	⬛	⬛ ▨
1986	▨	▨	⬜	⬜	⬜	⬜	⬜	⬜ open	⬛	⬛	⬛	⬛ ▨
1987	▨	▨	⬜	⬜	⬜	⬜	⬜ ⬛	⬛ open	⬛	⬛	⬛	⬛ ▨
1988	▨	▨	⬜	⬜	⬜	⬜	⬜ ⬛	⬛ open	⬛	⬛	⬛	⬛ ▨
1989	▨	▨	⬜	⬜	⬜	⬜	⬜ ⬛	⬛ open	⬛	⬛	⬛	⬛ ▨
1990	▨	▨	⬜	⬜	⬜	⬜	⬜ ⬛	⬛ open	⬛	⬛	⬛	⬛ ▨
1991	▨	▨	⬜	⬜	⬜	⬜	⬜ ⬛	⬛ open	⬛	⬛	⬛	⬛ ▨

Notes:

open = Culvert open.

⬜ = No barrier in place.

⬛ = Barrier in place.

▨ = Notched weir in barrier.

Table D-13. Summary of DSM2 Input Variables for Old River Temporary Agricultural Barrier Operations for 2001 and 2020 Baselines

Variable	Value
CFPIPEDOWN	0.60 when barrier is in place and culvert is tied open, 0.0 when operated as tidal flap gate
CFPIPEUP	0.60 when barrier is in place
CFWEIRDOWN	1.00 when barrier is not in place, 0.80 when barrier is in place
CFWEIRUP	1.00 when barrier is not in place, 0.80 when barrier is in place
CRESTELEV	-9.00 feet msl when barrier is not in place, 2.00 feet msl when barrier is in place, 0.00 foot msl or 1.47 feet msl when weir is notched (depending on San Joaquin River flow)
NPIPES	9
PIPEELEV	-6.0 feet msl
PIPERAD	2 feet
POS	1 (operate barriers based on values of these variables) when barrier is in place, 10 (remove entire structure from channel) when barrier is not in place
WIDTHDOWN	75 feet for regular barrier, 20 feet for low-flow notched weir
WIDTHUP	75 feet for regular barrier, 20 feet for low-flow notched weir

Note: msl = mean sea level.

Permanent Tidal Gate Operations

The DSM2 modeling of the SDIP alternatives has provided the opportunity for the DWR Delta modeling section staff to consider several gate operation strategies and test the results against the general objectives of maintaining water levels above 0.0 feet msl, maintaining good tidal flushing, and reducing the sometimes high EC values in south Delta channels upstream of the tidal gates (i.e., Middle River upstream of Victoria Canal, Old River upstream of the DMC intake, and Grant Line Canal). It has been determined through this adaptive modeling process that the following specific tidal gate operations will work well to provide operational flexibility and management of south Delta channels for local benefits.

Continuing to operate the existing CCF tidal gate using the Priority 3 schedule, which allows the higher-high tide to fill the south Delta channels by closing the CCF gates during the flood-tide period prior to the higher-high tide each day (Figure D-123). This operation must be balanced with the need to divert the full daily export pumping volume into CCF.

Using the head of Old River tidal gate to reduce the diversion of San Joaquin River water into Old River during the summer and fall, when the San Joaquin River EC tends to be relatively high. This operation also may improve DO conditions in the Stockton Deep Water Ship Channel during low-flow periods. This must be balanced with the possible effects of this high salinity water shifting from the CVP exports to the SWP exports and CCWD diversions, as well as the planned Stockton diversion.

Opening (lowering) the three agricultural gates during all periods of flood tide to provide the maximum possible flushing of the south Delta channels upstream of these gates. The Old River and Middle River gates will then be closed (raised) at each high tide, and all ebb-tide flows will drain from the south Delta channels through Grant Line Canal. The Grant Line Canal gate will remain open during the early part of the ebb-tide, and will be raised to elevation –0.5 foot msl when the upstream water elevation approaches the 0.0 feet msl target elevation, to maintain the upstream water level above the target elevation.

Some more details about the DSM2 modeling assumptions that were used to simulate these adopted tidal gate operations are described below. The actual tidal gate operations will be controlled by a combination of real-time field measurements of tidal elevation and salinity (EC) as well as guided by the gate operations review team (GORT) that will advise DWR and Reclamation operators through the normal procedures of the data analysis team (DAT) of the CALFED operations group.

Head of Old River Fish Control Gate

Permanent Agricultural Gates

The SDIP alternatives have permanent operable tidal gates, whereas the baseline conditions have temporary barriers (weirs) in the south Delta channels.

Head of Old River Permanent Fish Tidal Gate

For all SDIP operational scenarios, the permanent fish control gate at the head of Old River was closed from April 1 to May 31 and almost completely closed from October 1 to November 30 of every year unless monthly average San Joaquin River flows at Vernalis exceed 10,000 cfs. The closure was assumed to be complete in April and May, although the actual fish control gate may have some flow through the fish ladder or passage feature (i.e., submerged opening) that is designed for adult fish migration passage. The partial closure of the fish control gate in October and November was simulated by using a flow coefficient of 0.02. Simulation results indicate that about 10-15% of the San Joaquin River flow is diverted into Old River during the partial closure periods.

The head of Old River gate operation during the summer period of June–September was simulated by assuming that a diversion of 500 cfs would be regulated by partial gate closure, whenever the San Joaquin River flow was between 800 cfs and 2,500 cfs. This generally increased the San Joaquin River flow past Stockton during the summer months. This reduction in existing conditions diversions into Old River generally reduced the salinity in the south Delta channels. This 500-cfs diversion was simulated with the “object to object” transfer from node 8 to node 48.

Permanent Agricultural Tidal Gates

Three permanent agricultural tidal gates are proposed:

- a Middle River gate near the confluence of Middle River and Victoria Canal,
- a Grant Line Canal gate at the west end of the canal (the temporary Grant Line Canal barrier is at the east end of the canal),
- and an Old River gate near the DMC (Figure D-120).

These tidal gates will be able to be opened or closed to allow water to pass upstream of the gates during rising tides and to prevent water levels upstream of the gates from dropping below a target water level during receding tides.

These gates generally will be open during all flood-tide periods (upstream flow coefficient of 0.80) to allow water to pass upstream of the gates during rising tides. The Middle River and Old River gates would then be closed during ebb-tide periods (downstream flow coefficient of 0.0) to prevent water levels upstream of the gates from dropping below a target water level during receding tides (Figure D-124). The actual flow control would be achieved by raising the tidal gates after each high tide. The model simulated this flow control with the directional flow coefficients. The Grant Line Canal gate would be raised to an elevation of –0.5 foot during ebb-tide periods to allow the south Delta channels to partially drain through the Grant Line Canal tidal gate while maintaining water elevations of greater than the 0.0 feet msl target elevation. This was simulated with a series of culverts with a crest elevation of –0.5 feet. These agricultural gate operations were simulated in all months of the year, unless the San Joaquin River flow at Vernalis was greater than a specified threshold, as described below.

The gates were not all operated when the monthly average San Joaquin River flow at Vernalis was greater than specified thresholds because it was assumed that these gate operations would not be needed during these periods of higher flows. The head of Old River summer (i.e., June–September) diversion flow of 500 cfs was not simulated (gate remained fully open) whenever the San Joaquin River flow was less than 800 cfs or greater than 2,500 cfs. The Middle River gate was not closed during ebb-tide periods whenever the San Joaquin River flow was greater than 2,500 cfs. The Old River gate was not closed during ebb-tide periods whenever the San Joaquin River flow was greater than 4,000 cfs. The Grant Line Canal gate was not closed as a weir with elevation of –0.5 foot msl whenever the San Joaquin River flow was greater than 8,000 cfs. All three agricultural tidal gates were operated (as described above) during the periods when the head of Old River gate was closed or partially closed.

Adaptive Operation of the Permanent Agricultural Tidal Gates

Actual operation of these agricultural gates would be controlled by a combination of real-time field measurements of tidal elevation and salinity (EC) and would be generally guided by the GORT that will advise DWR and Reclamation operators through the normal procedures of the DAT of the CALFED operations group.

More discussion of the likely adaptive operations of the tidal gates is provided in Section 5.2, Delta Tidal Hydraulics.

Middle River Dredging

The DSM2 geometry was modified to reflect the anticipated dredging in Middle River. The dredging criteria call for a 1:3 slope (depth: width) starting at and below 100 feet channel width. The channel geometry input files for DSM2 were examined, and it was determined that the shallowest (–3.5 feet msl) cross section occurs at the upstream end of DSM2 channel 125. To accomplish an additional 2 feet of dredging, a whole number of -6 feet msl was chosen to be the approximate channel bottom for the dredged portion of Middle River, represented by DSM2 reaches from 125 to 129 (Figure D-125). Once these criteria were set, CSDP was used to generate the dredged geometry. This modified Middle River geometry was used for all SDIP alternatives. No changes were simulated for other south Delta channels.

Delta Cross Channel Gate Operations

The same operations were used for the DCC gates for all DSM2 simulations (baselines and SDIP alternatives). The number of days each month that the DCC gates were open for the 16-year DSM2 simulations is given in Table D-14. For months in which the gates were open for part of the month, DSM2 simulated that gate as open starting on the first day of the month and closed after the designated number of days. For example, in December 1975, the gates were open for the first 16 days of the month (December 1–16) and closed for the remainder of the month, starting on December 17. For this study, the two gates at the DCC were operated together, either both open or both closed.

Table D-14. Number of Days per Month That the Delta Cross Channel Gates Were Open

	Number of Days by Year																
Month	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
Jan		11	11	0	11	0	11	0	0	0	11	11	11	0	11	11	11
Feb		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mar		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Apr		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
May		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Jun		26	26	26	26	26	26	26	0	26	26	26	26	26	26	26	26
Jul		31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31
Aug		31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31
Sep		30	30	30	30	30	30	30	0	30	30	30	30	30	30	30	30
Oct	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	0
Nov	20	20	20	20	20	20	0	0	0	0	20	20	20	20	20	20	0
Dec	16	16	16	16	16	16	0	0	0	16	16	16	16	16	16	16	0

Delta Island Consumptive Use

In DSM2, DICU is represented by three components:

- irrigation diversions from channels onto Delta islands,
- drainage and return flows from Delta islands into the surrounding channels, and
- seepage.

Thus, the net DICU is computed by the following relationship:

$$\text{Net DICU} = \mathit{Diversions} - \mathit{Drainage} + \mathit{Seepage}$$

Positive values of net DICU indicate a net depletion of water from the Delta channels, whereas negative values indicate net return flows from the Delta islands into the channels.

For this study, DICU values for the 2001 and 2020 levels of development (Figure D-126) were computed for 257 locations in the Delta using DWR’s DICU model (Mahadevan 1995). The same DICU values were used for all simulations at the same level of development. In other words, DICU was not modified in the SDIP alternatives.

Monthly average DICU values for both the 2001 and 2020 levels of development are shown in Figure D-127. DICU follows a seasonal pattern, with the largest consumption during the summer, when water is withdrawn from the Delta for irrigation. The highest return flows occur during the winter, as runoff flows from the islands into the channels.

Water Quality

This section describes the methods used for the QUAL module and the validation of the salinity (EC) patterns simulated with this module. The QUAL module is described above in “Tidal Hydraulic and Water Quality Modeling Methods.”

Water Quality Boundary Conditions for SDIP Studies

For SDIP simulations, salinity was the main constituent considered for the water quality simulations. EC was simulated as a surrogate for salinity. EC boundary conditions are summarized in Table D-15.

Table D-15. Electrical Conductivity Boundary Conditions for DSM2 16-Year Simulations

Location	Boundary Condition
Martinez	Computed by modified G-model using adjusted astronomical tide and Net Delta Outflow from CALSIM II (15-minute)
Sacramento River	Constant value = 175 µS/cm
San Joaquin River	From CALSIM II, adjusted for VAMP (monthly, bimonthly during VAMP)
Mokelumne River	Constant Value = 150 µS/cm
Cosumnes River	Constant Value = 150 µS/cm
Calaveras River	Constant Value = 150 µS/cm
Yolo Bypass	Constant value = 175 µS/cm
Delta islands return flows	Monthly values that do not vary year to year (e.g., every January has the same value, every February has the same value), nor do the values vary with level of development (e.g., 2001 and 2020)

Note: µS/cm = microSiemens per centimeter.

Electrical Conductivity of Inflows

The major source of salinity in the Delta is tidal inflow from the ocean. Salinity from the ocean is represented in DSM2 by specifying EC concentrations at Martinez. An empirical model known as the “modified G-model” is used to compute a 15-minute time series of EC at Martinez, based on an adjusted astronomical tide and net delta outflow (Ateljevich 2001b). Thus, each simulation has a slightly different EC boundary condition at Martinez reflecting the Net Delta Outflow for that scenario. For illustrative purposes, the EC boundary condition at Martinez for the 2020 baseline conditions with temporary barriers is shown in Figure D-128.

Freshwater inflows into the Delta tend to have low salinity concentration except when the inflow is affected by agricultural return flows. For these SDIP simulations, EC values for the San Joaquin River at Vernalis were provided by CALSIM II, thus EC concentrations at Vernalis varied for each simulation. For illustration purposes, EC concentrations for the San Joaquin River at Vernalis for the 2020 baseline conditions with temporary barriers are shown in Figure D-129. At all other freshwater inflow locations, constant EC boundary conditions were specified (Table D-15).

Agricultural Drainage EC Estimates

Monthly, regional representative values for monthly EC values in the Delta were determined based on available historical data. These representative EC values were determined for three regions in the Delta: the north, west, and southeast regions (Figures D-130 and D-131). These monthly representative values of EC drainage follow a seasonal trend, with highest concentrations during the runoff season in late winter and spring and peak concentrations during January or February (north region approximately 820 microSiemens per centimeter [µS/cm], west region approximately 1,890 µS/cm, and southeast region approximately 1,350 µS/cm). Minimum drainage EC concentrations occur in July and August (north region approximately 340 µS/cm, west region approximately 920 µS/cm, and southeast region approximately 740 µS/cm). From a geographic point of view, representative EC concentrations were highest for the west region, which is closest to the ocean (the major EC source in the Delta), and lowest in the north region, which has the most freshwater inflow.

In DSM2, the monthly representative EC values for each region in the Delta were assigned to the DICU nodes located in that region. DSM2 uses these representative EC values for each month of the year and repeats the yearly sequence for each year of the simulation. In other words, although the drainage EC varies monthly in DSM2, the same values are used in the same month each year (e.g., the same EC values are used each January). Thus the drainage EC values do not reflect factors such as water year type. The same drainage EC values were used for all DSM2 simulations, regardless of the level of development (e.g., there were not separate drainage EC values for the 2001 and 2020 levels of development).

Validation of DSM2 (Electrical Conductivity) Results

DSM2 simulates EC as a function of the tidal boundary EC at Martinez and the tidal hydraulics and mixing in the Delta channels. One of the most important aspects of the DSM2 EC simulations is the seawater intrusion from Martinez. The EC at the western Delta locations is found to be a function of Delta outflow, with higher outflow reducing the seawater intrusion and lowering the EC at western Delta locations. The historical measurements of EC as a function of estimated Delta outflow are reviewed below to establish this outflow-EC relationship. The DSM2 results for a range of Delta outflows are then compared with these historical measurements.

Historical Measurements of Delta Outflow and Salinity

Models are simplifications of reality that allow our basic understanding of the processes within the system of interest to be tested and evaluated. The models are formulated based on a review of the available data and previous experiences with similar systems. The models must rely on historical measurements to provide inputs. The model results are then compared with the field measurements from other locations in the system (besides the boundaries or inflows) to determine whether the historical conditions can be accurately simulated with the model equations and calculations.

Continuous (15-minute) EC measurements were begun as early as 1961 at several important locations in the Delta. The minimum, average, and maximum daily EC values were stored in the EPA STORET database for 1968–1995. Many of the station's 15-minute EC data are now available from the IEP and CDEC databases (i.e., websites). The Delta EC data for water year 1987 will be used as an example to introduce and describe the basic EC patterns in the Delta as a function of Delta outflow and other environmental conditions.

Delta Outflow During Water Year 1987

The top of Figure D-132 shows the daily outflow estimated from the measured inflow, measured exports, estimated rainfall runoff, and estimated net agricultural diversions (i.e., channel depletions). There is some uncertainty in these Delta outflow estimates because the rainfall runoff (i.e., drainage) and net channel depletions in the Delta were not measured. The direct tidal flow measurements made by the USGS tidal flow stations at Rio Vista, Jersey Point, Threemile Slough, and Dutch Slough now (since 1997) provide an alternative estimate of Delta outflow. For this review of the 1987 EC data, without a direct measurement of the 1987 outflow, there is uncertainty in the Delta outflow values.

The bottom of Figure D-132 shows the seasonal response of the average EC at several western Delta stations. The daily salinity does show a short-term variation, but the general EC response appears to follow a lagged or moving average "effective" outflow.

The effective Delta outflow is the equivalent steady-state outflow that will maintain the observed EC value at a particular monitoring station. This methodology was introduced by CCWD staff (Denton 1993), as an appropriate calculation for understanding the response of salinity in western Delta locations to changes in Delta outflow. It was referred to as the G-model by CCWD staff. Calculations of effective outflow incorporate the sequence of previous Delta outflows. The end-of-month effective outflow is calculated as a function of the previous month's effective outflow and this month's average outflow:

$$\begin{aligned}&\text{End-of-Month Effective Outflow (cfs)} = \\ &\mathit{Monthly\ Outflow\ (cfs)} \times \frac{1}{\left[1 + \left(\dfrac{\mathit{Outflow}}{\mathit{Old\ Effective\ Outflow}} - 1\right) \times \exp\left(\dfrac{-\mathit{Outflow}}{6{,}600}\right)\right]}\end{aligned}$$

where the value of 6,600 cfs is the monthly response factor suggested by CCWD staff. A response factor of 175,000 cfs was used for the daily effective outflow equation.

A second adjustment is made to calculate the monthly average effective outflow, assuming that the monthly average flow is held constant through the month so that the effective outflow approaches the end of month value exponentially (i.e., a step change response). The overall change in the monthly effective outflow will be a delayed change in the monthly outflow values. For example, if the effective Delta outflow is 4,000 cfs (which is relatively low), a change in Delta outflow would require 3 months to adjust the monthly average effective outflow. If, however, the effective Delta outflow is 10,000 cfs, a change in Delta outflow would require only 2 months to adjust the monthly average effective outflow. And if the Delta outflow is 20,000 cfs (which is relatively high), a change in Delta outflow would require only 1 month to adjust the monthly average effective outflow.

Relationship between Effective Delta Outflow and Electrical Conductivity in the Western Delta

Figure D-133 shows the relationship between Delta outflow and the daily average EC measurements at Benicia, Collinsville, Antioch, and Jersey Point. The top of Figure D-133 indicates that the daily EC values show a somewhat scattered relationship with the daily outflow estimates. However, if the G-model equation is used to provide a moving-average or "effective outflow," the relationships between the daily EC values and the effective outflow follow more closely a negative exponential curve, which is the pattern expected for an estuary with tidal mixing and variable inflow.

The top of Figure D-134 shows the daily minimum, average, and maximum EC for the Martinez EC station, located at the downstream end of Suisun Bay (35 miles upstream of the Golden Gate Bridge), for water year 1987. A negative exponential has been estimated for the daily average EC as a function of effective outflow:

$$\text{Martinez EC}\,(\mu\text{S/cm}) = 30{,}000 \times \exp(-0.00007 \times \mathit{effective\,outflow}) + 250$$

The bottom of Figure D-134 shows the negative exponential relationship for Jersey Point, which was estimated as:

$$\text{Jersey Point EC}\,(\mu\text{S/cm}) = 12{,}000 \times \exp(-0.0006 \times \mathit{effective\,outflow}) + 250$$

This same estimation procedure works reasonably well for other years of data at most of the western Delta stations from Martinez (Benicia) to Jersey Point.

Confirmation of DSM2 Outflow-Salinity Relationship

The DSM2 results for the 16-year period of 1976–1991 indicated similar negative exponential relationships between effective Delta outflow and EC at four locations (Chipps Island, Emmaton, Jersey Point, and Old River at the mouth of Rock Slough). The negative exponential relationships between effective Delta outflow and EC can therefore be used to provide an assessment of salinity effects from changes in Delta outflow caused by the SDIP operations for the entire 73-year assessment period.

Figure D-135 shows the adjustments in monthly average effective outflow for the 1976–1991 period of monthly outflows in the 2001 baseline CALSIM II simulation. The effective outflow never drops below the 3,000-cfs minimum required Delta outflow specified in the State Water Board water right decision D-1641. The effective (G-model) outflow values throughout this period remain above 4,000 cfs. The salinity (EC) will therefore be higher than if the monthly CALSIM II outflow values were directly controlling salinity values. Figure D-135 also shows a comparison of the effective outflow for the 2001 baseline conditions and the historical effective outflow for 1976–1991. Some of the lowest historical effective outflow values were less than 4,000 cfs and approached 3,000 cfs at the beginning of water year 1978, 1986, 1988, and 1989. The D-1641 objectives as simulated in CALSIM II will maintain the effective outflow above 4,000 cfs.

The following equations were used for the selected western Delta locations where the effective outflow could be used to approximate salinity changes from effective outflow changes:

$$\text{Benicia EC } (\mu\text{S/cm}) = 30{,}000 \times \exp(\text{-}0.00007 \times \text{effective outflow}) + 250$$

$$\text{Chipps Island EC } (\mu\text{S/cm}) = 29{,}000 \times \exp(\text{-}0.00025 \times \text{effective outflow}) + 250$$

$$\text{Emmaton EC } (\mu\text{S/cm}) = 20{,}000 \times \exp(\text{-}0.00050 \times \text{effective outflow}) + 250$$

$$\text{Jersey Point EC } (\mu\text{S/cm}) = 12{,}000 \times \exp(\text{-}0.00060 \times \text{effective outflow}) + 250$$

The CCWD has suggested that estimates of Rock Slough chloride concentration generally follow a weighting of the current (0.55) and previous (0.45) Jersey Point EC values. The Rock Slough chloride was assumed to be 0.11 times the weighted Jersey Point EC values. This method introduces an additional lag of about a month between when the effective outflow shifts and when the Rock Slough chloride will increase:

$$\begin{gathered}\text{Rock Slough chloride (milligrams per liter [mg/l])} = \\ 0.11 \times \left(0.45\ previous\ Jersey\ Po\text{int}\ \ EC + 0.55\ Jersey\ Po\text{int}\ \ EC\right)\end{gathered}$$

At high outflows, salinity intrusion from the bay will be a minimum, and each of these negative exponential equations will approach the assumed background values. Because of the variation in the chloride/EC ratio, a second estimate of the negative exponential relationship between effective outflow and chloride at Rock Slough was used. The two methods give nearly equivalent results. This second method will show a change in the same month that effective outflow changes. The negative exponential that matches the historical monthly Rock Slough chloride is:

$$\text{Rock Slough chloride (mg/l)} = 1{,}250 \times \exp\left(\text{-}\ 0.00050 \times \text{effective outflow}\right) + 25$$

The following sections summarize observed historical Delta EC patterns and compare observed and DSM2-simulated EC values to demonstrate confirmation that the DSM2 model simulations of Delta salinity conditions follow the effective outflow (G-model) patterns.

Benicia (Martinez)

This station is considered the downstream limit of the Delta and is the “ocean tidal boundary” for DSM2. The relationship between effective Delta outflow and salinity at Benicia provides important confirmation of the validity of this boundary designation, although there are no water quality objectives at this station.

Figure D-136 shows the times series of measured monthly EC and estimated EC calculated from the historical effective outflow and the assumed negative exponential equation for the 1976–1991 simulation period. The bottom of the figure indicates that the negative exponential shape does describe most of the variation in monthly average EC values. Variations in the predicted values may be caused by uncertainty in the Delta outflow (these must be estimated from measured inflows minus exports and minus approximate net Delta channel depletions). Additional variations arise from monthly average EC values, which may deviate from the average monthly estimates if substantial daily changes in flow occurred. There are no potential salinity impacts at Benicia because there are no salinity objectives at Benicia.

Pittsburg (near Chipps Island)

Figure D-137 shows the measured monthly average EC at Pittsburg (1.2 miles upstream of Chipps Island) for 1976–1991 and the effective outflow and negative exponential EC estimates for historical Delta outflows. The effective outflow estimates of EC match relatively well the measured monthly average EC values. The negative exponential relationship with effective Delta outflow is generally confirmed. The variations in the EC data are most apparent during periods of low Delta outflow, when effects of salinity intrusion are greatest and Delta outflow values are most uncertain.

EC values at Pittsburg increase to above 3,000 µS/cm at an effective outflow of about 10,000 cfs. Because Chipps Island is slightly downstream of Pittsburg, the effective Delta outflow necessary to maintain the X2 position downstream of Chipps Island, as required under the 1995 WQCP (D-1641), is slightly more, about 12,500 cfs. The response of EC at Chipps Island to changes in Delta outflow caused by SDIP operations can be adequately estimated from the effective outflow estimates, based on the CALSIM II monthly outflow for each alternative. Although there is no EC objective at Chipps Island, this historical comparison demonstrates the general validity of the effective outflow (G-model) methodology that uses the monthly CALSIM II model outflow to estimate equivalent salinity values.

Emmaton

Figure D-138 shows the measured monthly average EC at Emmaton for 1976–1991 and the effective outflow estimates of EC at Emmaton. There is a general match with the measured monthly average EC values, but there is considerable variability in the negative outflow pattern.

EC values at Emmaton increase above 3,000 µS/cm at an effective outflow of about 4,000 cfs. Emmaton has agricultural EC objectives that apply from April 1 to August 15, which vary with the Sacramento water year type. The EC objective is generally 450 µS/cm from April 1 to a specified date and then increases to a second EC objective for the remainder of the period. The EC objective is relaxed to 2,780 µS/cm in critical years. The objective is satisfied if the maximum 14-day running average is less than the objective. These variable EC objectives at Emmaton can only be matched approximately with the monthly CALSIM II model.

Jersey Point

Figure D-139 shows the measured monthly average EC at Jersey Point for 1976–1991 and the effective Delta outflow estimates for historical Delta outflows. The effective outflow estimates match the measured monthly average EC values relatively well. The negative exponential relationship with effective Delta outflow at Jersey Point is generally confirmed.

EC values at Jersey Point increase above 2,000 µS/cm at an effective outflow of about 4,000 cfs. The historical EC values at Jersey Point are lower (by about 25%) than the EC values at Emmaton. The effective outflow estimates of EC at Jersey Point provide generally accurate simulations of Jersey Point historical EC patterns.

The agricultural EC objectives at Jersey Point are similar to those at Emmaton. The objective is applied from April 1 to August 15. During critical years, the objective is relaxed to 2,200 µS/cm. Because Jersey Point EC objectives are lower than Emmaton, Jersey Point is often the controlling location when the salinity intrusion from relatively low effective outflow is substantial during the irrigation season.

Rock Slough

Figure D-140 shows the measured monthly average EC at the CCWD Rock Slough intake for 1976–1991 and the G-model estimated EC for historical Delta outflow. The negative exponential relationship with effective Delta outflow is generally confirmed at low Delta outflows. Some of the scatter in the CCWD EC measurements may be attributed to uncertain monthly outflow estimates and monthly averaging of EC during periods of large outflow changes. The effects of San Joaquin River inflows and local agricultural drainage on CCWD EC measurements are also likely causes for some of the differences between measured and simulated EC values at the CCWD diversion. The graph suggests that the EC at Rock Slough can be maintained below the objective of 1,000 µS/cm with an effective outflow of at least 3,750 cfs.

Figure D-141 shows the measured monthly average chloride concentration at the CCWD Rock Slough Pumping Plant #1 for 1968–1994 compared with the estimated EC values. The negative exponential relationship with effective Delta outflow is generally confirmed at low Delta outflows. An effective outflow of 3,500 cfs will apparently maintain the chloride concentrations below the 250 mg/l objective. An effective outflow of 4,500 cfs will maintain the 150 mg/l objective during the portions of each year that it is required. Only the outflow effects on Rock Slough chloride are simulated with the effective outflow (G-model) relationships.

DSM2-Simulated Salinity (Electrical Conductivity) for the No Action Alternative

Possible impacts of the SDIP alternatives are compared with Delta water quality conditions represented by the (2001 baseline) No Action Alternative. The No Action Alternative is simulated with CALSIM II to represent likely Delta conditions that would result from a repeat of the historical hydrologic sequence but with existing water project facilities (i.e., reservoirs, diversions, and canals) and with current levels of demands for upstream diversions and Delta exports. Delta water quality conditions are assumed to be controlled by objectives of the 1995 WQCP (D-1641) and other applicable water rights, agreements, and requirements.

No Action Alternative conditions and historical conditions are different because of the changes in upstream reservoir operations and diversions, revisions in Delta water quality objectives and requirements, and increased demands for Delta exports. The comparison between salinity conditions simulated for the No Action Alternative and those simulated for historical conditions are presented here to provide a reference.

For the 1976–1991 period, the DSM2-simulated baseline EC values are shown compared to the effective outflow estimates and the historical EC data.

Simulated Electrical Conductivity at Benicia (Martinez)

Figure D-142 shows the comparison of DSM2-simulated EC values and effective outflow estimates of EC at Benicia for 1976–1991 for the 2001 baseline (No Action Alternative). The DSM2 EC values are compared with the effective outflow EC estimates and with the historical EC measurements. The No Action Alternative will generally have slightly lower EC values than historical EC because the minimum-allowed Delta outflows are now generally higher than during the historical period. The DSM2 EC values are slightly lower than the effective outflow estimates, but the boundary conditions estimated from the downstream end of this model segment (441) are closer to the data. The DSM2-simulated values generally confirm the relationship between effective outflow and EC values caused by the salinity intrusion from San Pablo Bay at low Delta outflow.

Simulated Electrical Conductivity at Chipps Island

Figure D-143 shows the comparison of DSM2-simulated EC values and effective outflow estimates of EC at Chipps Island for 1976–1991 for the 2001 baseline (No Action Alternative), with historical Pittsburg EC measurements shown as a reference. The Pittsburg EC data are lower than the corresponding Chipps Island EC measurements because Pittsburg is 1.2 miles upstream of Chipps Island. The current EC measurements for Chipps Island are actually collected across the channel at Mallard Slough. The DSM2-simulated EC values are higher than the effective outflow estimates because the effective outflow estimates were based on the slightly lower Pittsburg data. The negative exponential equation could be adjusted to better match the DSM2 EC values. The DSM2-simulated EC values directly confirm the relationship between effective outflow and EC values caused by the salinity intrusion from Suisun Bay at low Delta outflow.

Simulated Electrical Conductivity at Emmaton

Figure D-144 shows the comparison of DSM2-simulated EC values and effective outflow estimates of EC at Emmaton for 1976–1991 for the 2001 baseline (No Action Alternative). The CALSIM II model includes an estimate of EC at Emmaton (part of the ANN module to maintain compliance with salinity standards). Also shown are the effective outflow EC estimates. The DSM2 and the CALSIM-ANN estimates generally confirm the negative exponential relationship with effective outflow. There are additional variations in the DSM2 and ANN estimates, which are generally higher than the effective outflow estimates.

Simulated Electrical Conductivity at Jersey Point

Figure D-145 shows the DSM2-simulated EC values and effective outflow estimates of EC at Jersey Point for 1976–1991 for the 2001 baseline (No Action Alternative). The DSM2 and the CALSIM II estimates generally confirm the negative exponential relationship with effective outflow. However, the DSM2 and the CALSIM estimates of EC at Jersey Point are slightly higher than the effective outflow estimates. It appears that the DSM2-simulated EC at Jersey Point is too high. This high EC value may cause CALSIM to estimate too high of an outflow during months when Jersey Point EC is controlling the Delta outflow.

There are additional variations in the DSM2 and ANN estimates that are likely caused by EC contributions from agricultural drainage. However, because these components of the Jersey Point EC are not expected to change substantially with SDIP alternatives, only the changes in simulated outflow will produce significant EC changes. For impact assessment purposes, the negative exponential relationship of Jersey Point EC with effective outflow will provide a consistent EC estimate for evaluating the potential salinity impacts at Jersey Point.

Simulated Electrical Conductivity at Rock Slough

Figure D-146 shows the DSM2-simulated EC values and effective outflow estimates of EC at Rock Slough for 1968–1991 for the 2001 baseline (No Action Alternative). The DSM2 and the CALSIM estimates generally confirm the negative exponential relationship with effective outflow. The DSM2 and the CALSIM estimates of EC at Rock Slough are sometimes higher than the effective outflow estimates. This is likely caused by agricultural drainage contributions to EC at Rock Slough.

Rock Slough EC is the most “upstream” location where the salinity intrusion effects can be accurately estimated with the negative exponential relationship with effective outflow. It is also the most upstream location with CALSIM-ANN estimates of EC values. The monthly EC values at all south Delta locations are simulated only in DSM2 for the 1976–1991 period.

Validation of DSM2-Simulated Salinity (Electrical Conductivity) Patterns

This last section shows the direct historical confirmation of the DSM2 salinity (EC) calculations for the 1990–1999 period. The calibrated DSM2 QUAL module was used to simulate this 10-year period. The daily average EC values are compared to the measured data from several western Delta stations to demonstrate the accuracy of the DSM2 simulations of EC.

Martinez

Figure D-147 shows the simulated and measured EC values at Martinez, the downstream boundary for DSM2. The simulated average daily EC values for segment 441 are slightly less than the measured values, which were used as the downstream boundary for model segment 441. The maximum EC value at Martinez is often about 25,000 µS/cm, corresponding to an effective outflow of about 5,000 cfs. The first 3 years were quite dry, with extended periods of EC values around 25,000 µS/cm. EC values below 10,000 µS/cm require an effective outflow of more than 20,000 cfs. Periods of higher outflow were observed in 1993 and 1995–1999. The match is very good because these measured values are used as boundary conditions for the historical simulations.

Port Chicago

Figure D-148 shows the simulated and measured EC values at Port Chicago, the downstream compliance location for the X2 objective. The simulated average daily EC values are slightly (i.e., 10%) less than the measured values. The changes between the initial calibration and the final calibration are small because there is not much to adjust (only three model segments) between the downstream boundary and this location. The maximum EC value at Port Chicago is often about 20,000 µS/cm, corresponding to an effective outflow of about 5,000 cfs. The simulated and measured EC values at Port Chicago are a slightly dampened image of the Martinez EC patterns.

Pittsburg

Figure D-149 shows the simulated and measured EC values at Pittsburg. The simulated average daily EC values are close to the measured EC values. The change between the initial calibration and the final calibration raised the EC values by about 20% to match the measured data more closely. The maximum measured EC value at Pittsburg is about 15,000 µS/cm, corresponding to an effective outflow of about 3,000 cfs. The simulated and measured EC values at Pittsburg are lower than 1,000 µS/cm for longer periods because an outflow of more than 15,000 cfs will substantially reduce the salinity intrusion at Pittsburg.

Collinsville

Figure D-150 shows the simulated and measured EC values at Collinsville, the upstream X2 compliance location. The simulated average daily EC values are very close to the measured EC values most of the time. However, there are several periods when the simulated EC values are higher than the measured values, indicating that the estimated Delta outflow values used in the historical simulation were too low. The change between the initial calibration and the final calibration raised the EC values considerably to match the measured data more closely. The maximum measured EC value at Pittsburg is about 10,000 µS/cm, while the simulated EC was 12,000 µS/cm at the end of water year 1990 and 1991.

Emmaton

Figure D-151 shows the simulated and measured EC values at Emmaton. The simulated average daily EC values are close to the measured EC values most of the time. However, there are several periods when the simulated EC values are higher than the measured values, indicating that the estimated Delta outflow values used in the historical simulation were too low. There are also a few periods when the simulated EC is too low (January 1998), suggesting that the Delta outflow was slightly lower than simulated. The periods of discrepancies are the same as at Collinsville. The change between the initial calibration and the final calibration raised the EC values considerably to match the measured data more closely. The maximum measured EC value at Emmaton is about 4,000 µS/cm, corresponding to an effective outflow of about 3,500 cfs.

Jersey Point

Figure D-152 shows the simulated and measured EC values at Jersey Point. The simulated average daily EC values are close to the measured EC values most of the time after 1992. However, there are several periods when the simulated EC values are higher than the measured values in the first 3 years, indicating that the estimated Delta outflow values used in the historical simulation were too low. There are also a few periods when the simulated EC is too low (January 1998), suggesting that the Delta outflow was slightly lower than simulated. The periods of discrepancies are generally the same as at Emmaton. The change between the initial calibration and the final calibration raised the EC values considerably to match the measured data more closely. The maximum measured EC at Emmaton is about 2,000 µS/cm, corresponding to an effective outflow of about 4,000 cfs.

San Andreas Landing

Figure D-153 shows the simulated and measured EC values at San Andreas Landing, which is upstream of Jersey Point and just downstream of the Mokelumne River mouth. The simulated average daily EC values are similar to the measured EC values most of the time, remaining less than 500 µS/cm. There is very little seawater intrusion at this location, and the EC value is similar to the Sacramento River inflow EC value of less than 200 µS/cm. The change between the initial calibration and the final calibration lowered the EC values considerably during the periods of highest EC to match the measured data more closely.

Old River at Bacon Island

Figure D-154 shows the simulated and measured EC values in Old River at Bacon Island, near the mouth of Rock Slough. The simulated average daily EC values are similar to the measured EC values most of the time, remaining less than 1,000 µS/cm. These EC values are higher than the San Andreas Landing EC values because some water is transported through Dutch Slough and False River through Franks Tract to the Old River channel upstream of San Andreas Landing. There is more seawater intrusion at this location than at San Andreas Landing. The change between the initial calibration and the final calibration raised the EC values considerably during the periods of highest EC to match the measured data more closely. The periods of discrepancies are the same as at Jersey Point and Emmaton, suggesting that they are caused by the simulated Delta outflow values.

These confirmation graphs suggest that the DSM2-simulated EC values will closely match the measured EC values when accurate estimates of Delta outflow are simulated. The DSM2-simulated EC values can be used as a reliable tool for assessing the salinity impacts of the SDIP alternatives.

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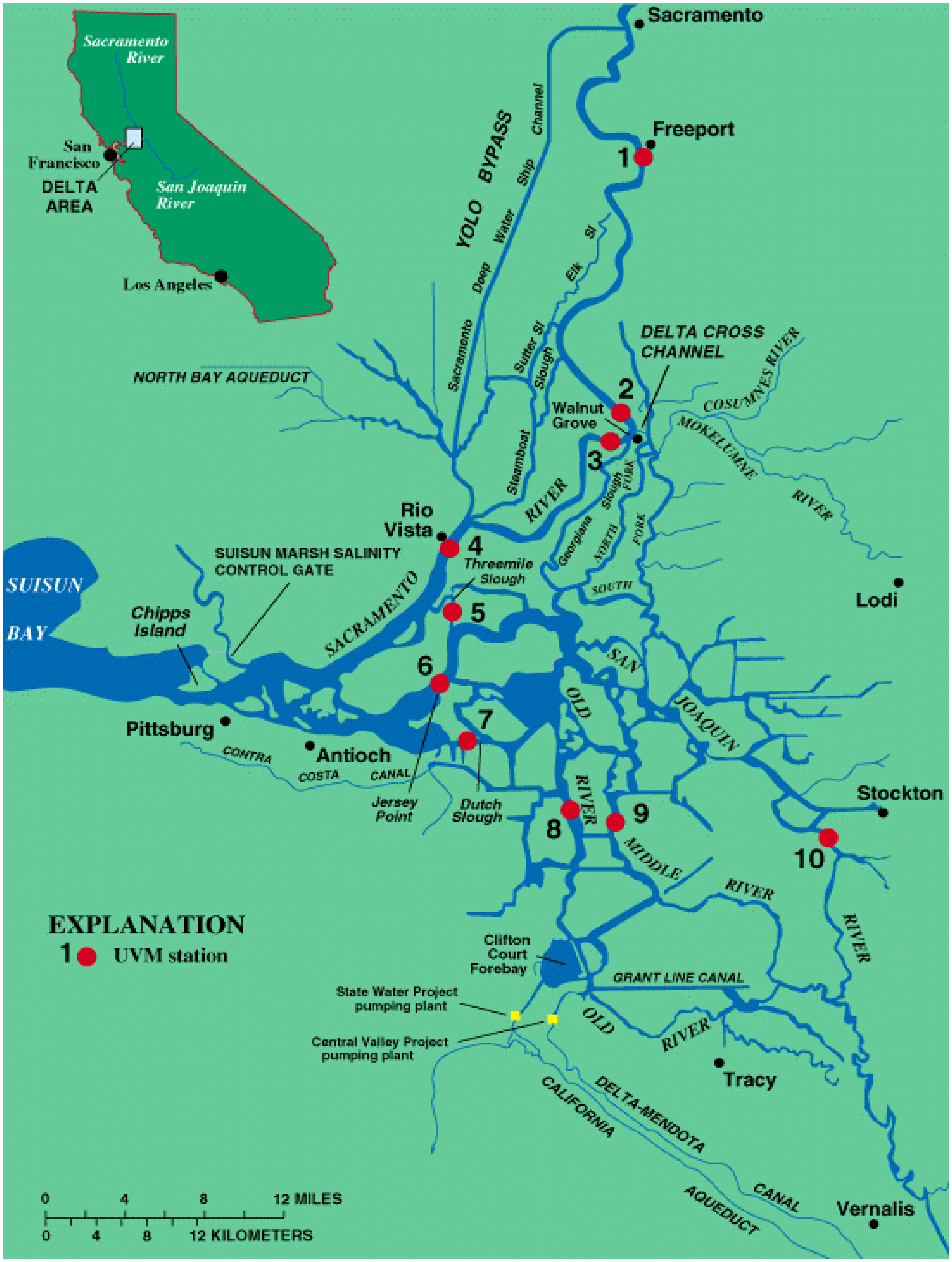

(Source: Oltmann and Simpson 1997.)

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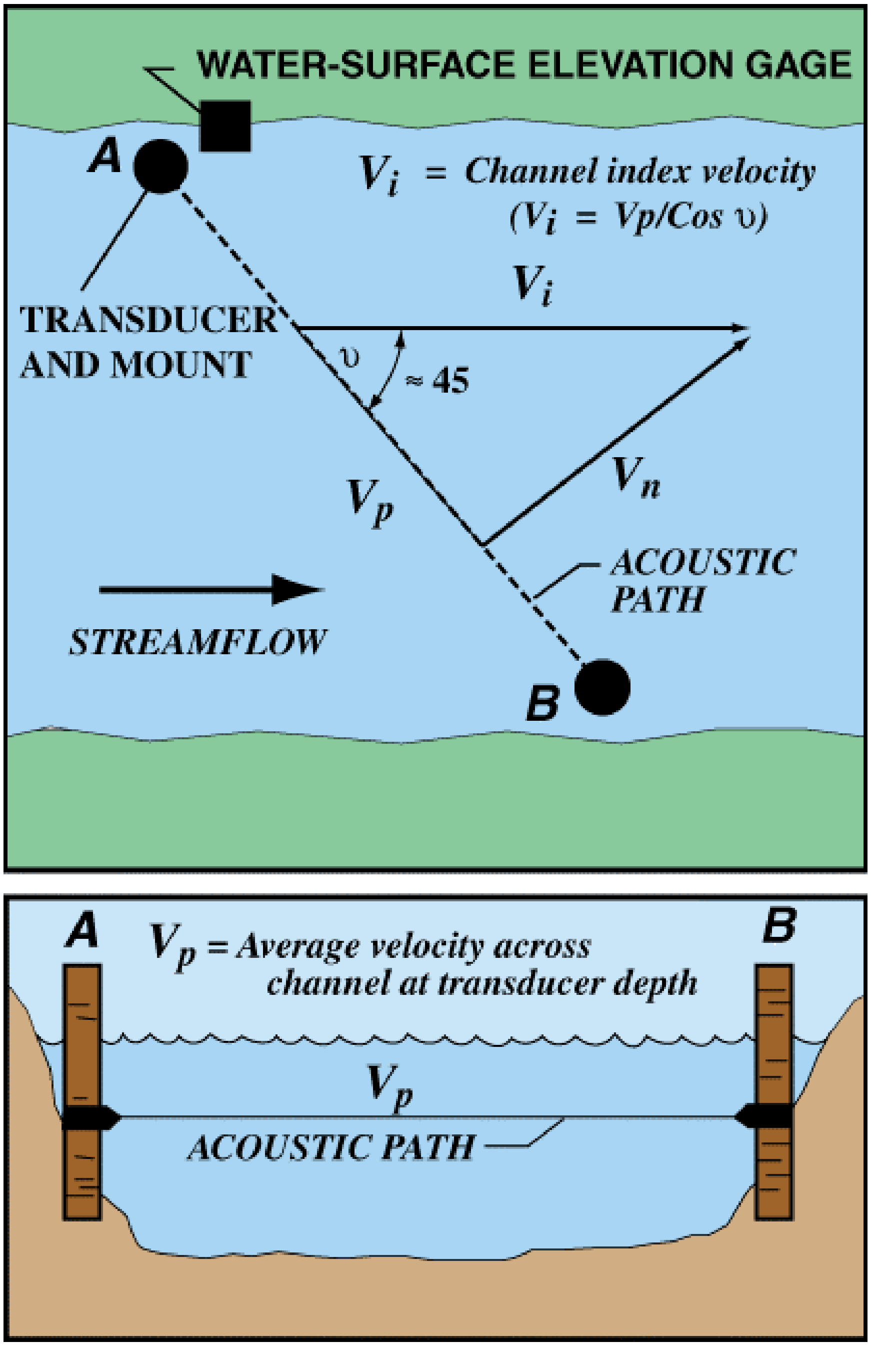
Figure D-1

Map of Delta Showing Locations of U.S. Geological Survey Tidal Ultrasonic Velocity Meters



(Source: Oltmann and Simpson 1997.)

Figure D-2

Diagram Showing the Operation of a Tidal Ultrasonic Velocity Meter Station

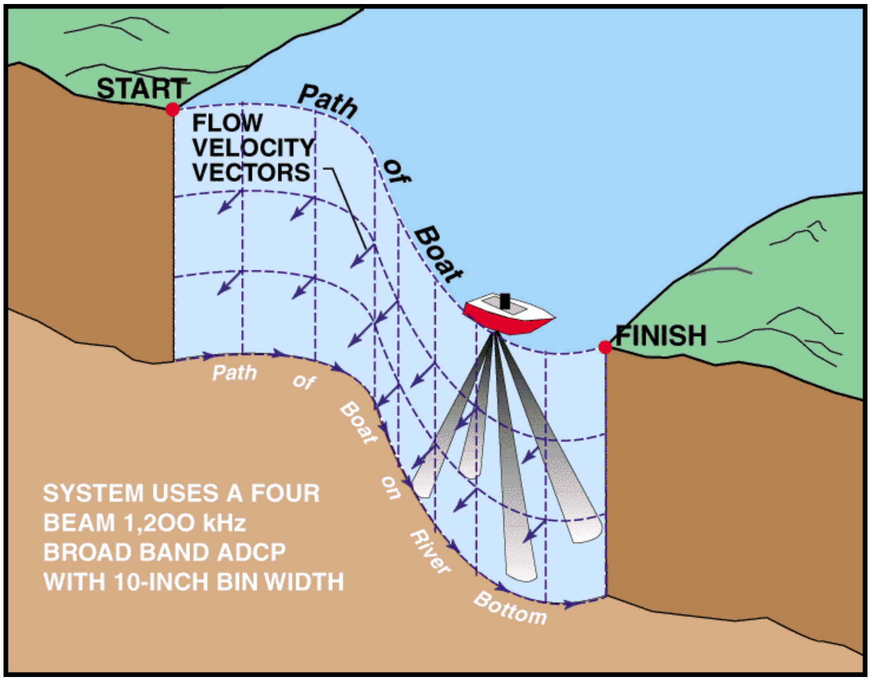


Figure D-3. Diagram of Acoustic-Doppler Current Profiling System Measurements of Tidal Flow for Providing a "Rating Curve" for Ultrasonic Velocity Meter Tidal Flow Station
(Source: Oltmann and Simpson 1997.)

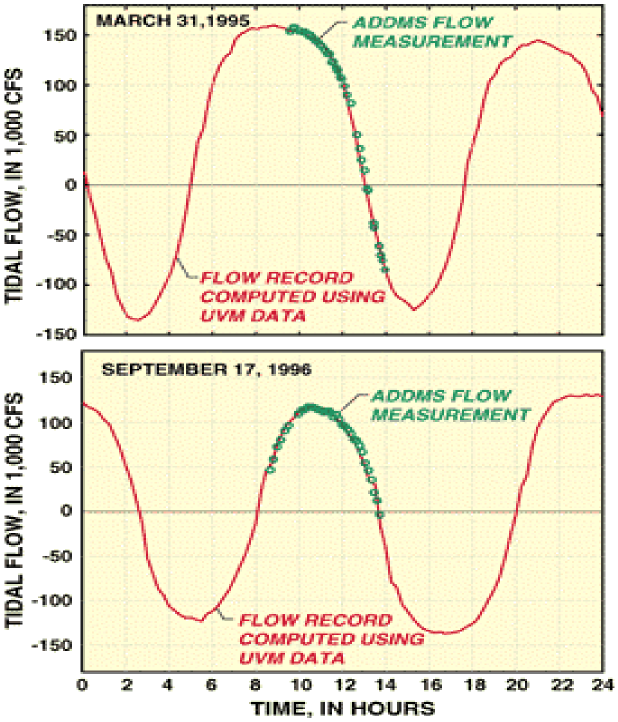


Figure D-4. Example of Comparison between the Acoustic-Doppler Current Profiling System Discrete Flows and Continuous Ultrasonic Velocity Meter Tidal Flows for San Joaquin River at Jersey Point
(Source: Oltmann and Simpson 1997.)

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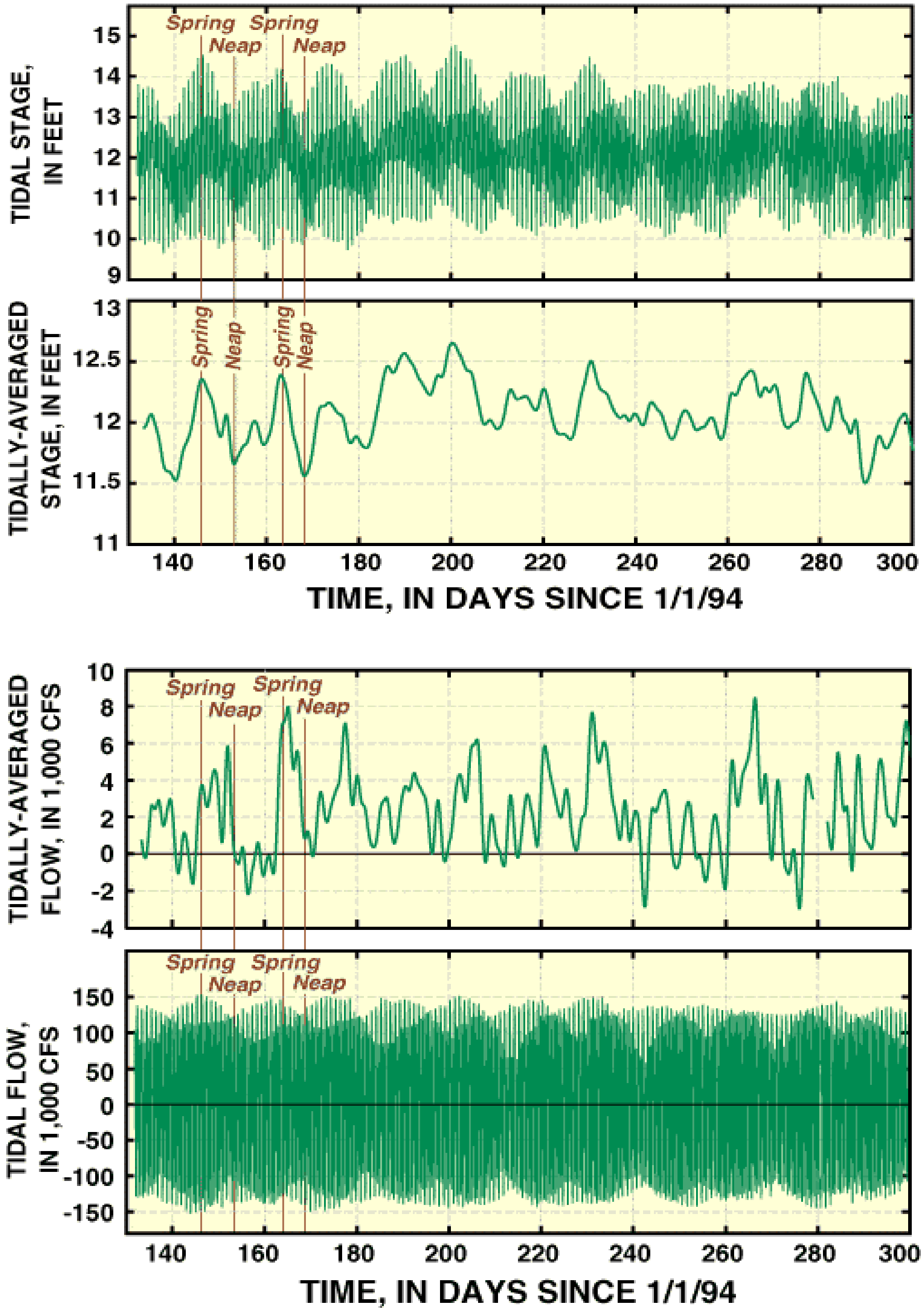
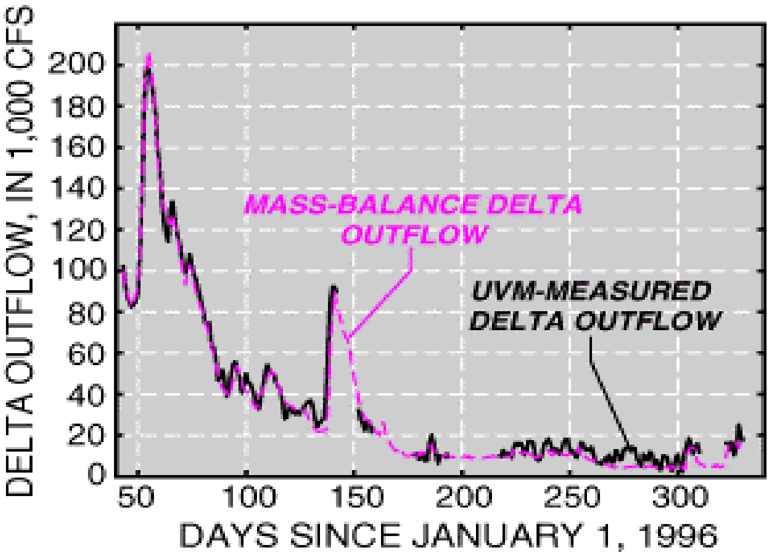


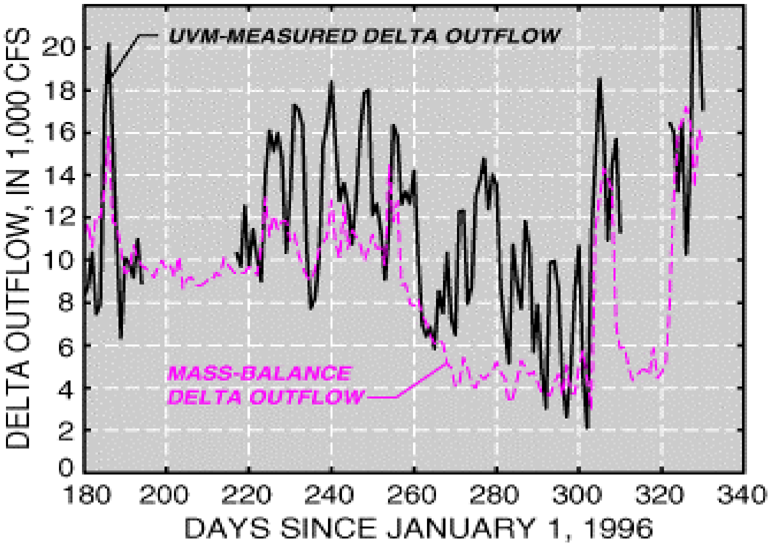
Note: Sea level is at approximately 12 feet on the gage datum.
(Source: Oltmann and Simpson 1997.)

Figure D-5

Tidal Stage Elevation and Tidal Flow at Jersey Point Ultrasonic Velocity Meter Station

Comparison of Delta outflow measured with the four U.S. Geological Survey Ultrasonic Velocity Meter stations and calculated from the DAYFLOW mass-balance using estimates of Delta channel depletions.





(Source: Oltmann 1998.)

Figure D-6

Comparison of Delta Outflow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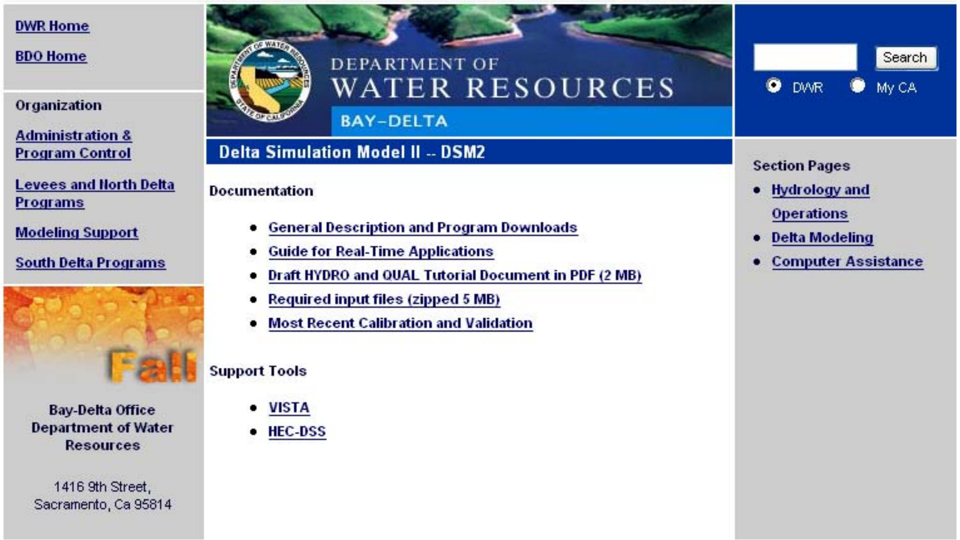
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Figure D-7
Main DSM2 Modeling Web Sites

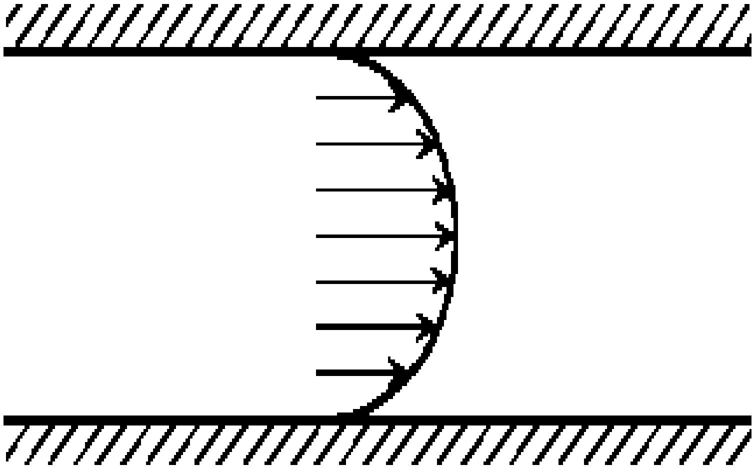

Figure D-8a. Assumed Lateral Velocity Profile: Fourth-Order Polynomial Function

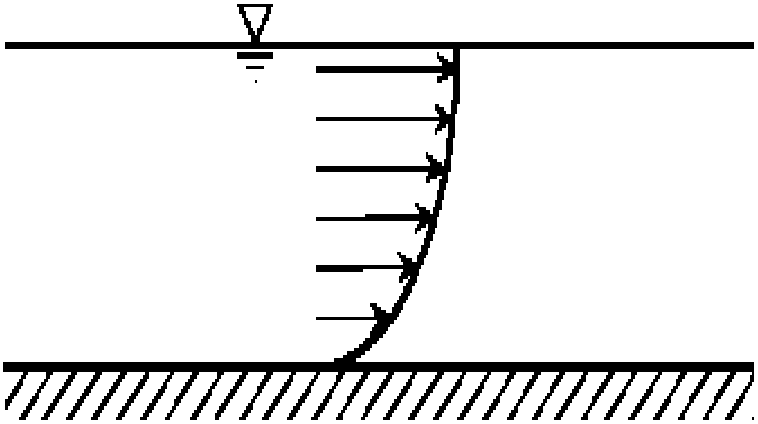

Figure D-8b. Assumed Vertical Velocity Profile: Von Karman Log Function

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Figures D-8a and D-8b

Assumed Velocity Profiles

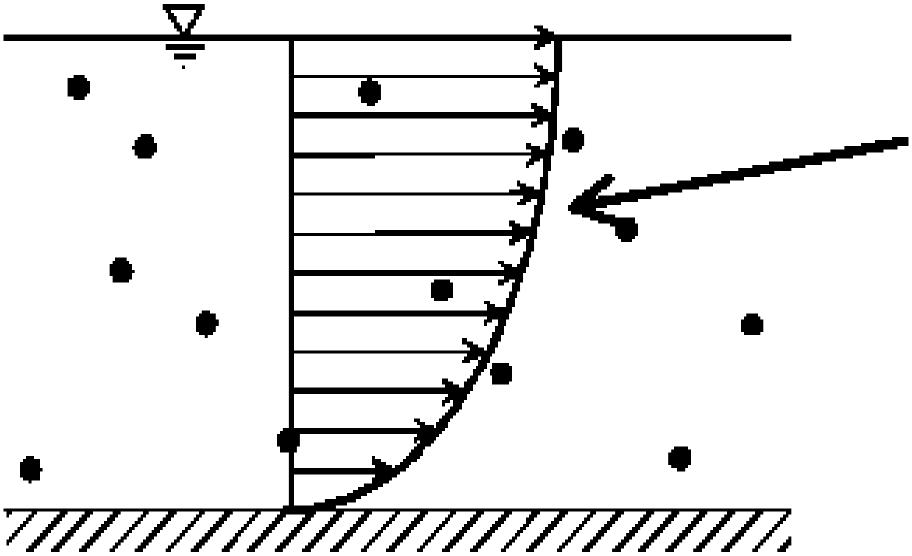

Figure D-9a. Normal Particles with Unrestricted Distribution

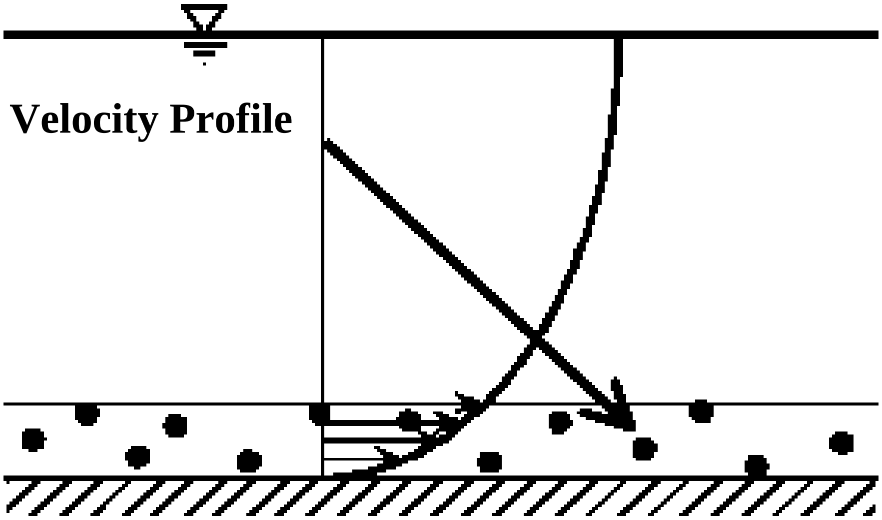

Figure D-9b. Particles Restricted to Lower (Slower) Portion of Channel

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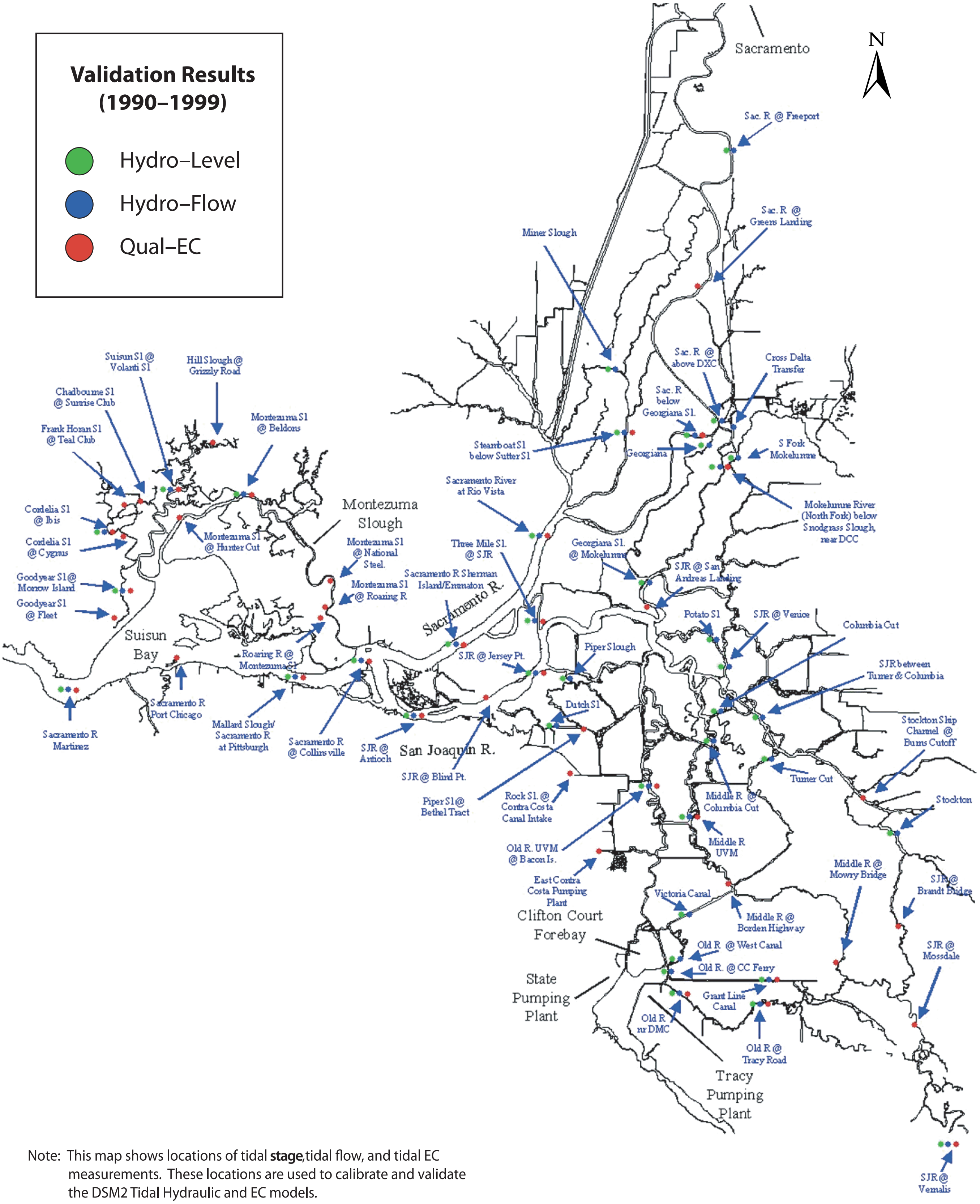
Figure D-9

Particle Vertical Distribution Behaviors in Particle-Tracking Model



Note: This map shows locations of tidal **stage**, tidal flow, and tidal EC measurements. These locations are used to calibrate and validate the DSM2 Tidal Hydraulic and EC models.

Source: California Department of Water Resources 2002b.

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Figure D-10
Location of Tidal Stage, Tidal Flow, and Electrical Conductivity Data Used for Validation of DSM2

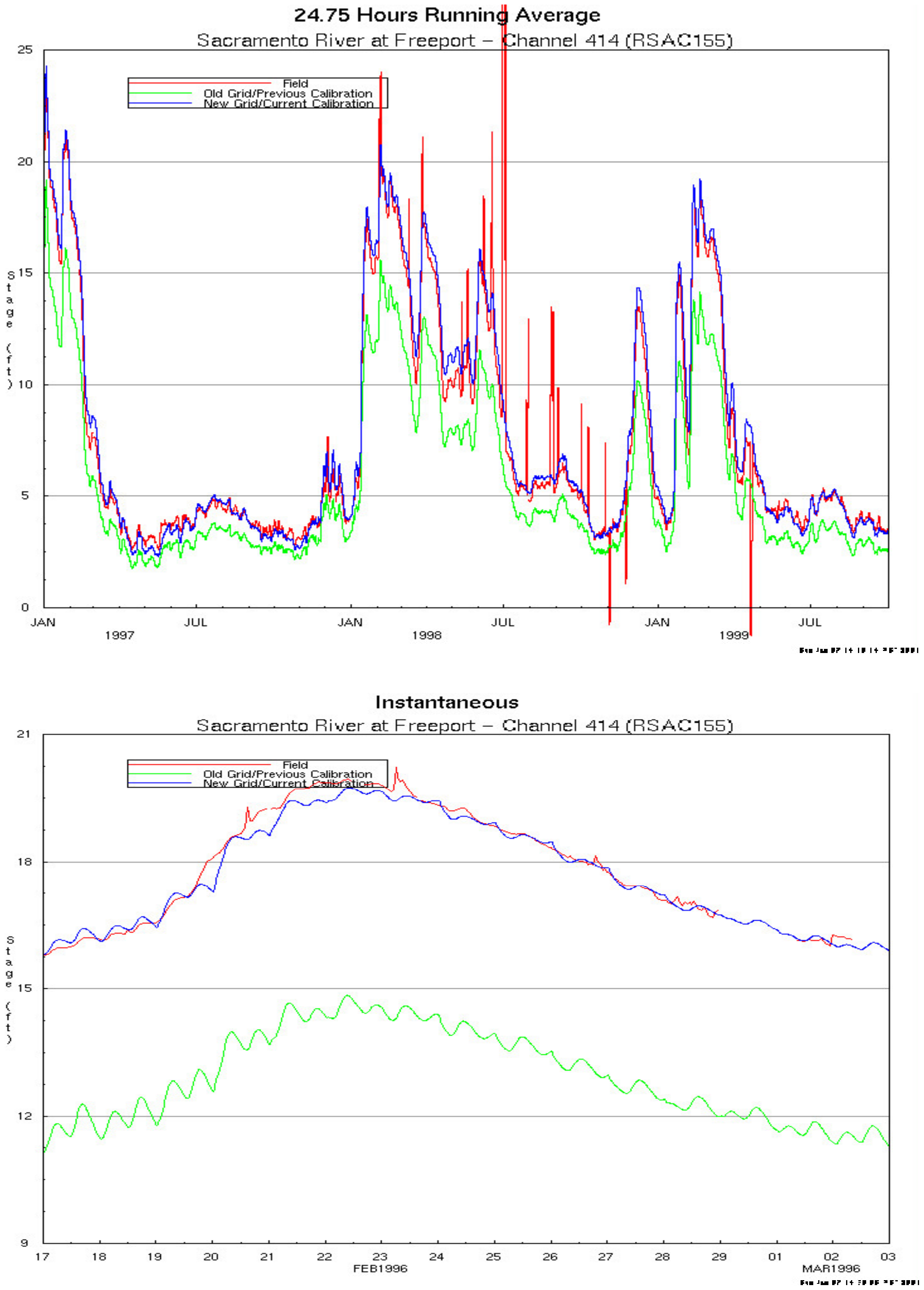

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Figure D-11

DSM2-Simulated and Measured Tidal Stage in the Sacramento River at Freeport for January 1997–September 1999 and February 17–March 2, 1996

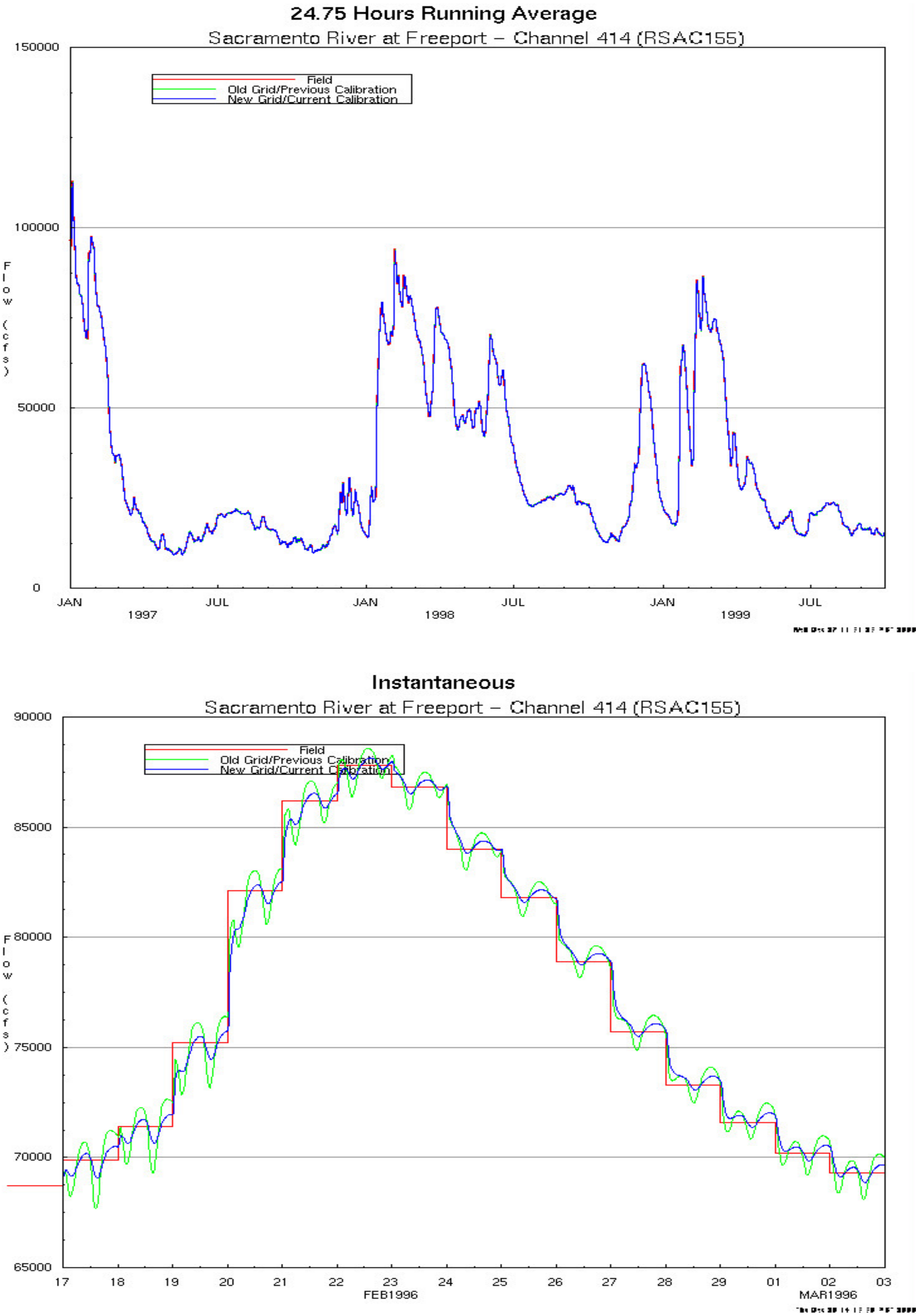

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Figure D-12

DSM2-Simulated and Measured Tidal Flow in the Sacramento River at Freeport for January 1997–September 1999 and February 17–March 2, 1996

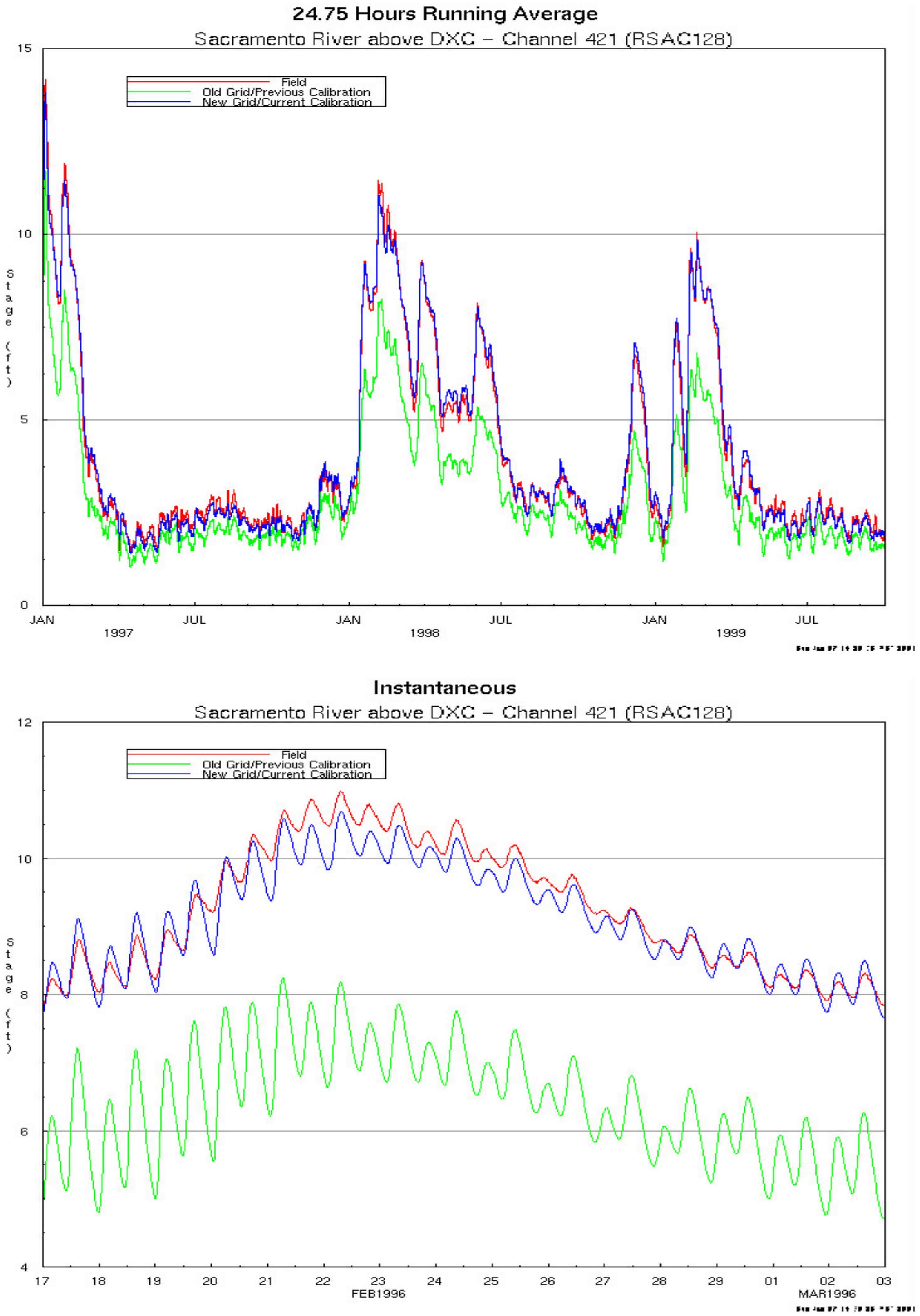

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Figure D-13

DSM2-Simulated and Measured Tidal Stage in the Sacramento River above the Delta Cross Channel near Walnut Grove for January 1997–September 1999 and February 17–March 2, 1996

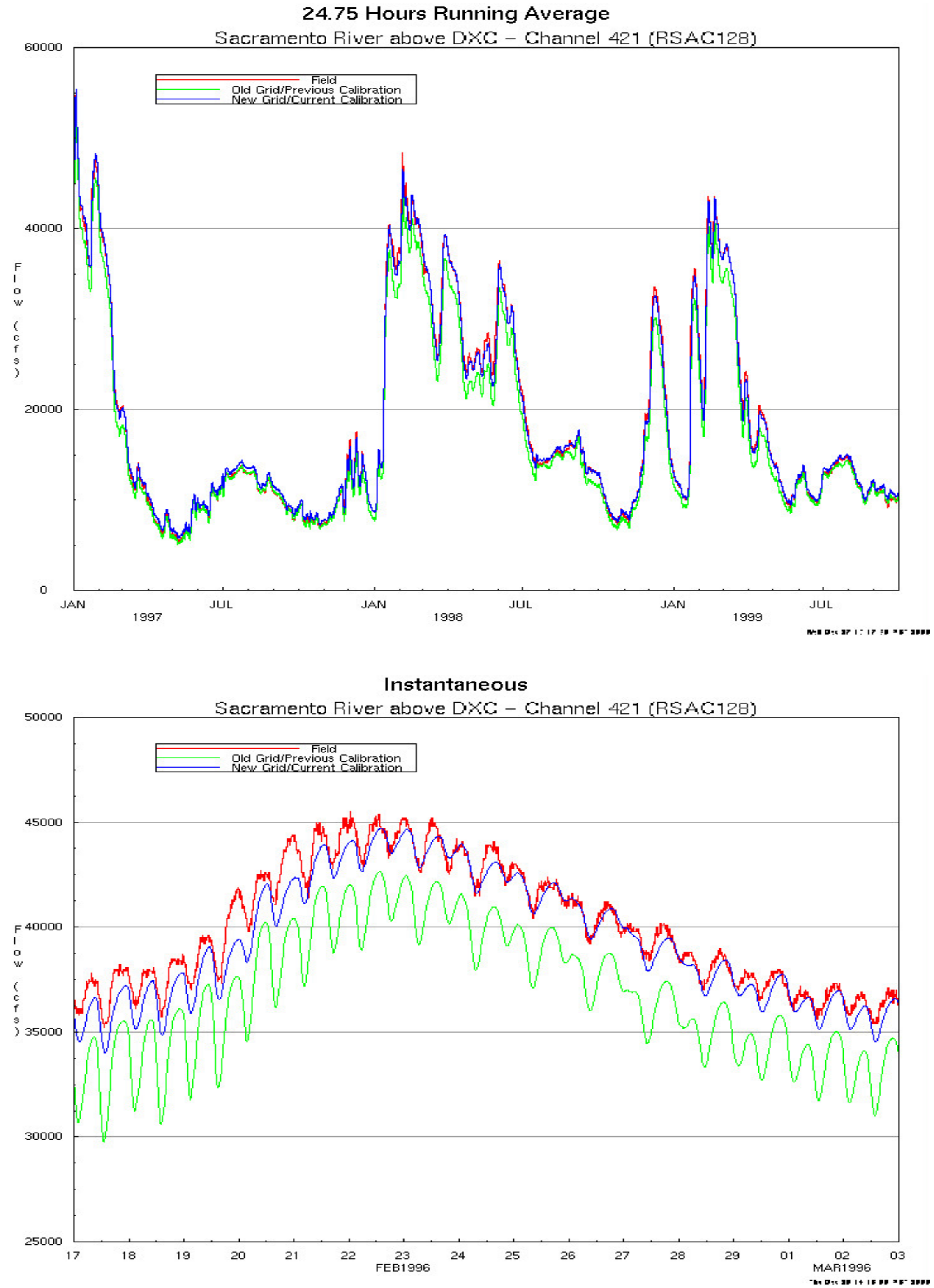

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Figure D-14

DSM2-Simulated and Measured Tidal Flow in the Sacramento River above the Delta Cross Channel near Walnut Grove for January 1997–September 1999 and February 17–March 2, 1996 (Delta Cross Channel Closed)

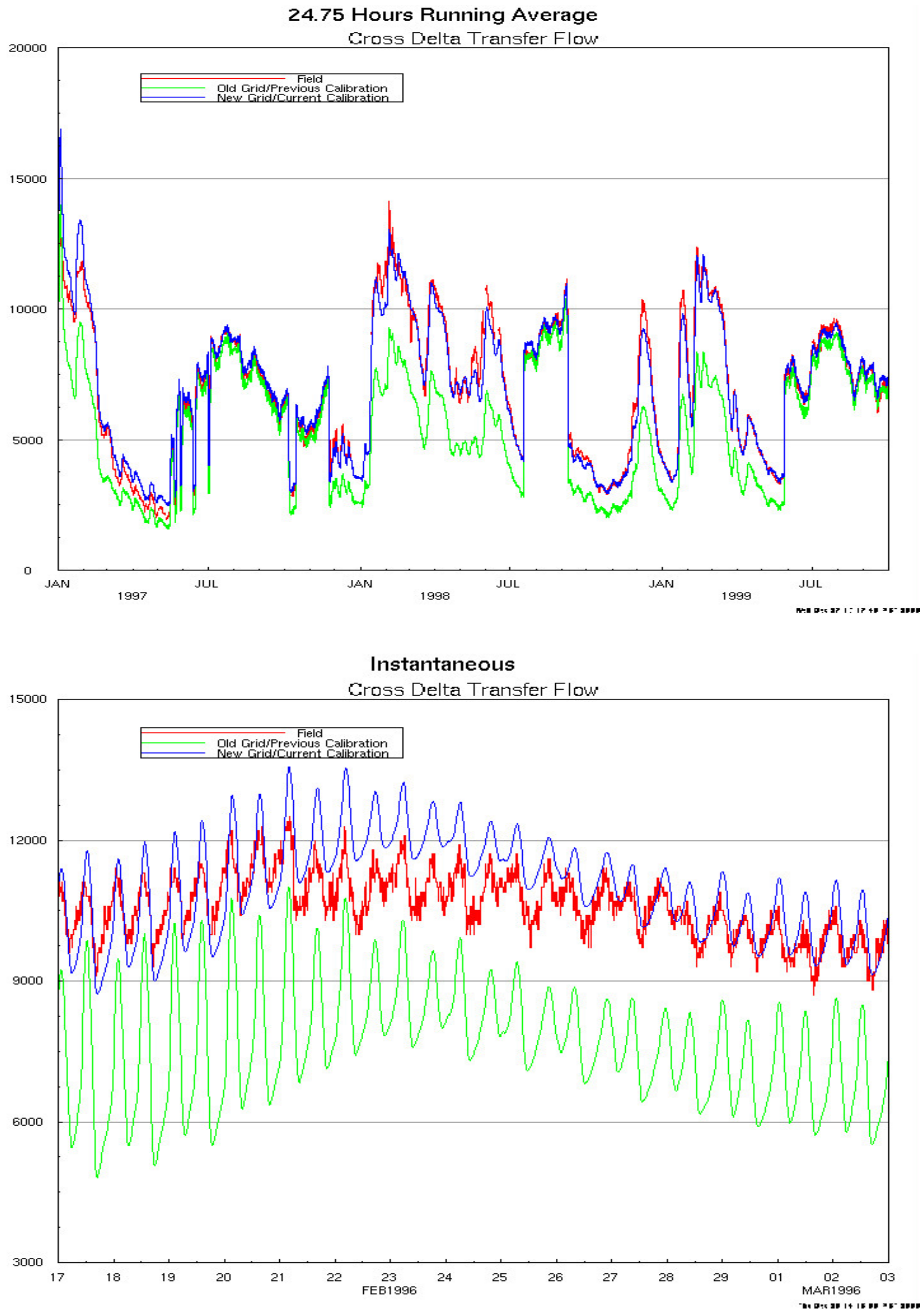

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Figure D-15

DSM2-Simulated and Measured Tidal Flow in the Delta Cross Channel and Georgiana Slough near Walnut Grove for January 1997–September 1999 and February 17–March 2, 1996 (Delta Cross Channel Closed)

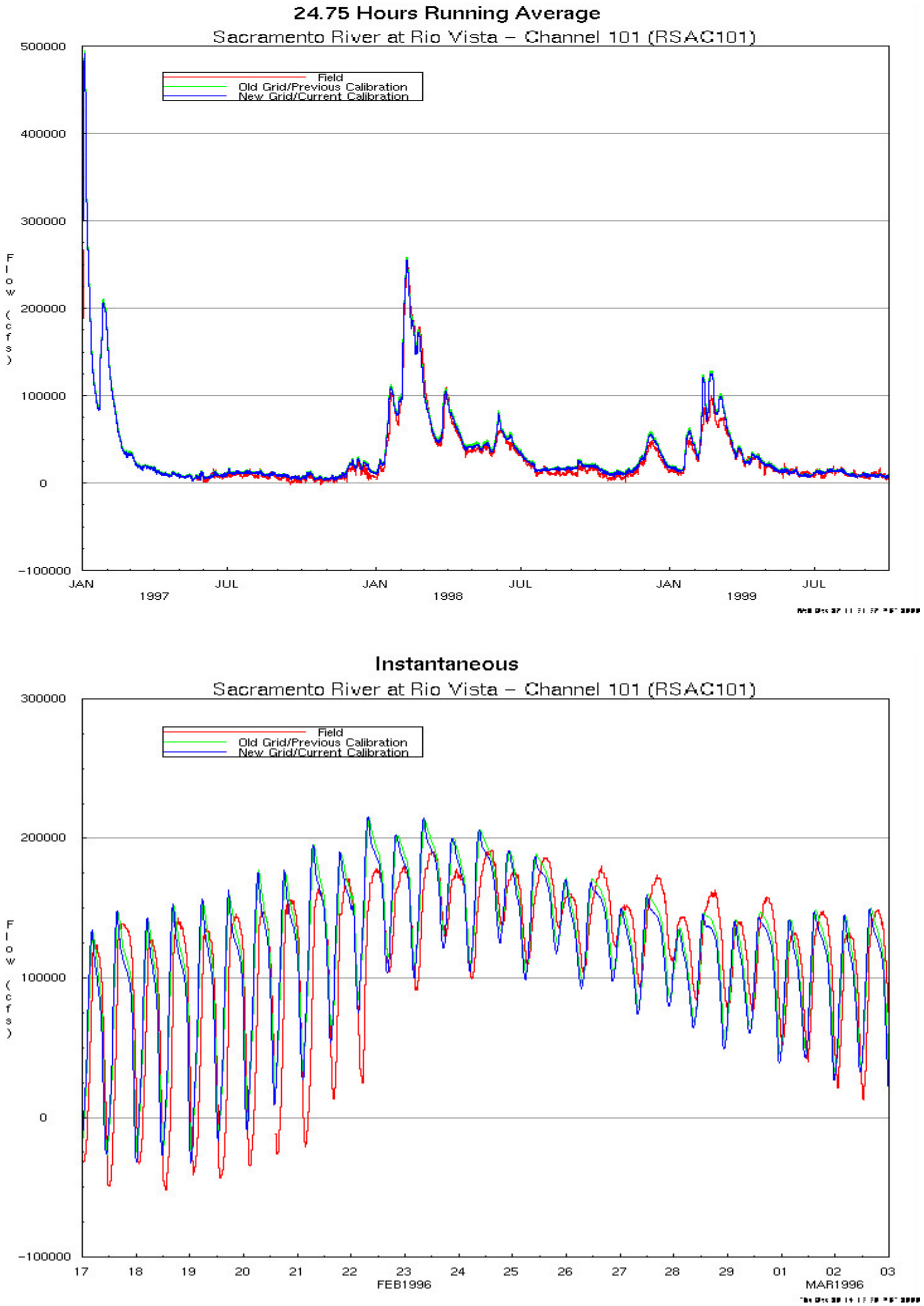

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Figure D-16

DSM2-Simulated and Measured Tidal Stage in the Sacramento River at Rio Vista for January 1997–September 1999 and February 17–March 2, 1996

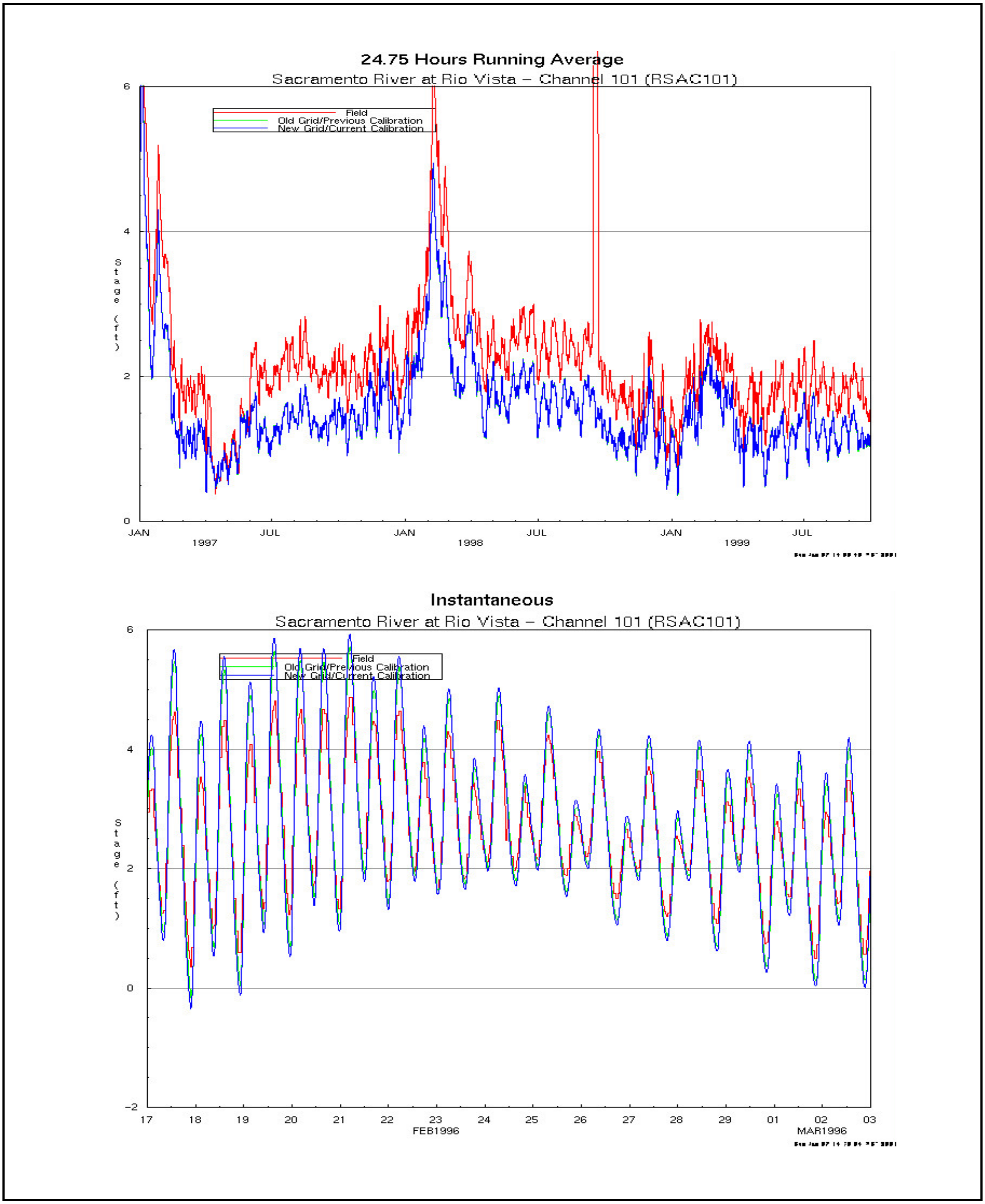

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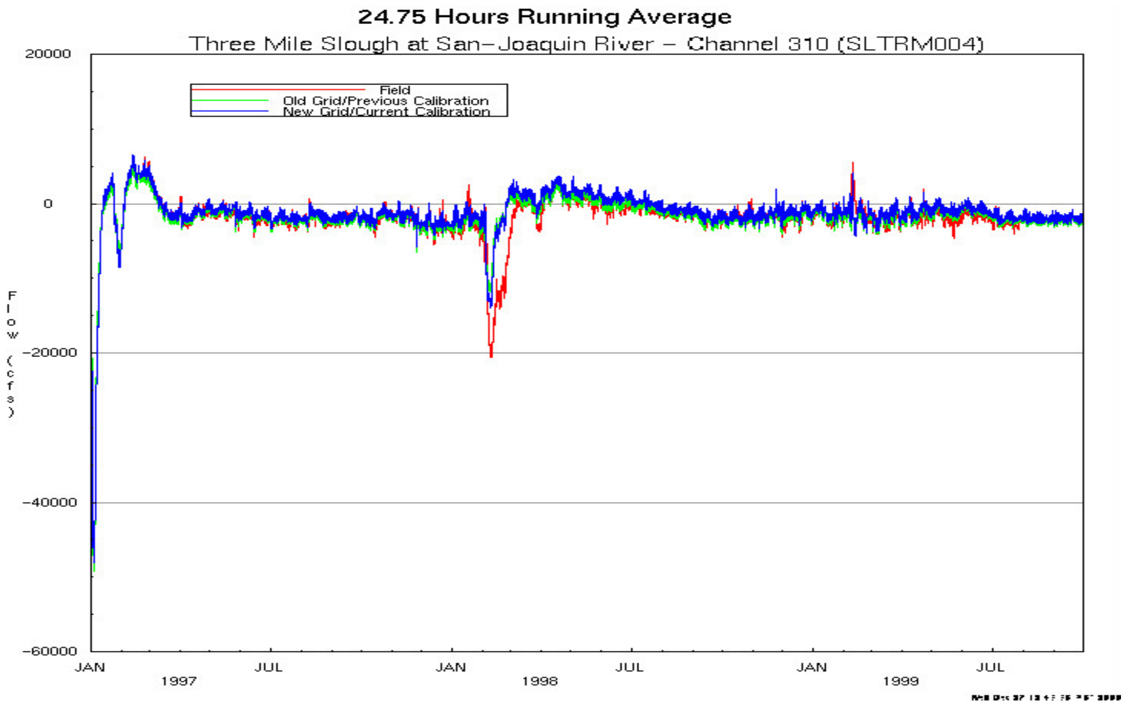
Figure D-17

DSM2-Simulated and Measured Tidal Stage in the Sacramento River at Rio Vista for January 1997–September 1999 and February 17–March 2, 1996



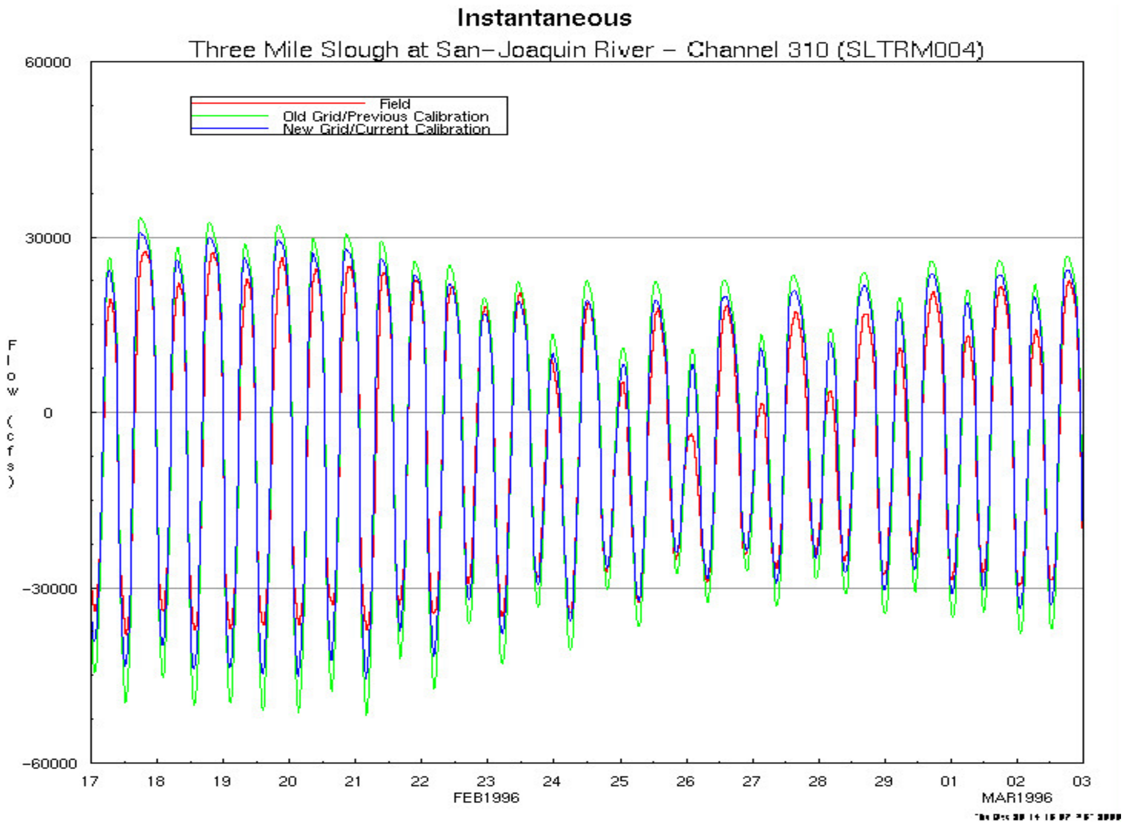


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Figure D-18

DSM2-Simulated and Measured Tidal Flow in Threemile Slough for 1997–1999 and February 17–March 2, 1996 (Positive Flow toward Sacramento River)

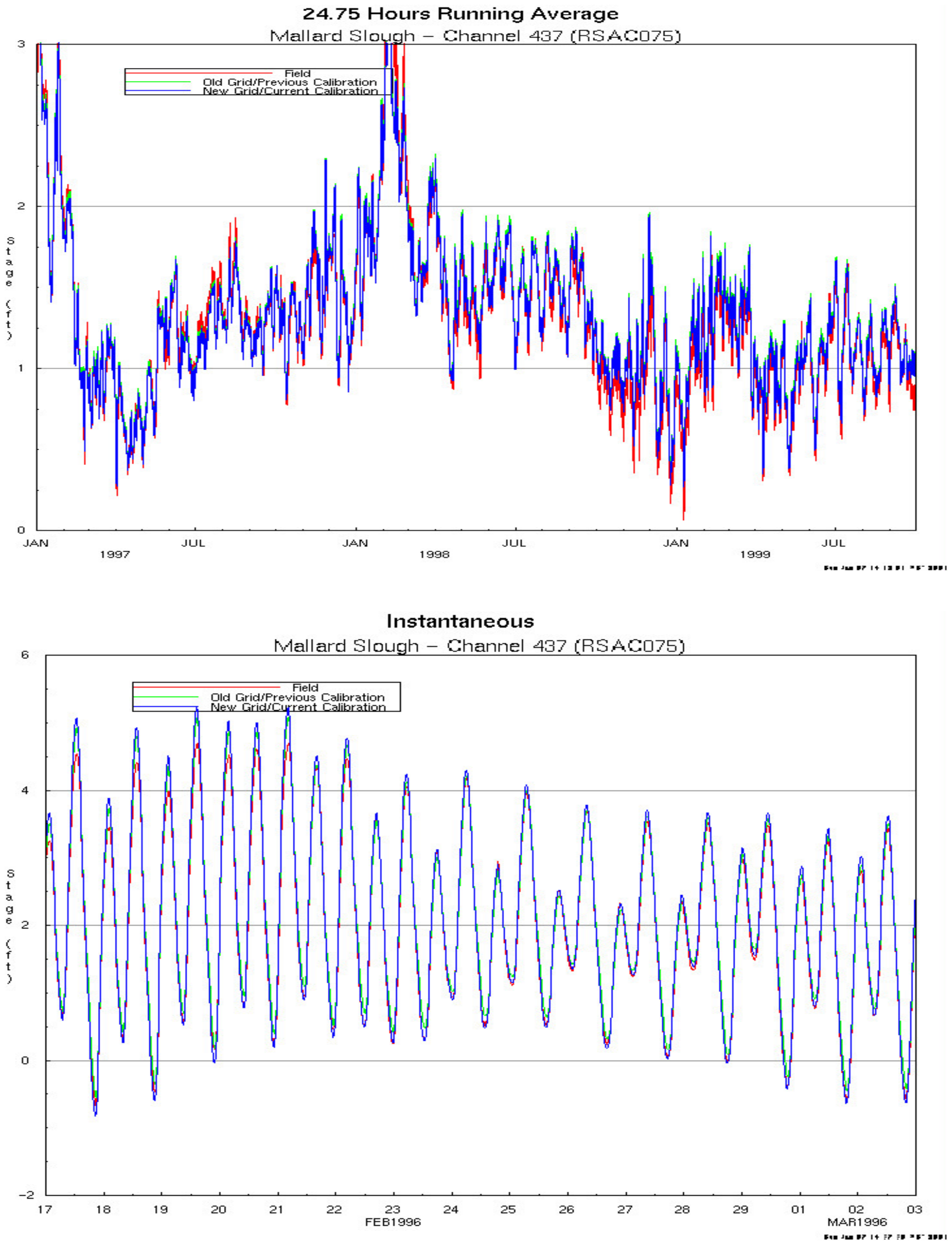

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Figure D-19

DSM2-Simulated and Measured Tidal Stage in Mallard Slough (Chipps Island) for January 1997–September 1999 and February 17–March 2, 1996

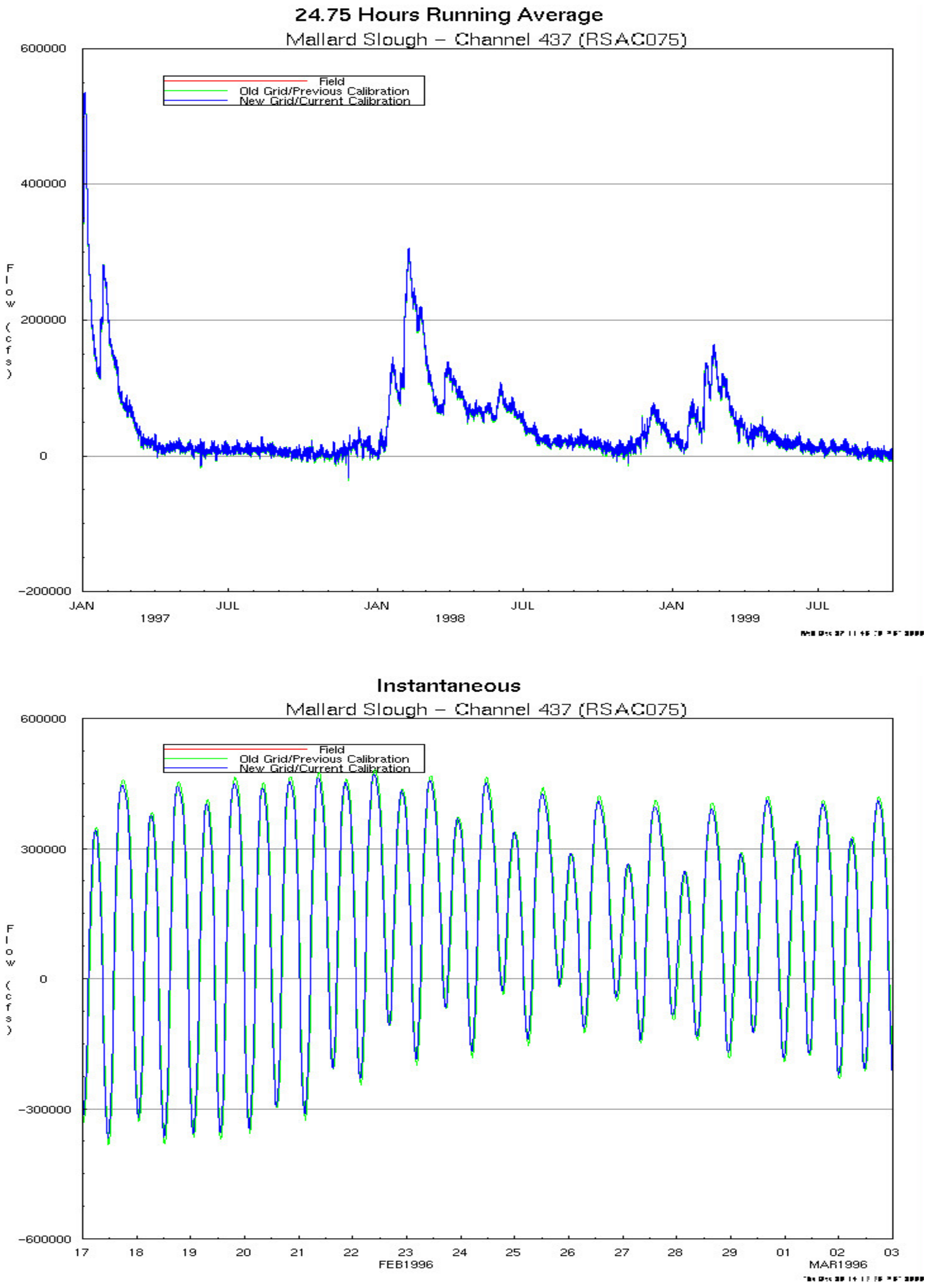
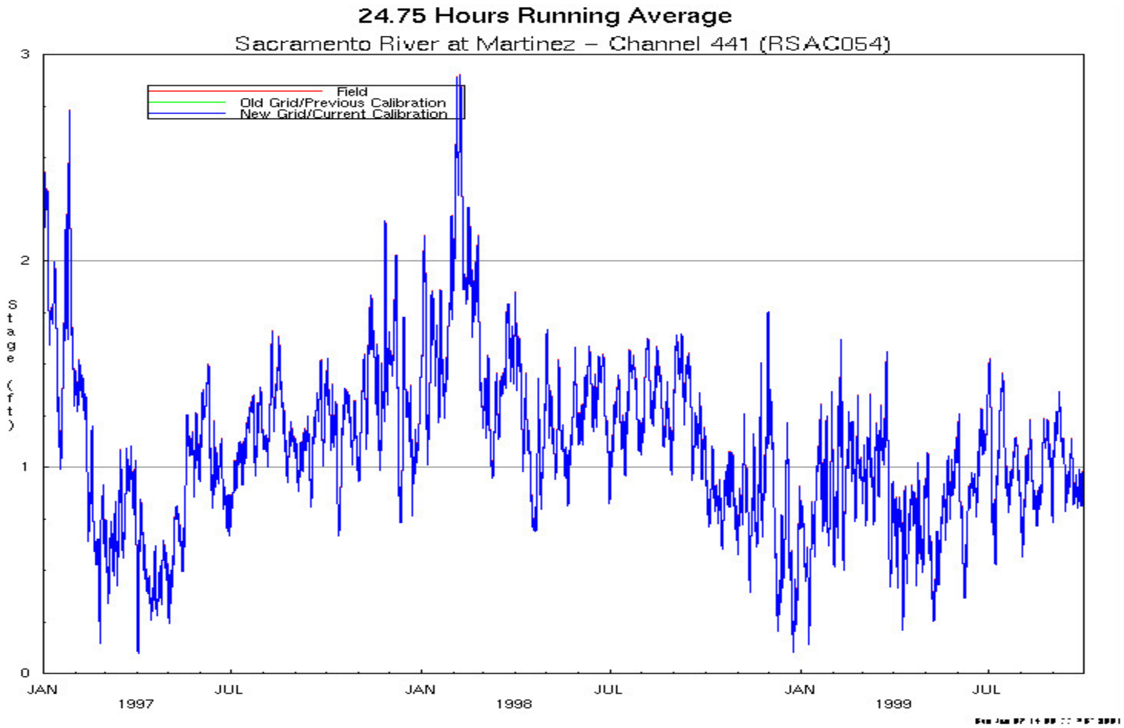


Figure D-20

DSM2-Simulated and Measured Tidal Flow in Mallard Slough (Chipps Island) for January 1997–September 1999 and February 17–March 2, 1996



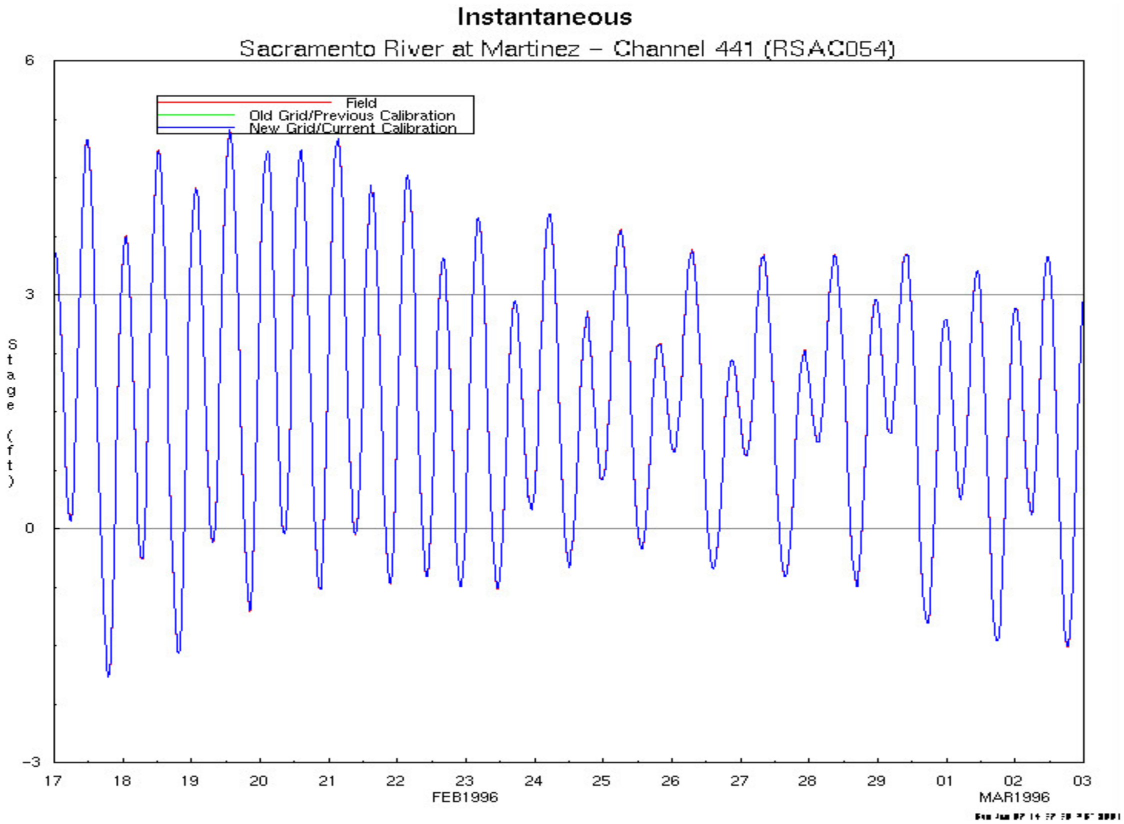


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Figure D-21

Measured Tidal Stage Variations in the Sacramento River at Martinez (DSM2 Model Boundary) for January 1997–September 1999 and February 17–March 2, 1996

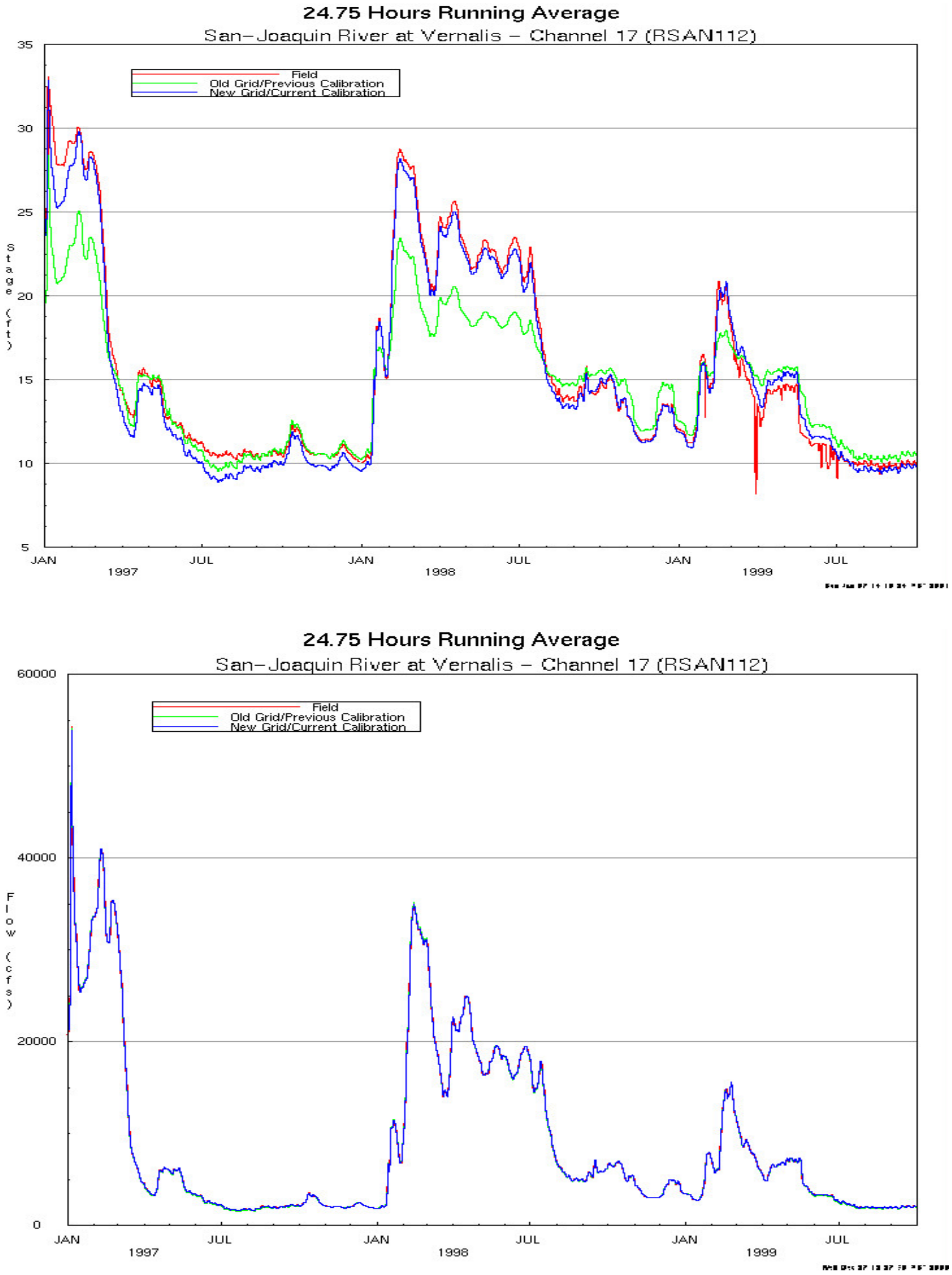

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Figure D-22

DSM2-Simulated and Measured Daily Average Stage and Flow in the San Joaquin River at Vernalis (Upstream Model Boundary) for 1997–1999

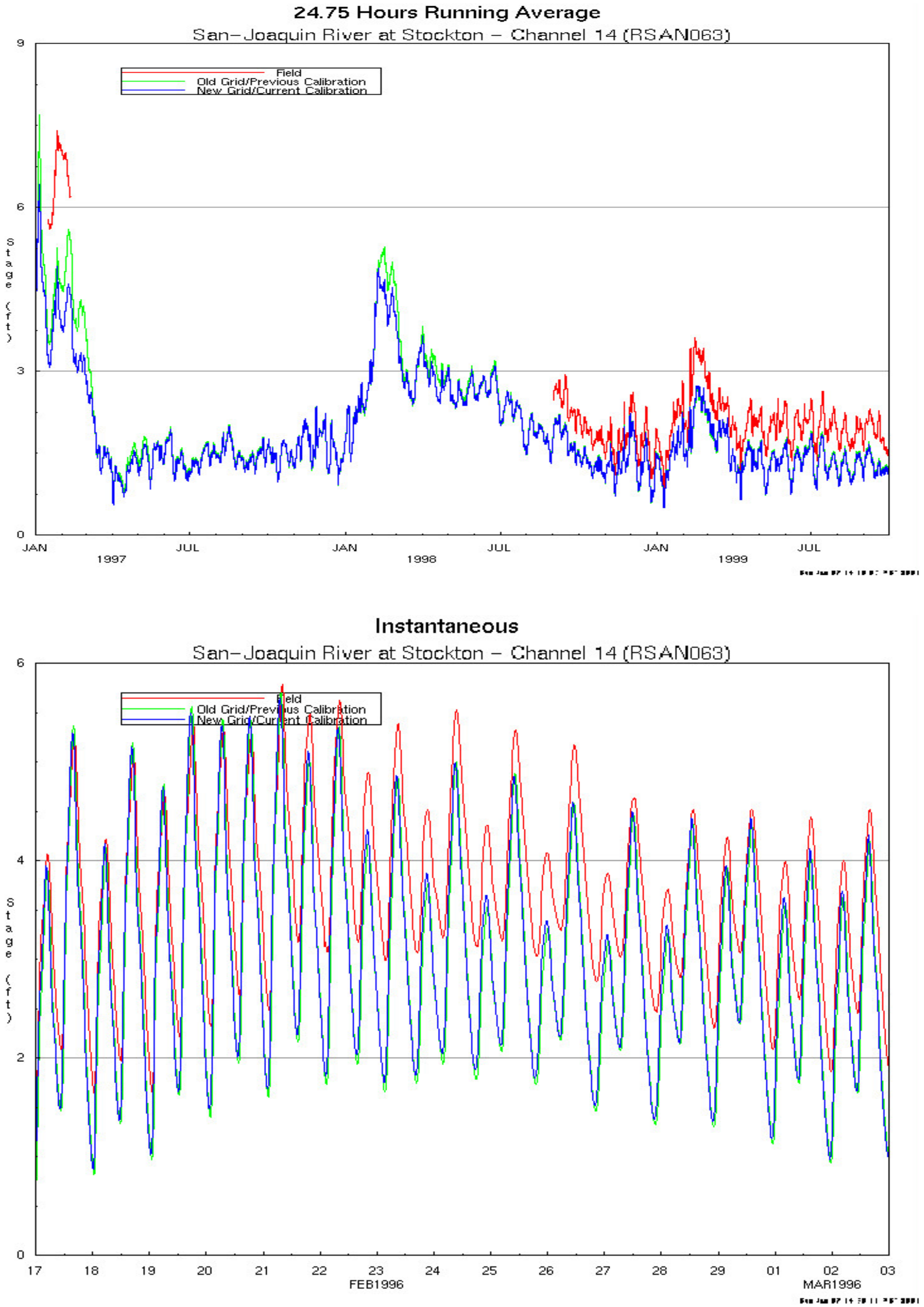

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Figure D-23

DSM2-Simulated and Measured Tidal Stage in the San Joaquin River at Stockton (U.S. Geological Survey Ultrasonic Velocity Meter Station) for January 1997–September 1999 and February 17–March 2, 1996

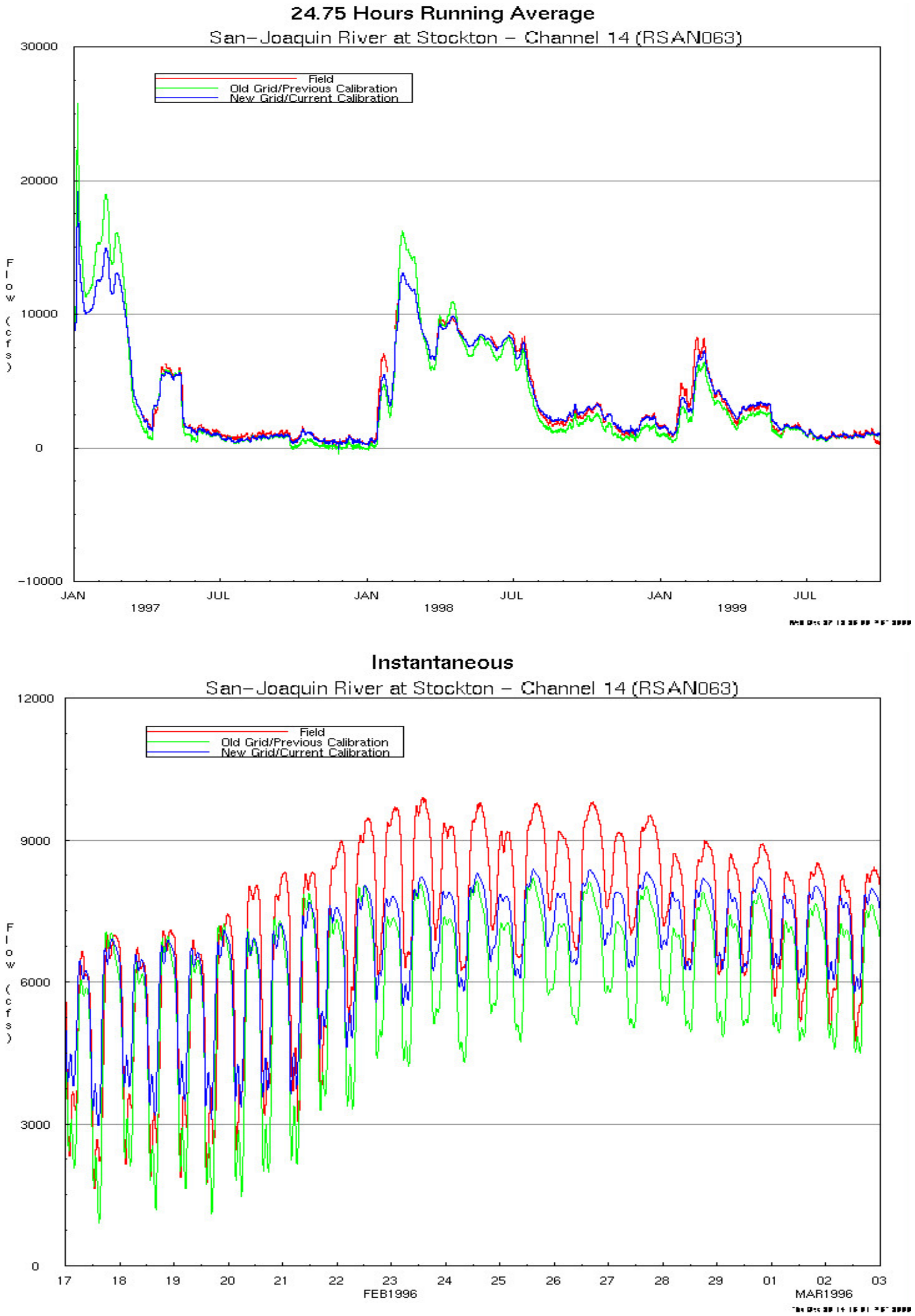

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Figure D-24

DSM2-Simulated and Measured Tidal Flow in the San Joaquin River at Stockton (U.S. Geological Survey Ultrasonic Velocity Meter Station) for January 1997–September 1999 and February 17–March 2, 1996

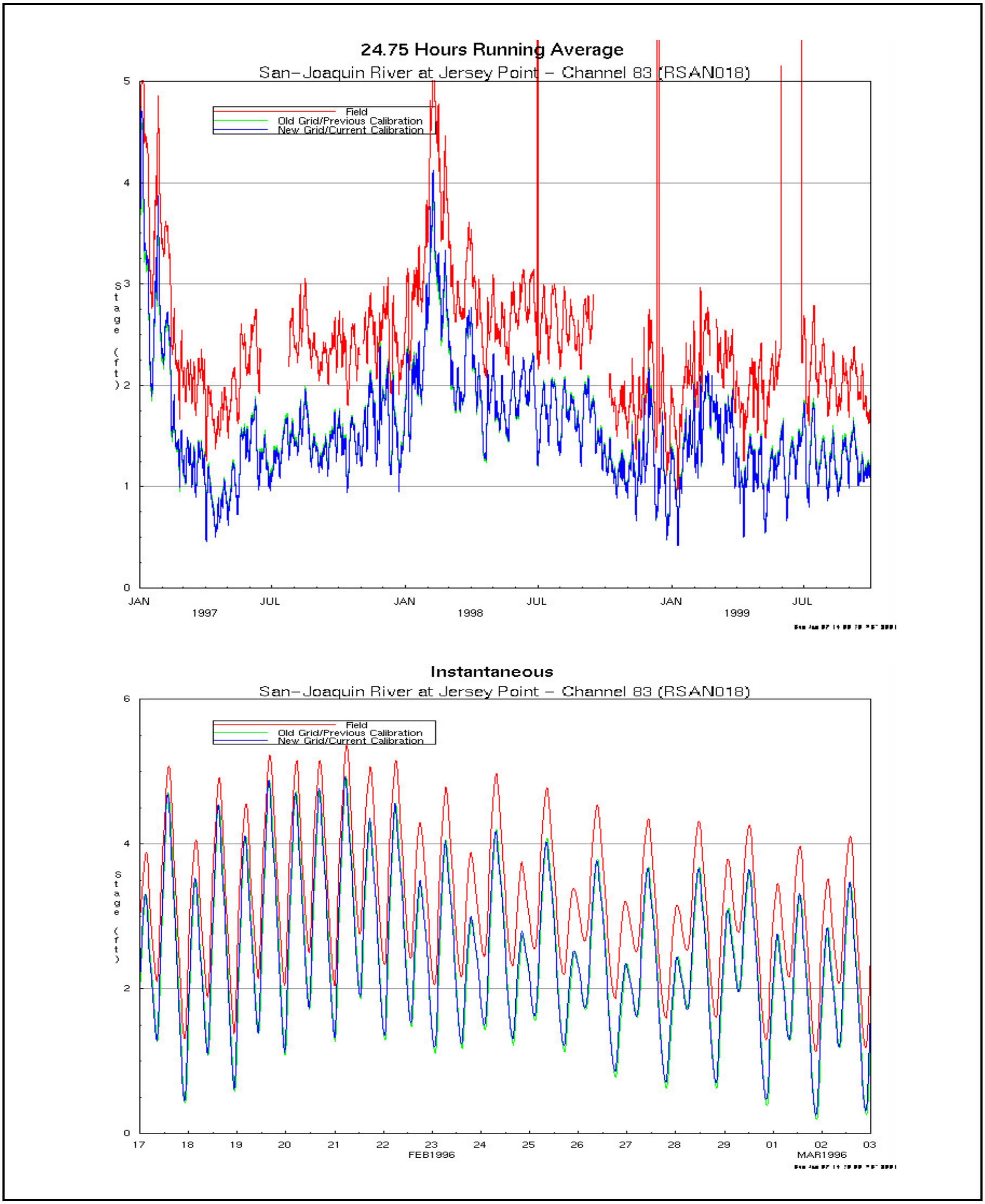

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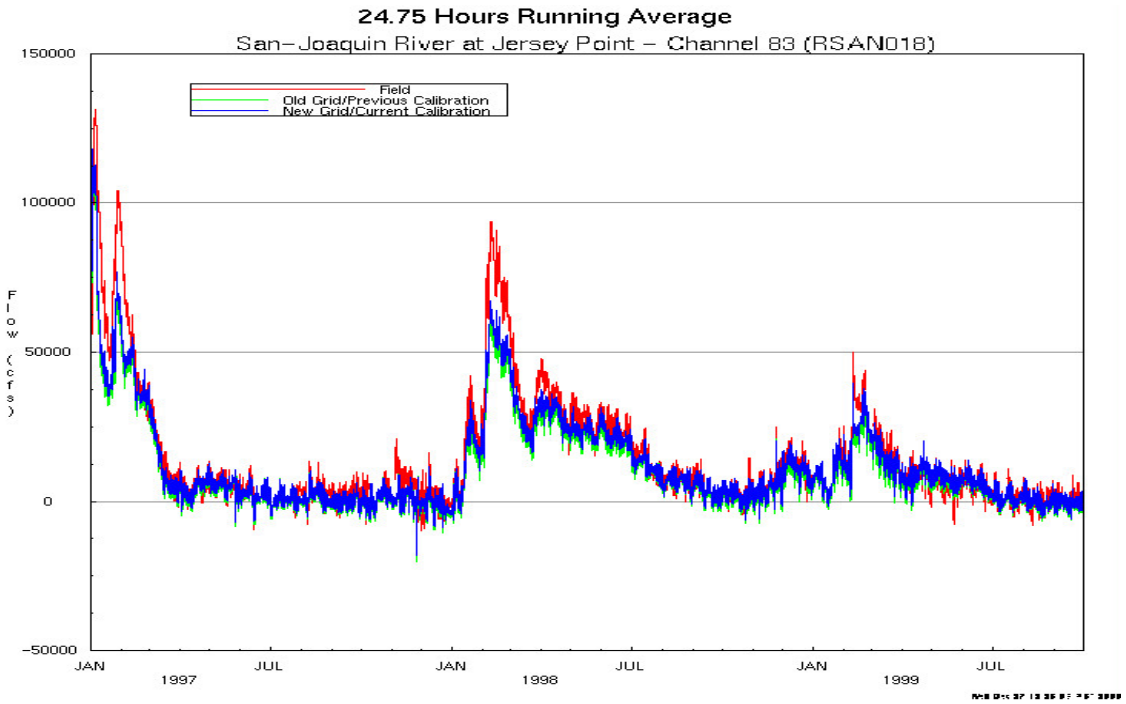
Figure D-25

DSM2-Simulated and Measured Tidal Stage in the San Joaquin River at Jersey Point for January 1997–September 1999 and February 17–March 2, 1996



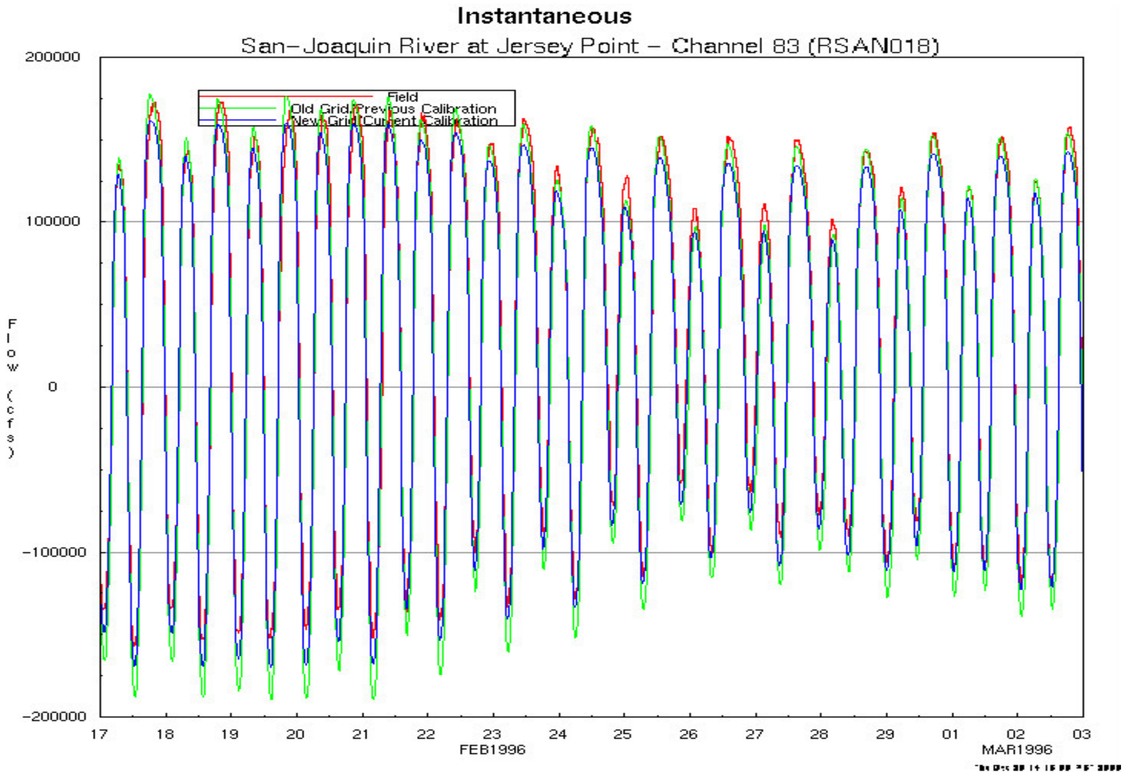


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Figure D-26

DSM2-Simulated and Measured Tidal Flow in the San Joaquin River at Jersey Point for January 1997–September 1999 and February 17–March 2, 1996

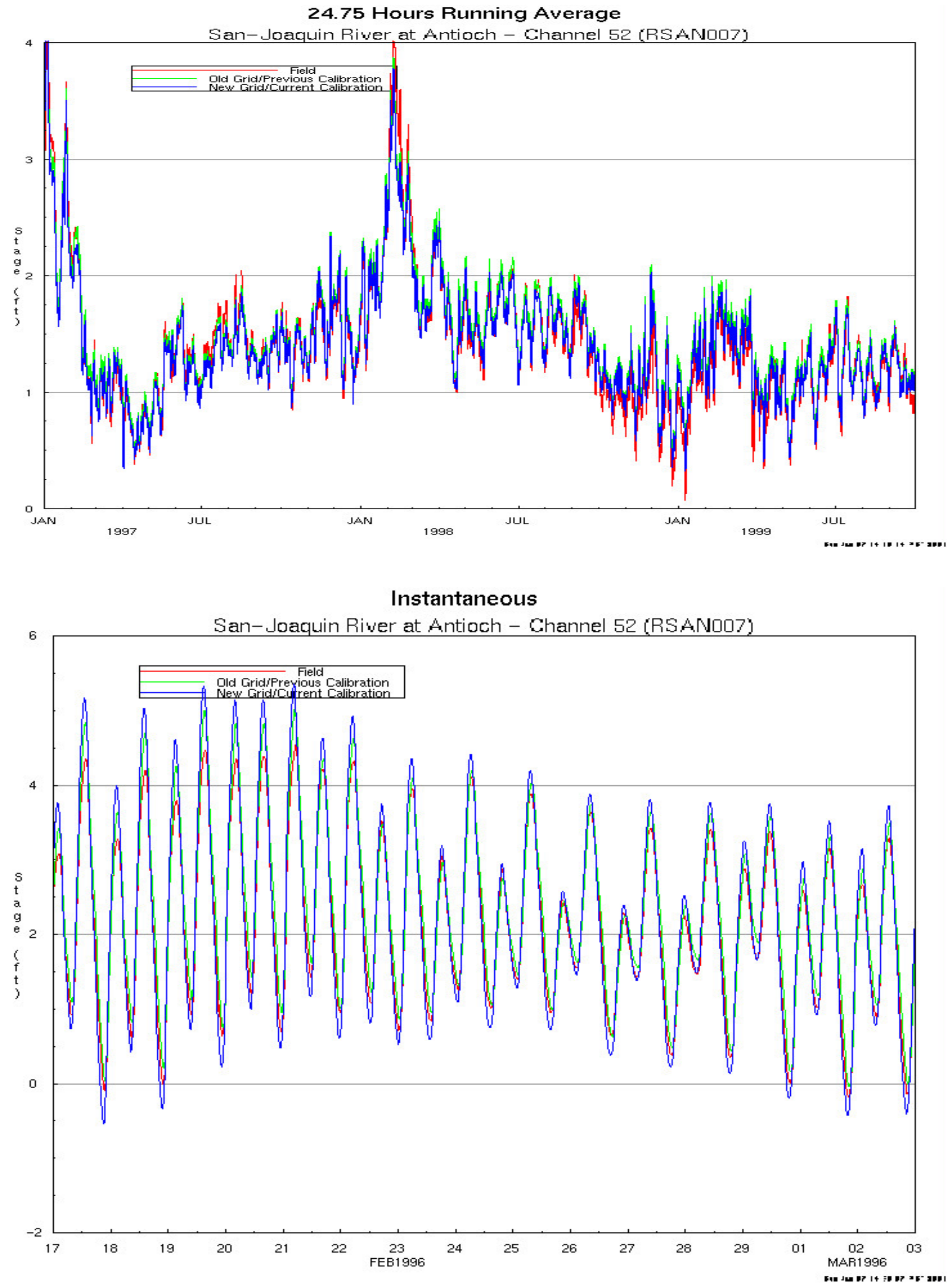

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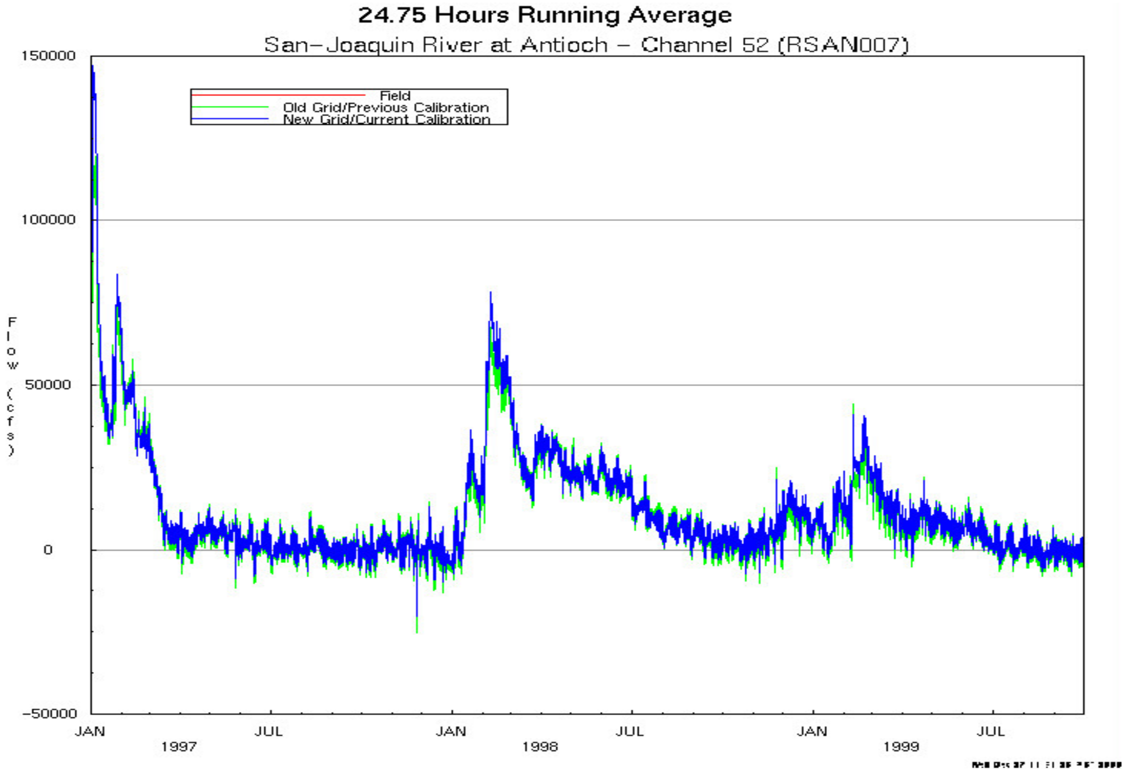
Figure D-27

DSM2-Simulated and Measured Tidal Stage in the San Joaquin River at Antioch for January 1997–September 1999 and February 17–March 2, 1996



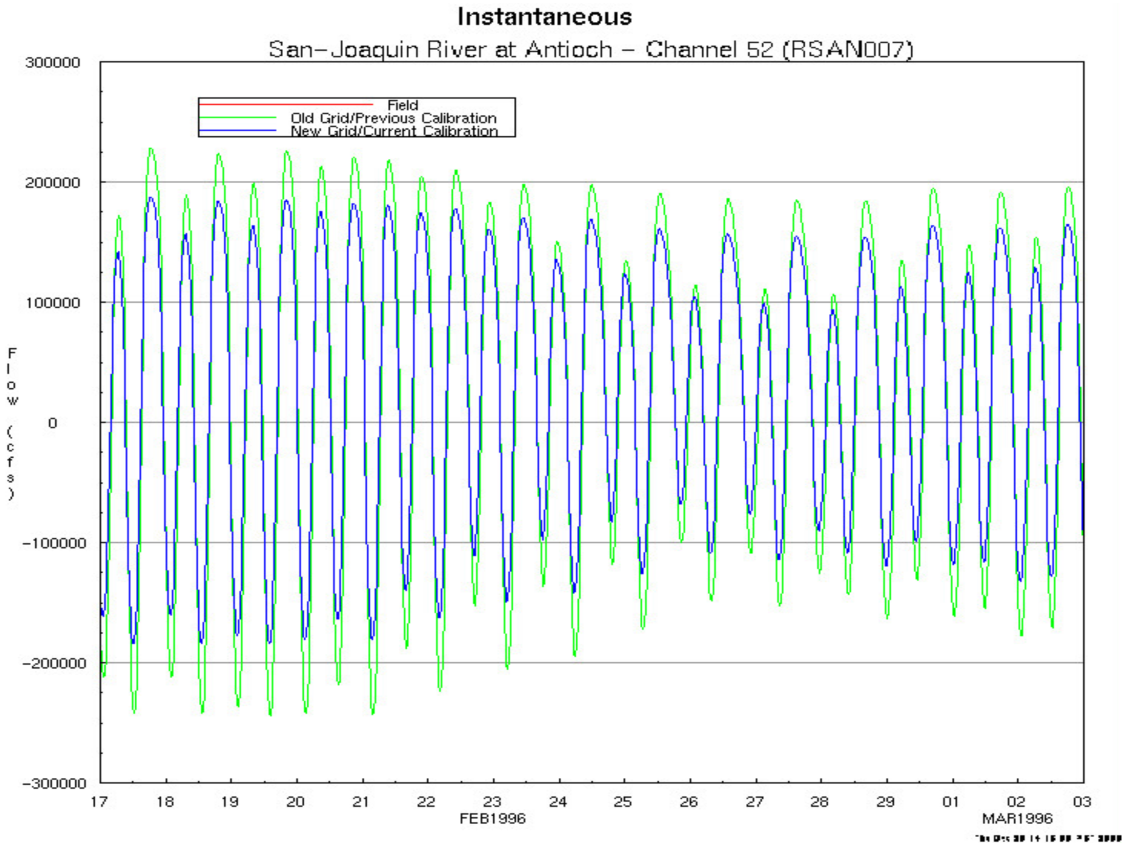


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Figure D-28

DSM2-Simulated and Measured Tidal Stage in the San Joaquin River at Antioch for January 1997–September 1999 and February 17–March 2, 1996

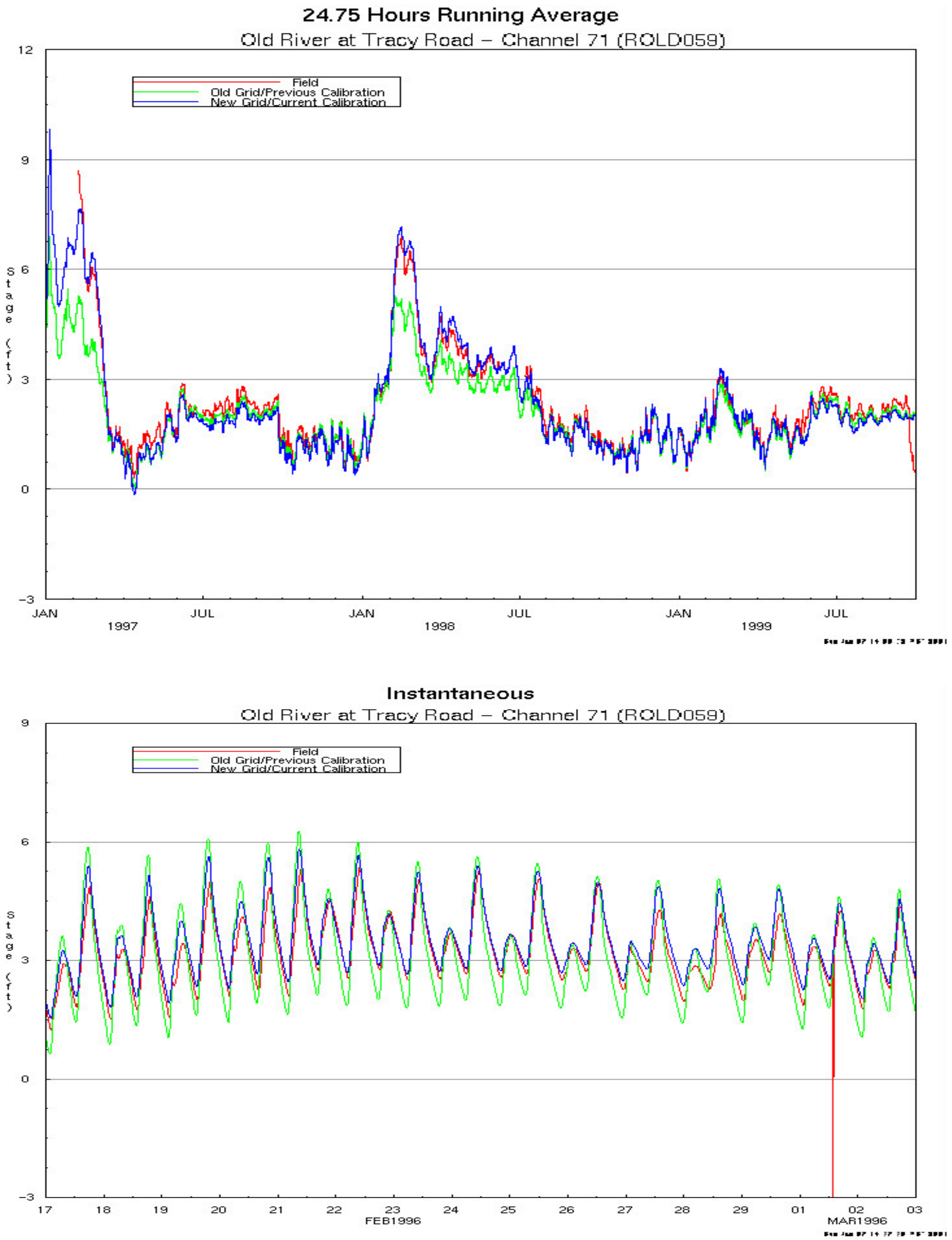

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Figure D-29

DSM2-Simulated and Measured Tidal Stage in Old River at Tracy Boulevard Bridge for January 1997–September 1999 and February 17–March 2, 1996

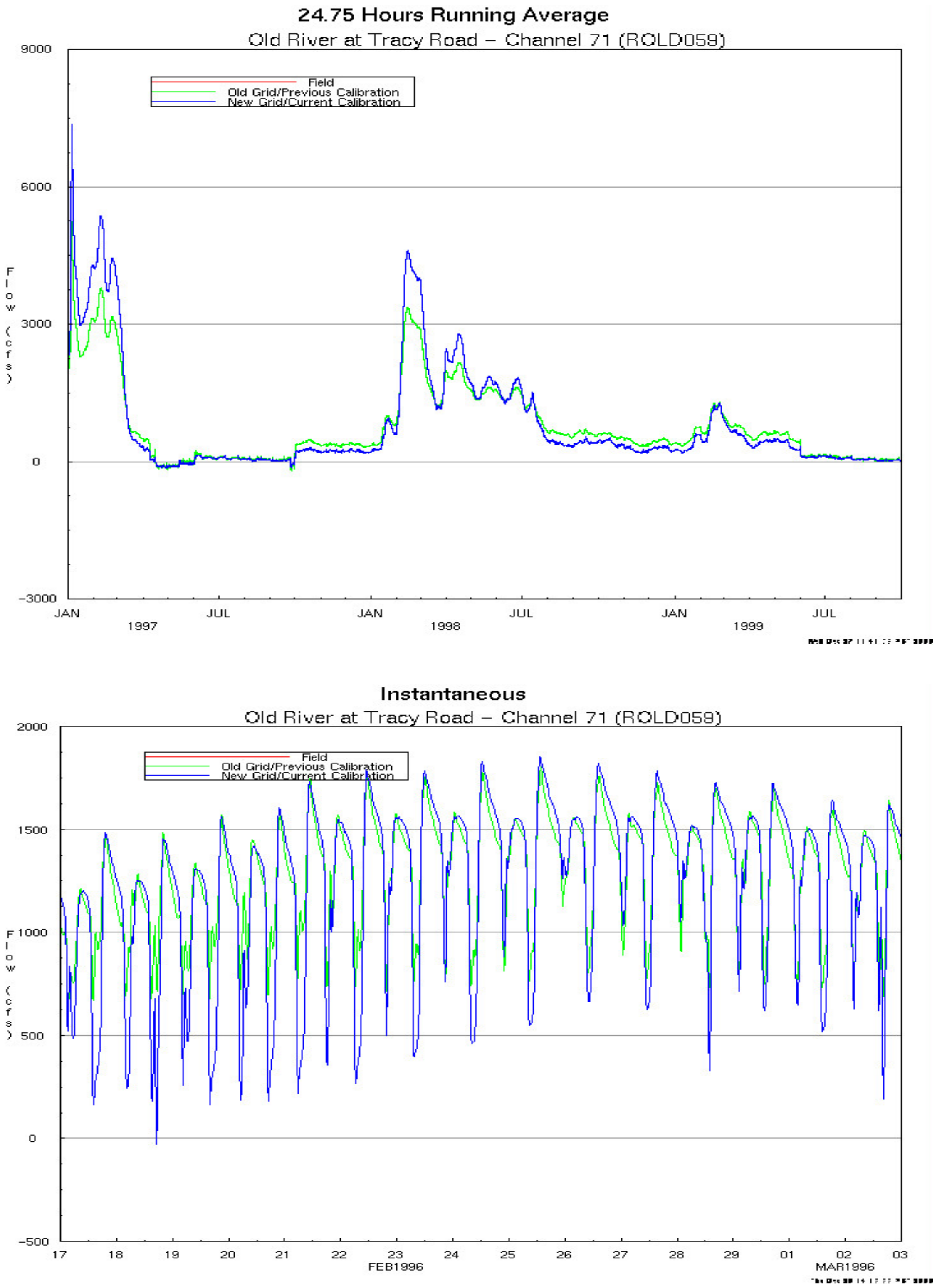

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Figure D-30

DSM2-Simulated and Measured Tidal Flow in Old River at Tracy Boulevard Bridge for January 1997–September 1999 and February 17–March 2, 1996

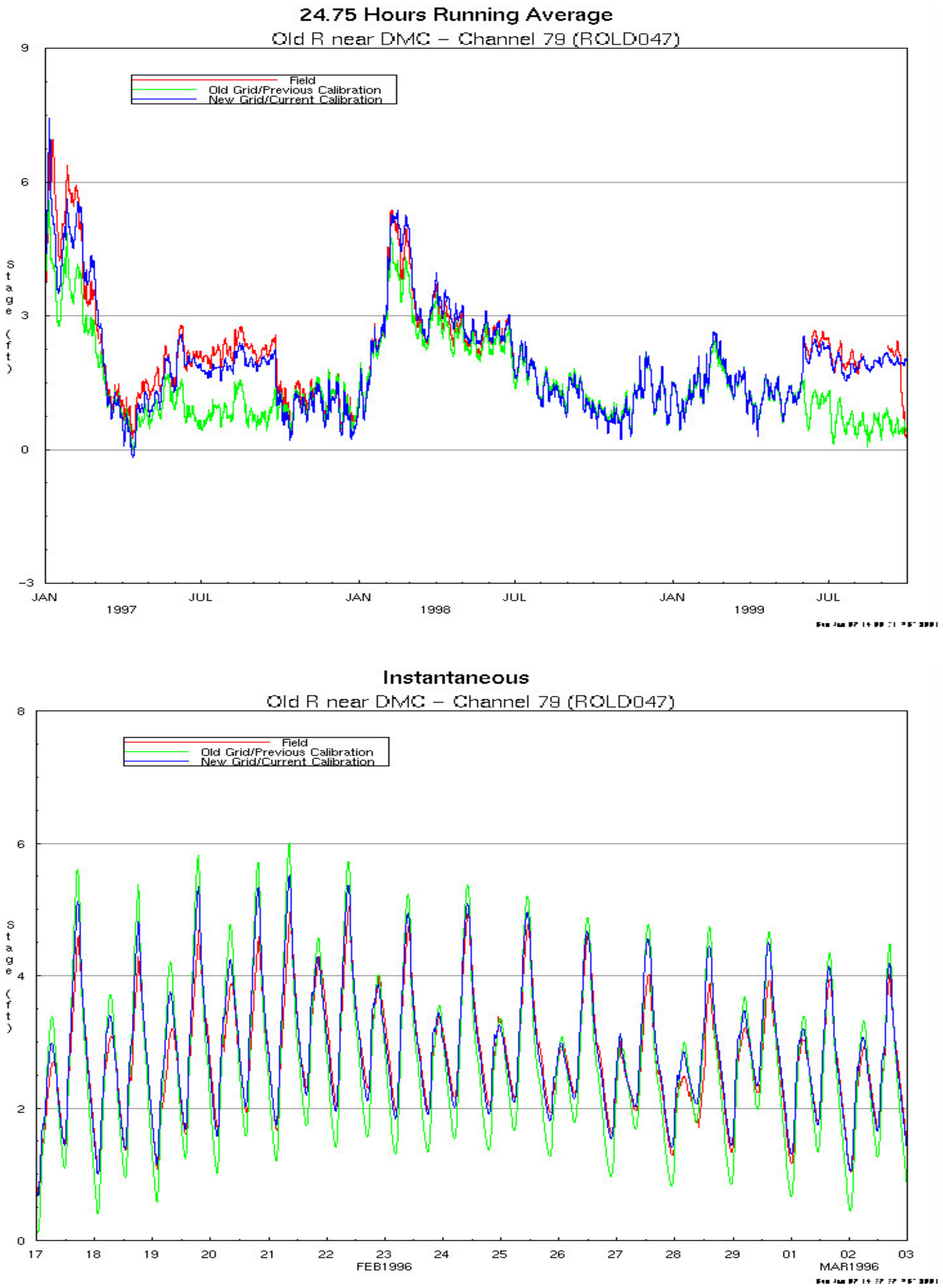

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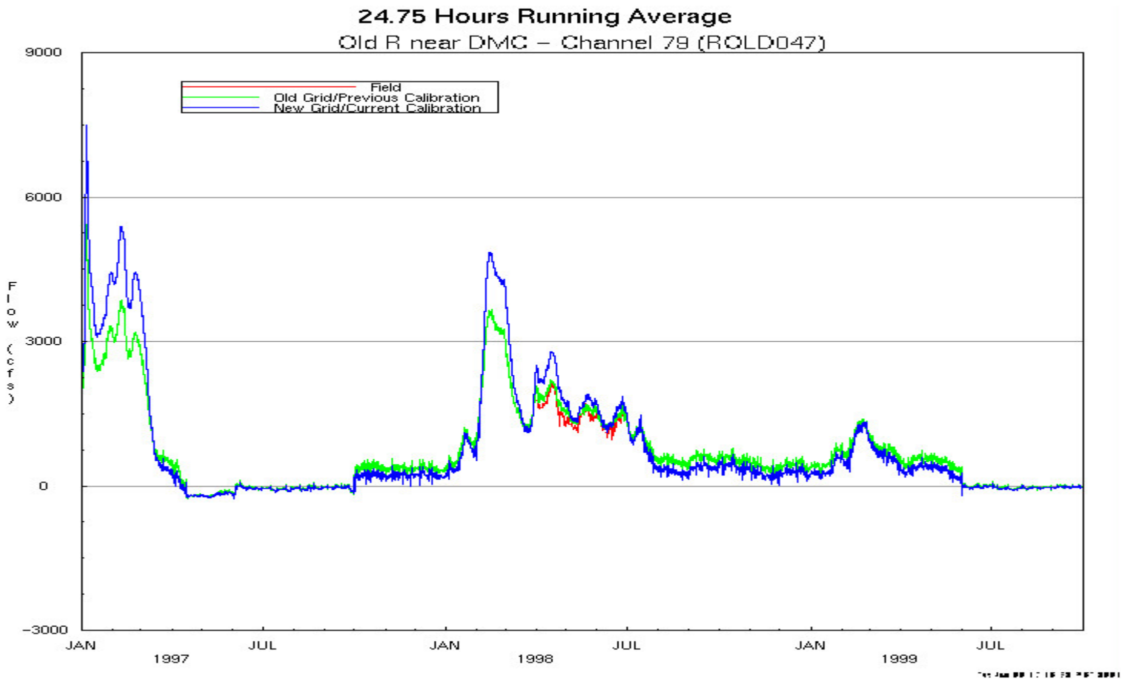
Figure D-31

DSM2-Simulated Tidal Stage in Old River near Delta-Mendota Canal for January 1997–September 1999 and February 17–March 2, 1996



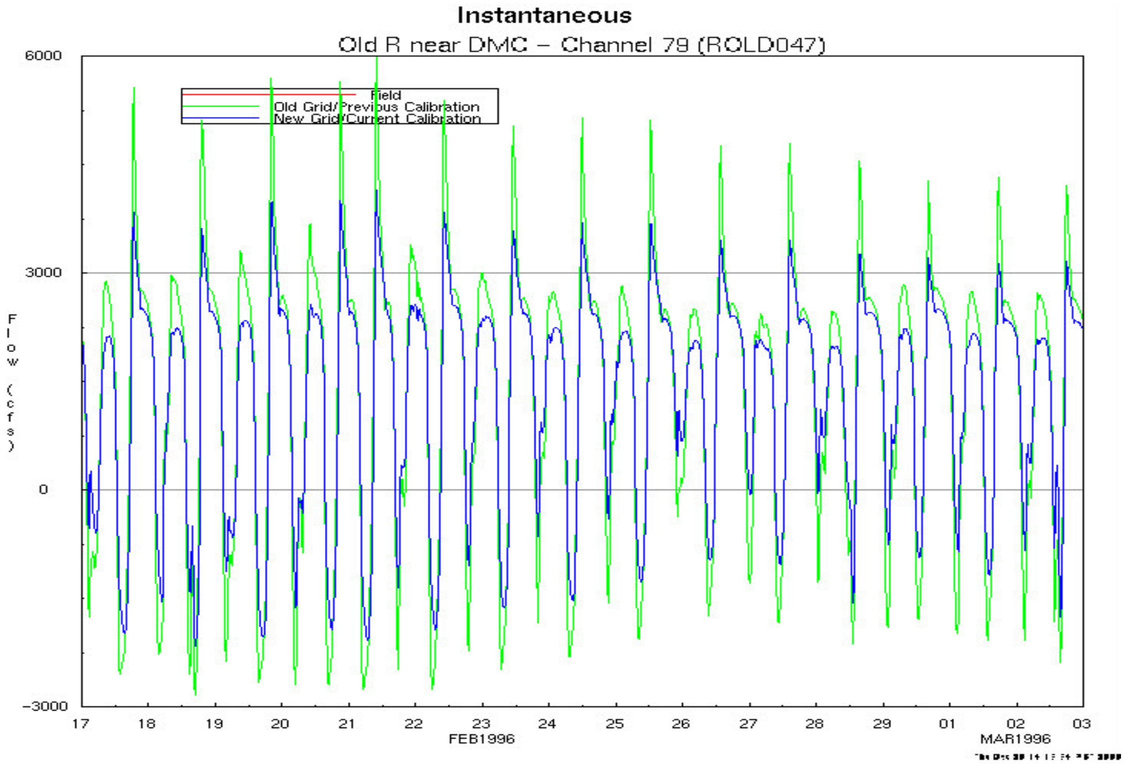


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Figure D-32

**DSM2-Simulated Tidal Flow
in Old River near Delta-Mendota Canal for
January 1997–September 1999 and February 17–March 2, 1996**

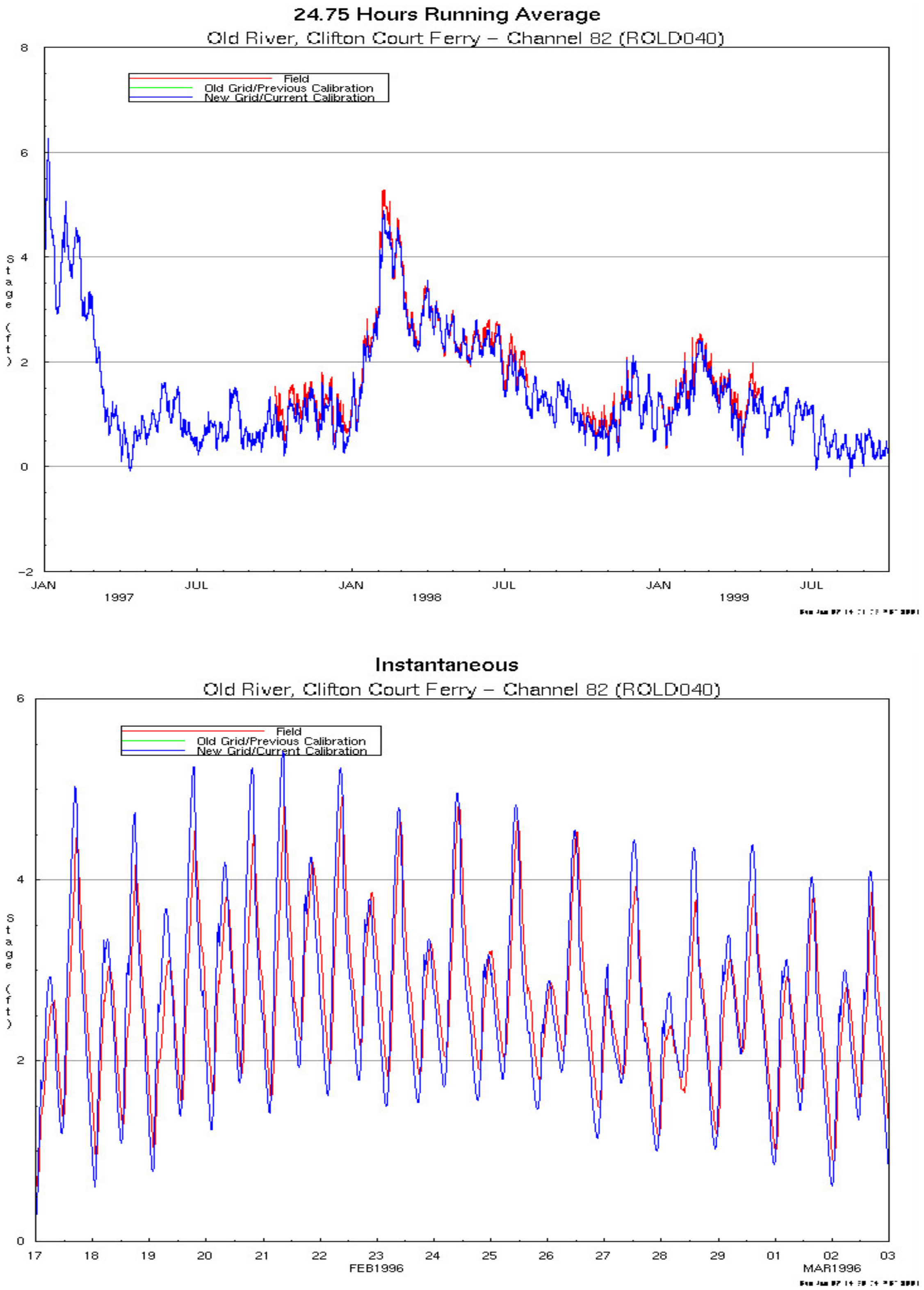

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Figure D-33

Validation of DSM2 for Old River at Clifton Court Ferry for January 1997–September 1999 and February 17–March 2, 1996

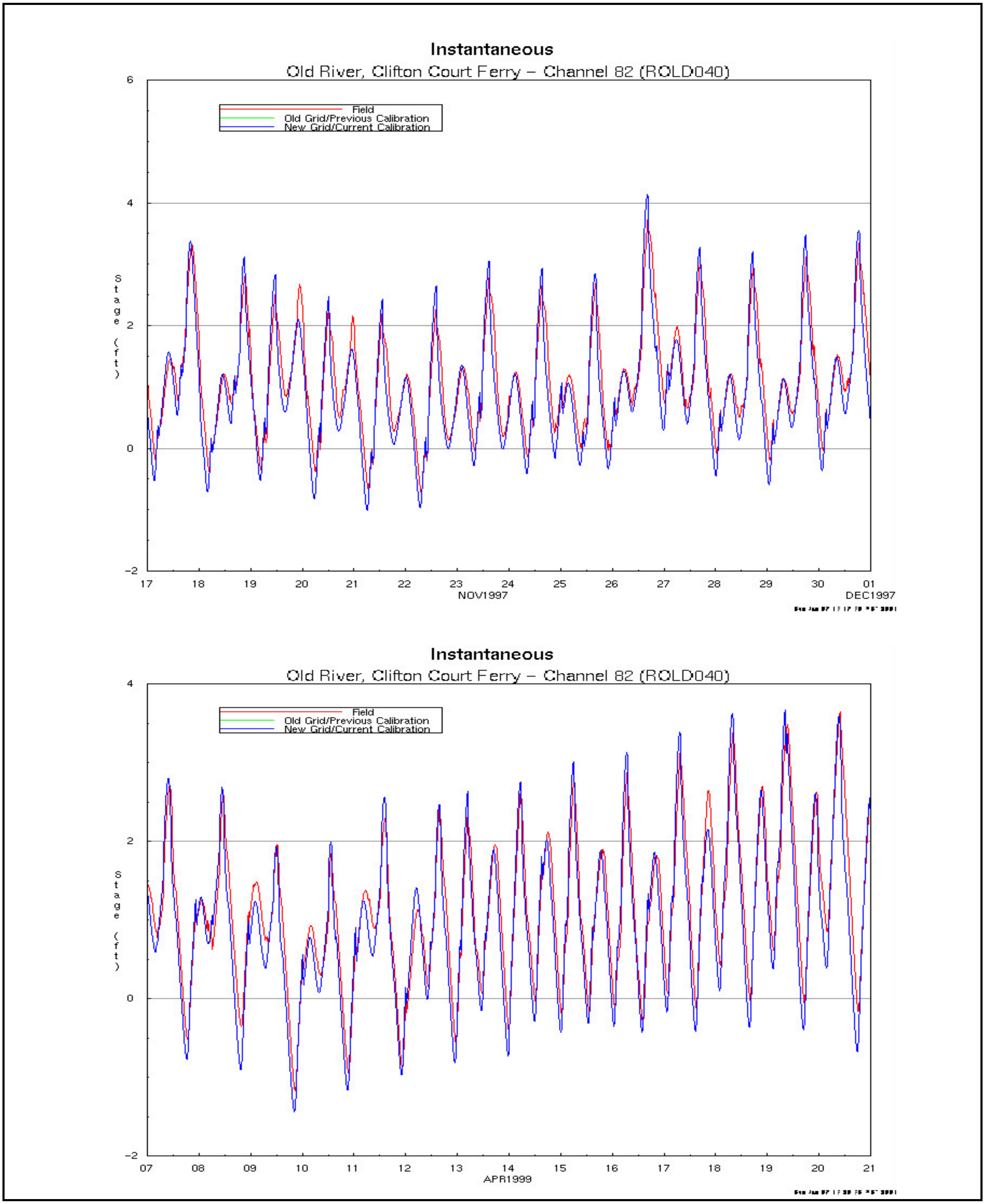

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Figure D-34

DSM2-Simulated and Measured Tidal Stage in Old River at Clifton Court Ferry for November 17–30, 1997 and April 7–20, 1999

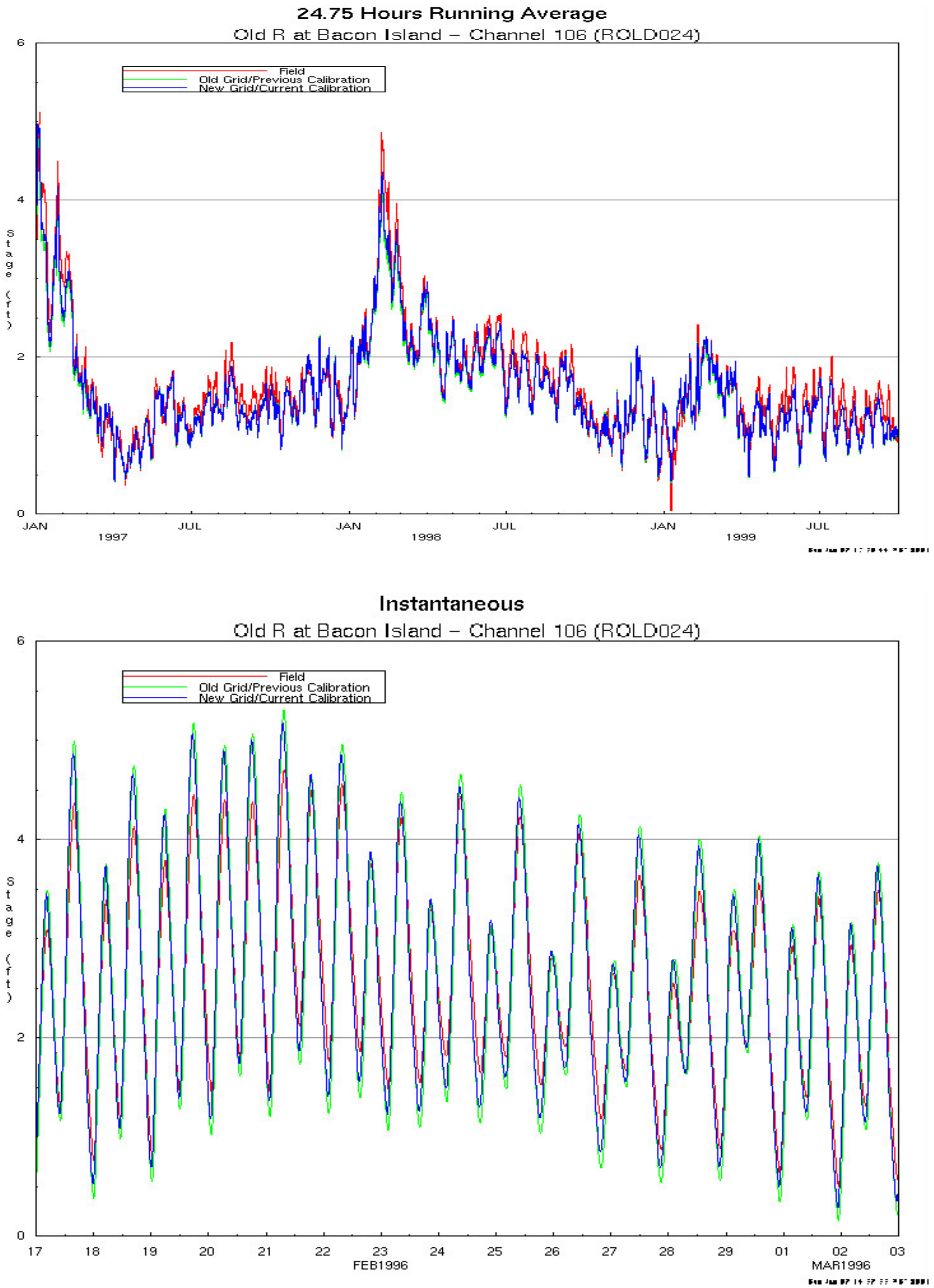

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Figure D-35

DSM2-Simulated and Measured Tidal Stage in Old River at Bacon Island (U.S. Geological Survey Ultrasonic Velocity Meter Station) for January 1997–September 1999 and February 17–March 2, 1996

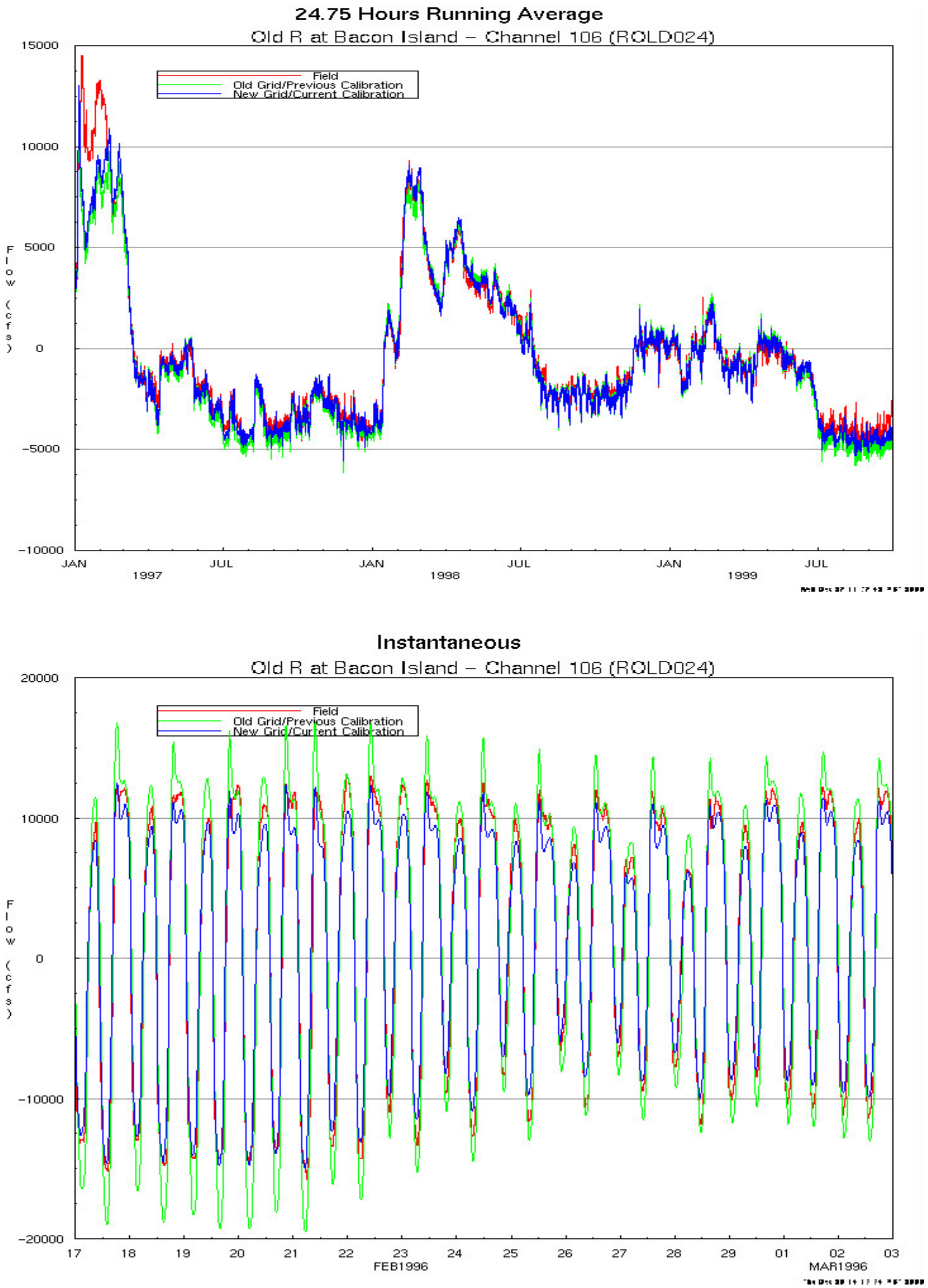

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Figure D-36

DSM2-Simulated and Measured Tidal Flow in Old River at Bacon Island (U.S. Geological Survey Ultrasonic Velocity Meter Station) for January 1997–September 1999 and February 17–March 2, 1996

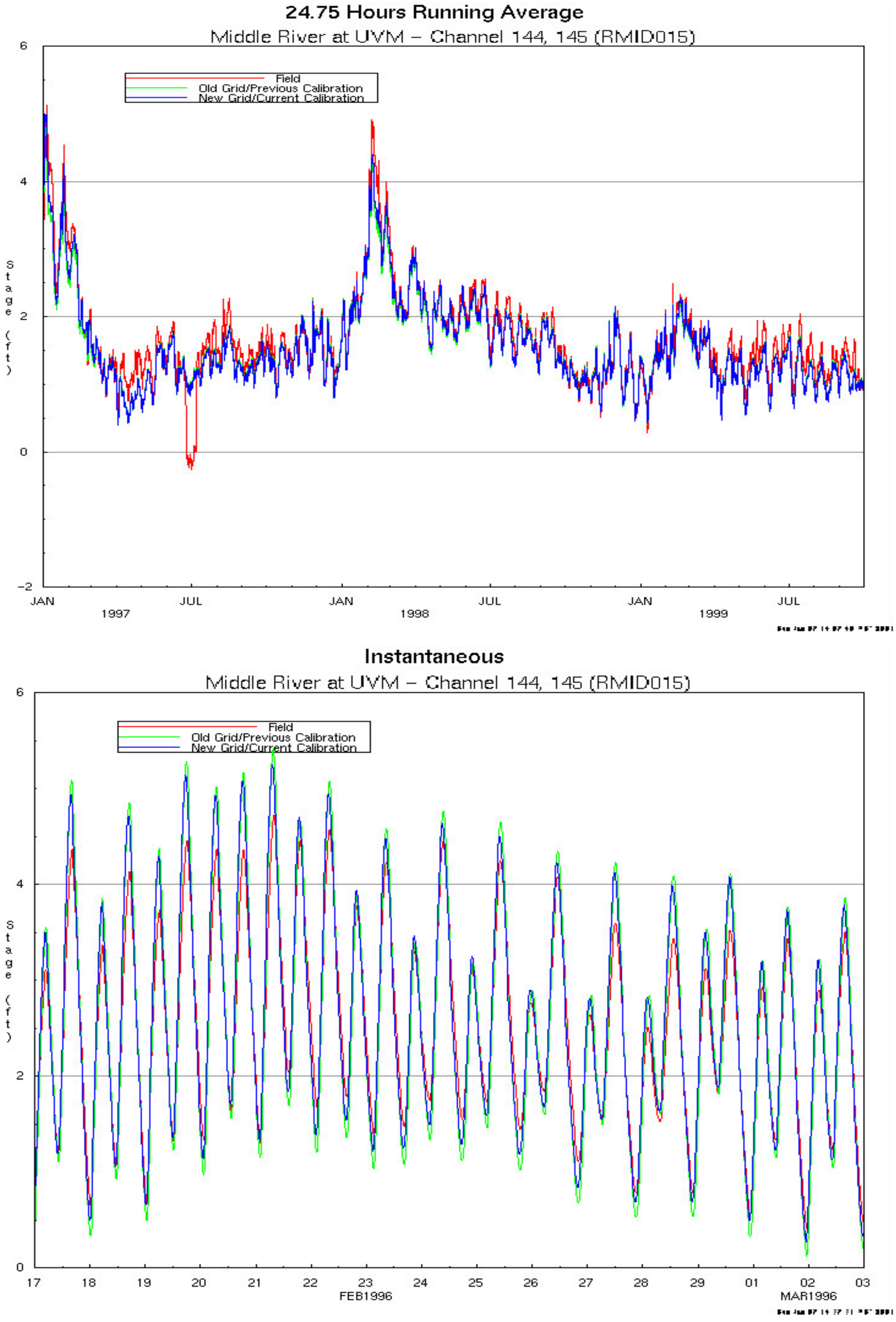

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Figure D-37

DSM2-Simulated and Measured Tidal Flow in Middle River at Bacon Island (U.S. Geological Survey Ultrasonic Velocity Meter Station) for January 1997–September 1999 and February 17–March 2, 1996

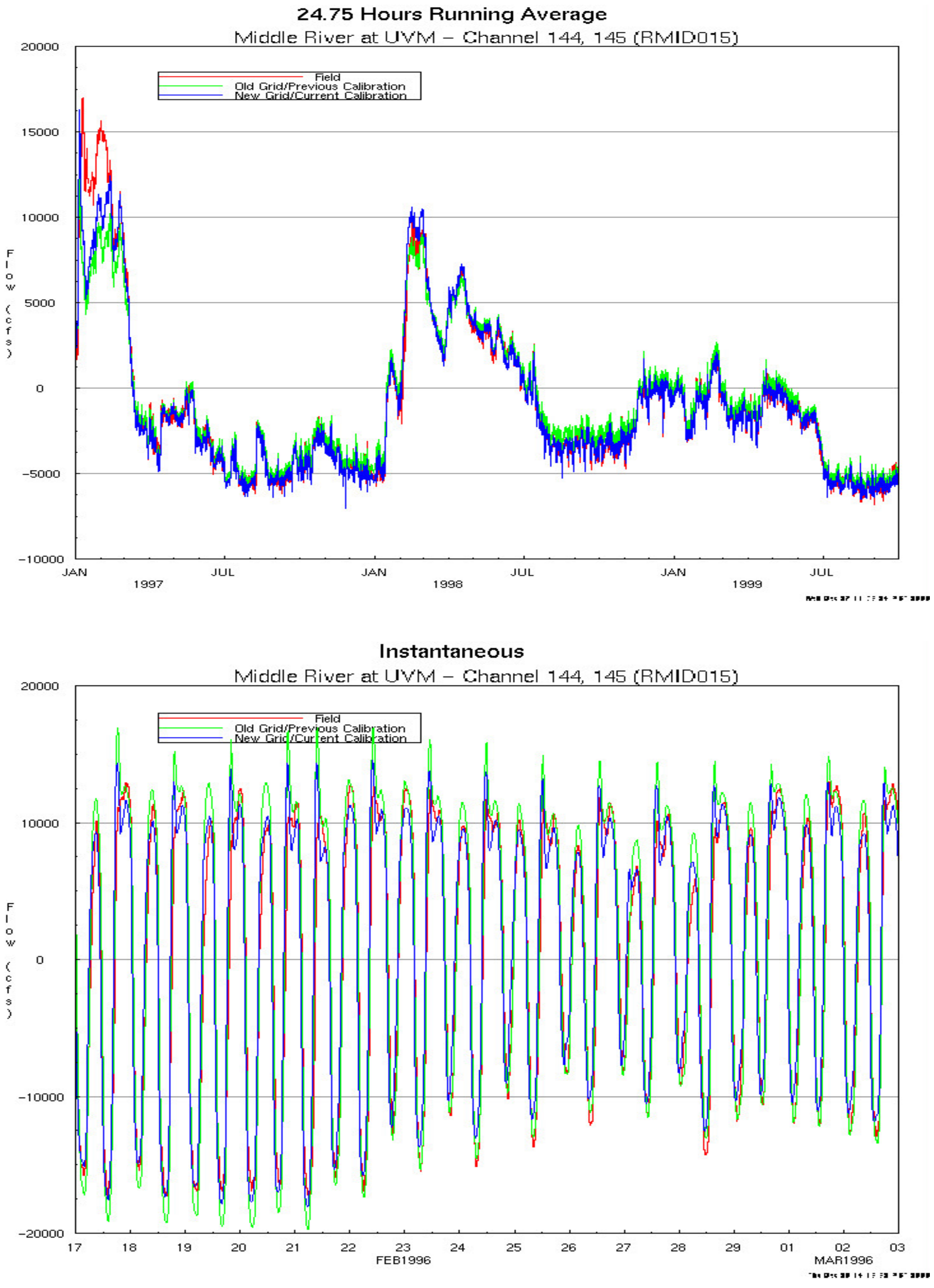

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Figure D-38

DSM2-Simulated and Measured Tidal Flow in Middle River at Bacon Island (U.S. Geological Survey Ultrasonic Velocity Meter Station) for January 1997–September 1999 and February 17–March 2, 1996

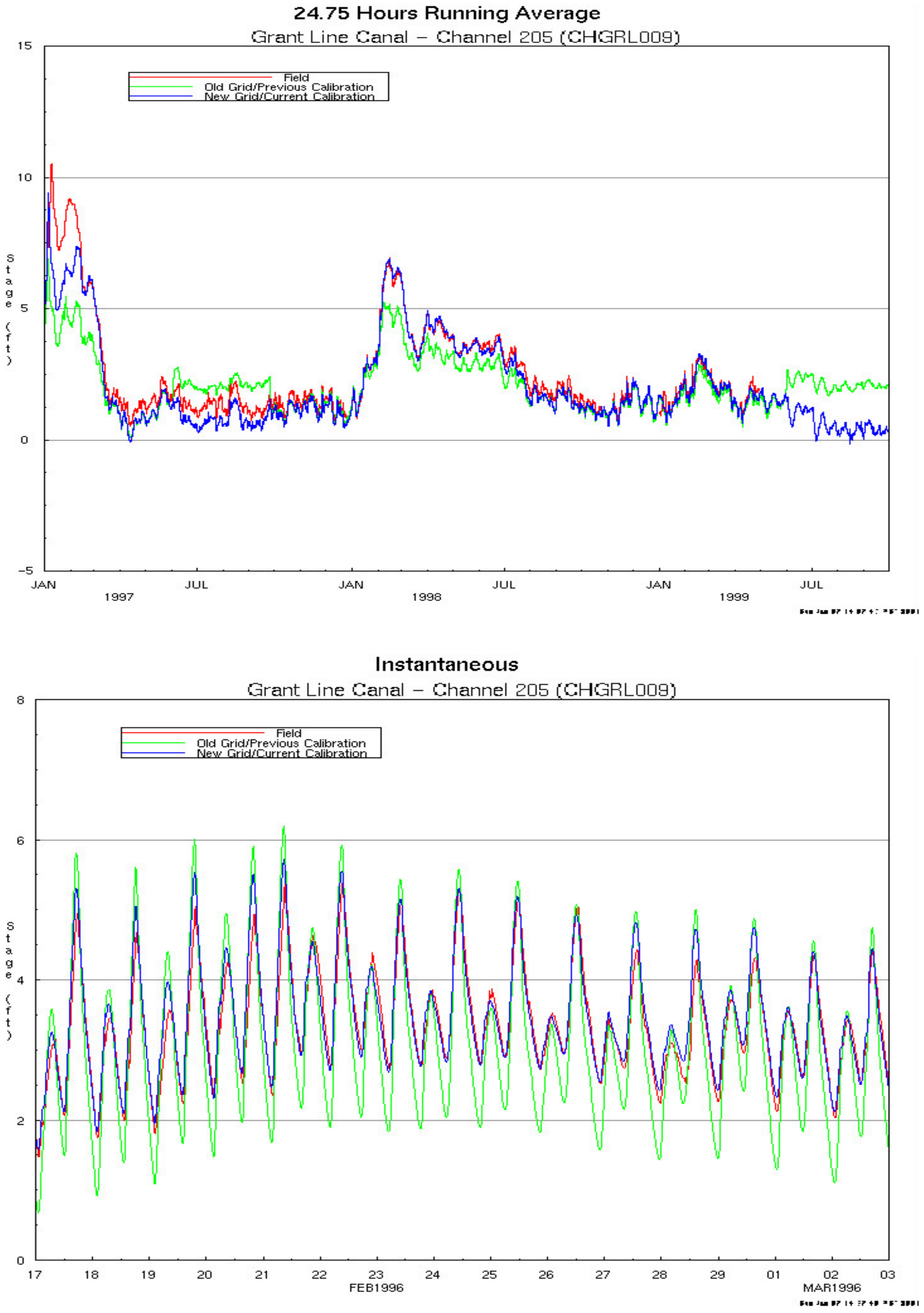

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Figure D-39

DSM2-Simulated and Measured Tidal Stage in Grant Line Canal at Tracy Boulevard Bridge for January 1997–September 1999 and February 17–March 2, 1996

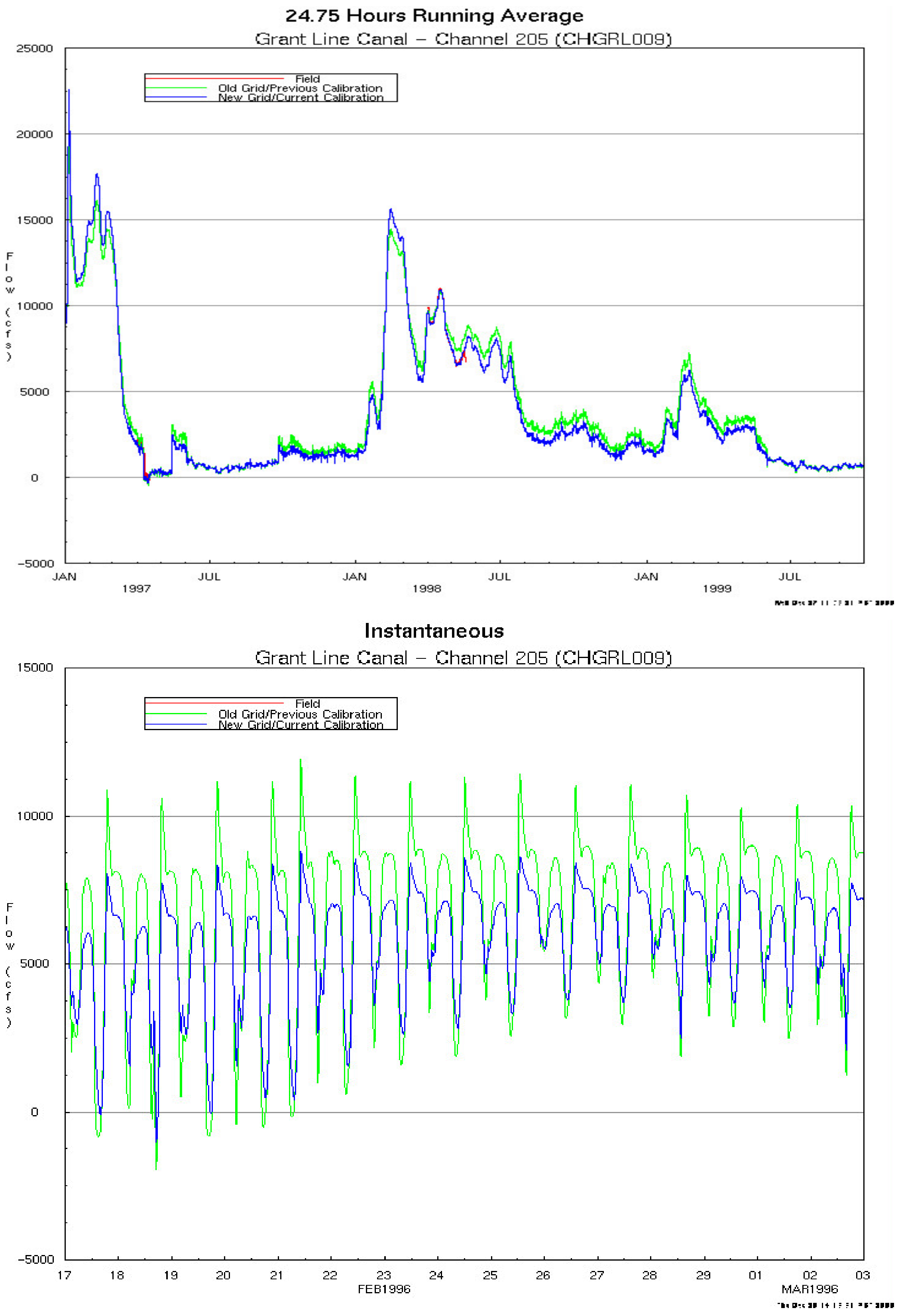

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Figure D-40

DSM2-Simulated and Measured Tidal Flow in Grant Line Canal at Tracy Boulevard Bridge for January 1997–September 1999 and February 17–March 2, 1996

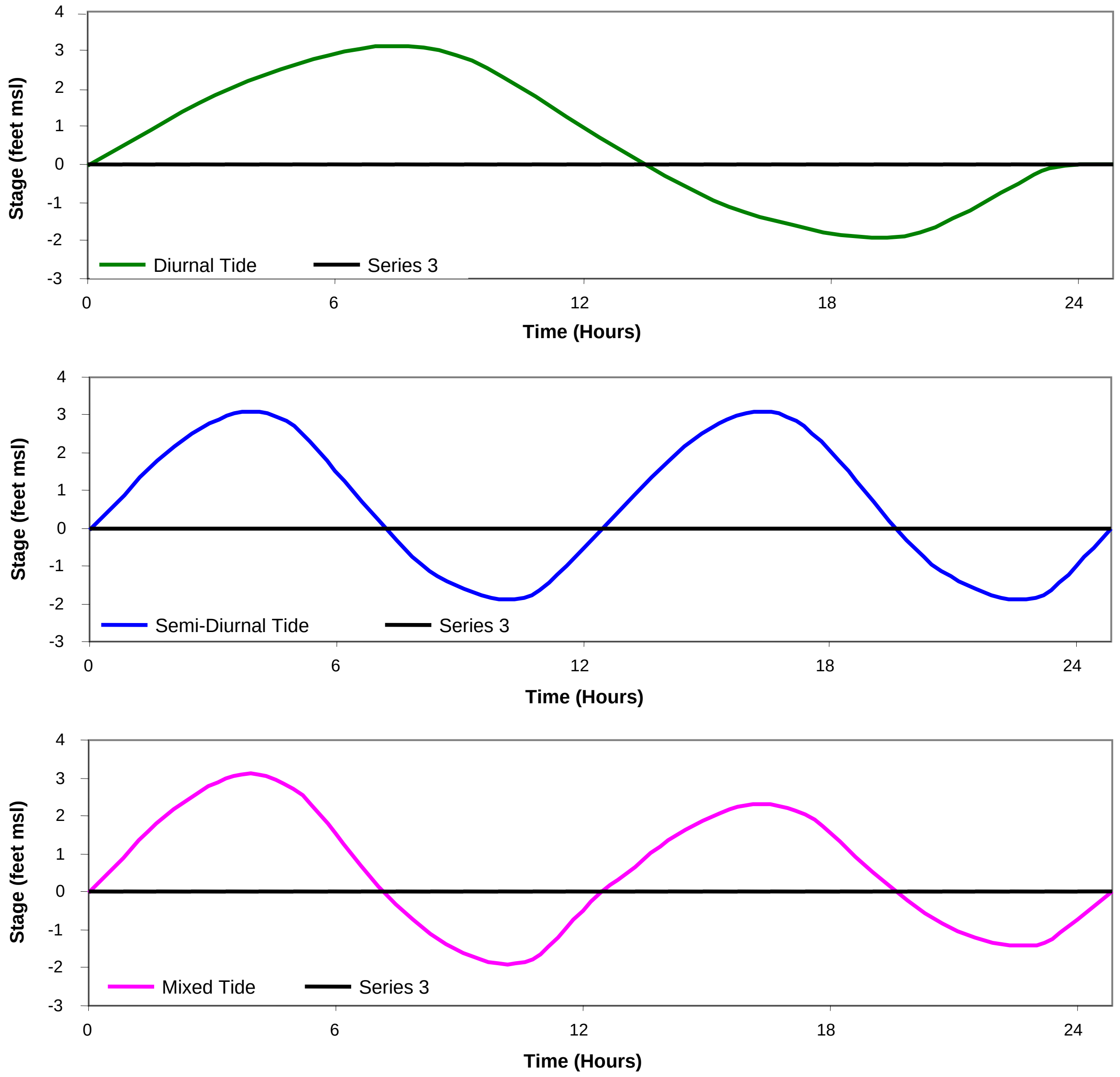

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Figure D-41

General Types of Tidal Cycles

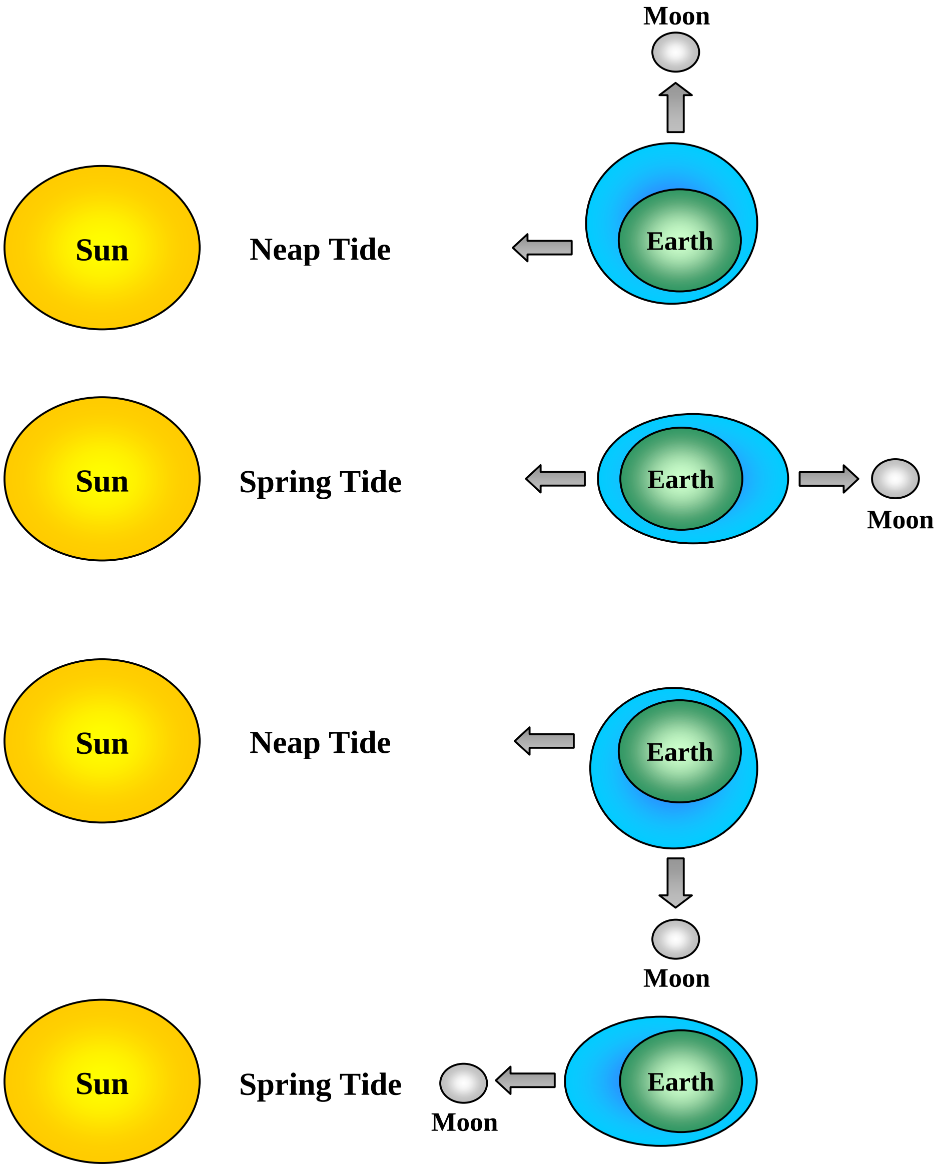

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Figure D-42

Conceptualization of the Effects of the Sun and Moon on Tides

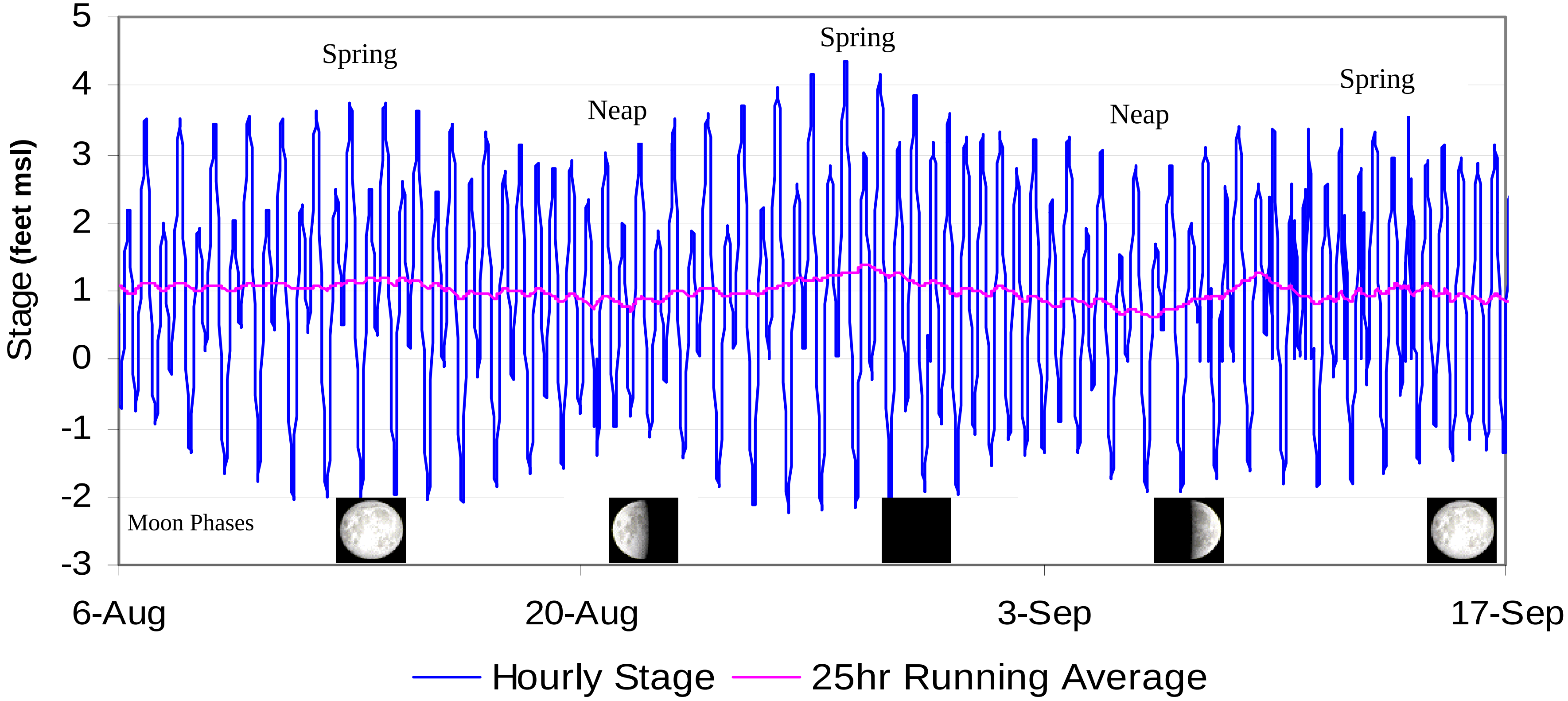

Figure D-43

Spring and Neap Tides at Martinez, California, August and September 2000

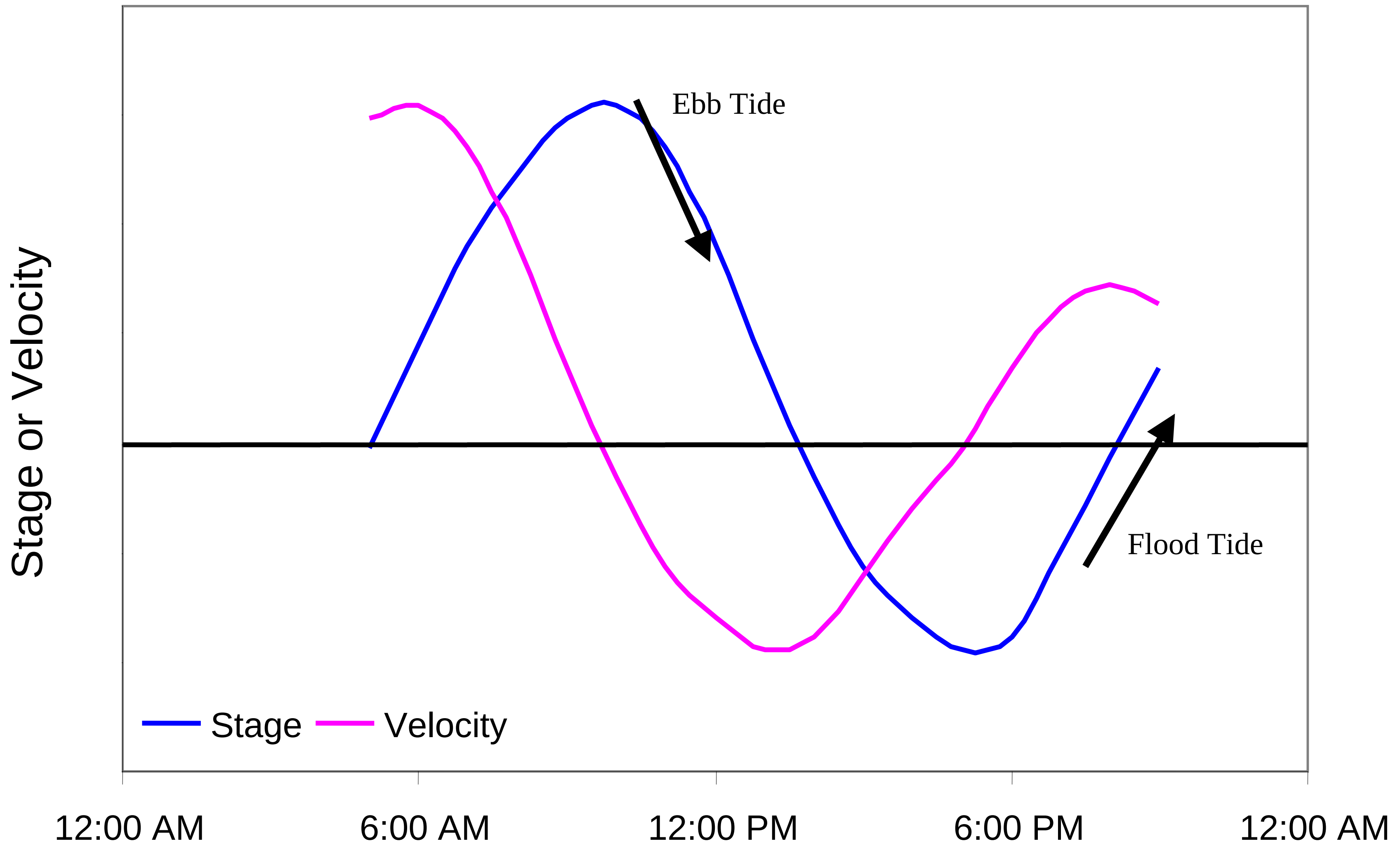

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Figure D-44

Relationship between Tidal Stage and Velocity

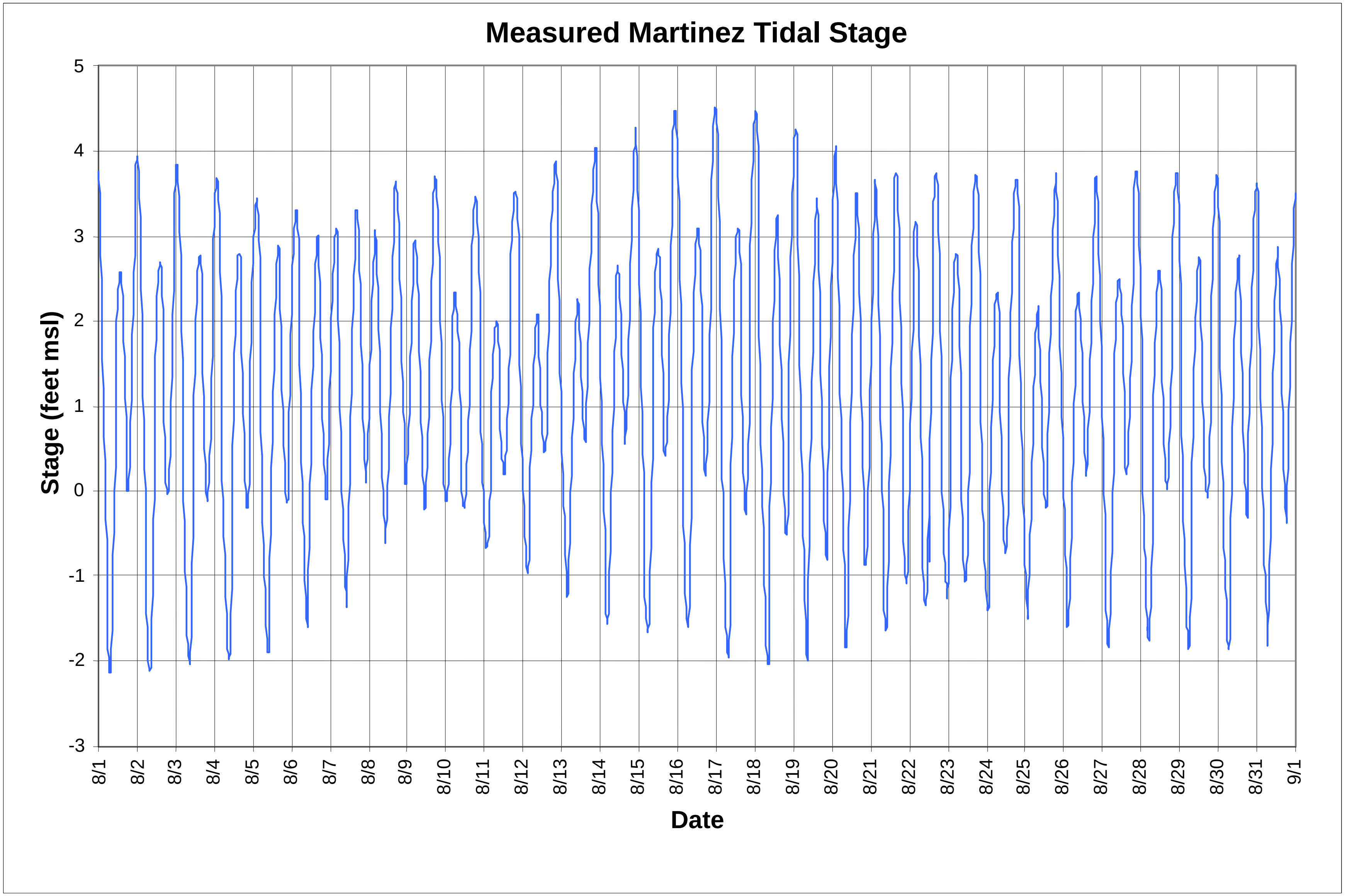

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Figure D-45

Measured Tidal Stage at Martinez, August 1997

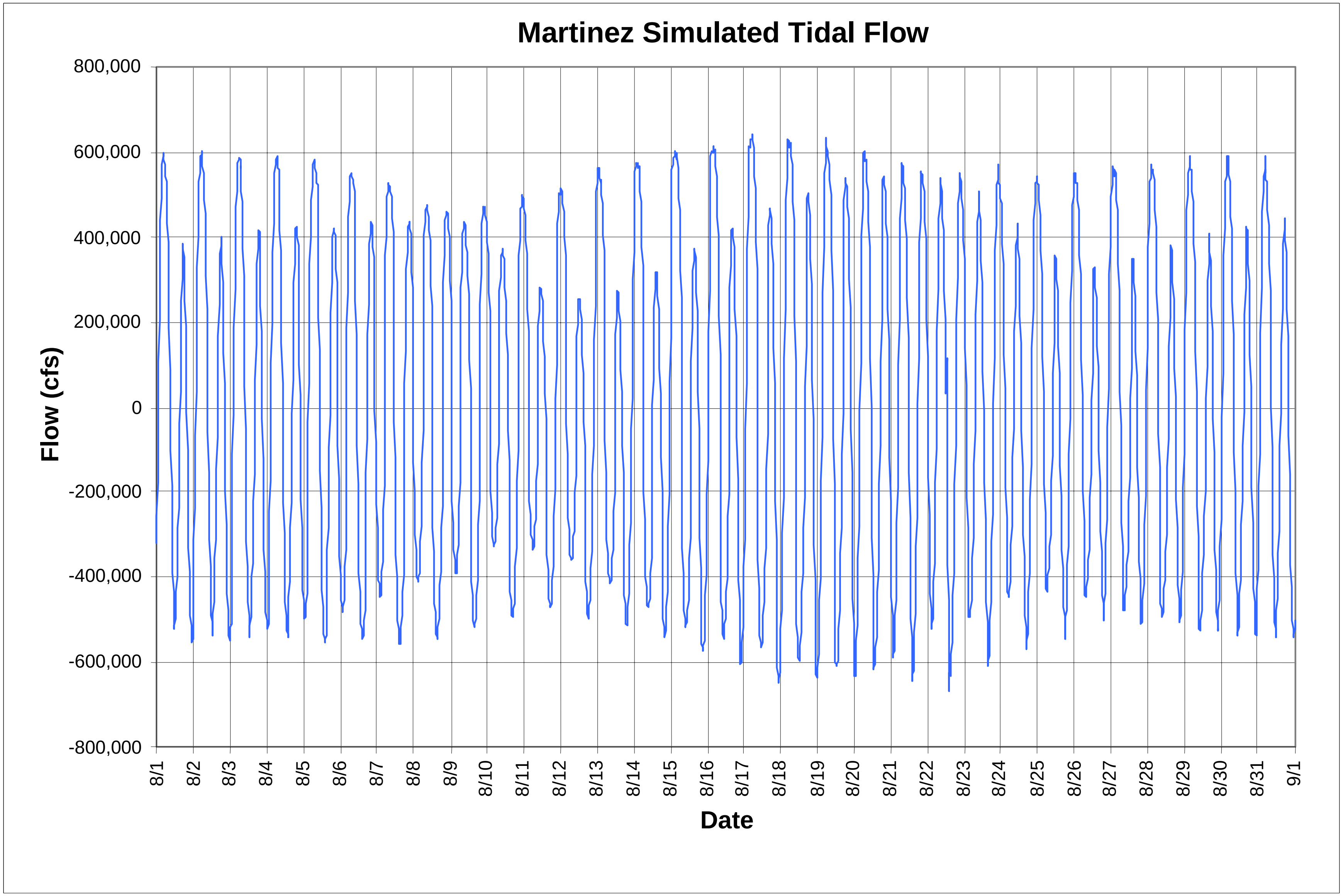

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Figure D-46

Simulated Tidal Flow at Martinez, August 1997

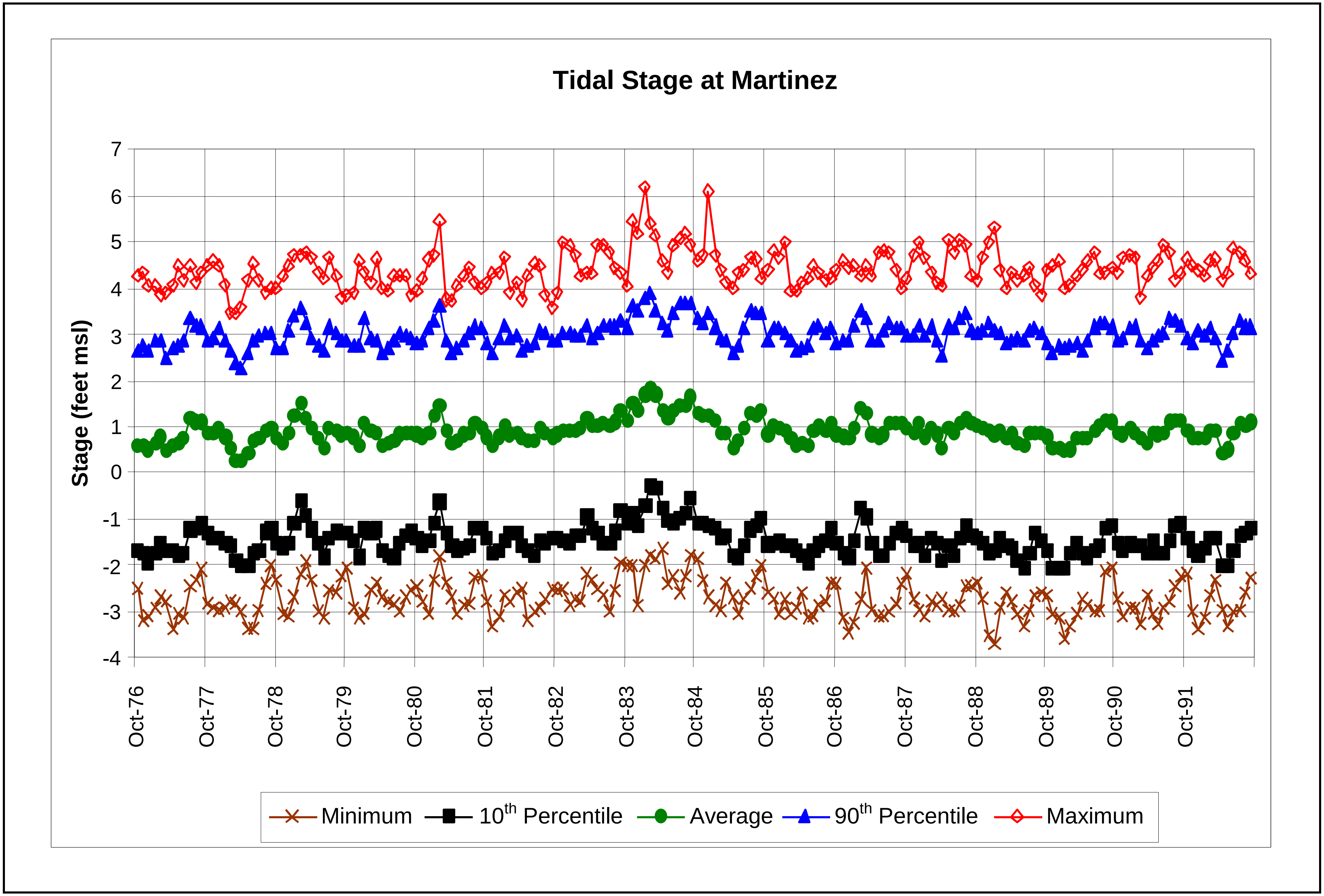

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Figure D-47

Distribution of Simulated Tidal Stage at Martinez, Water Years 1976–1991

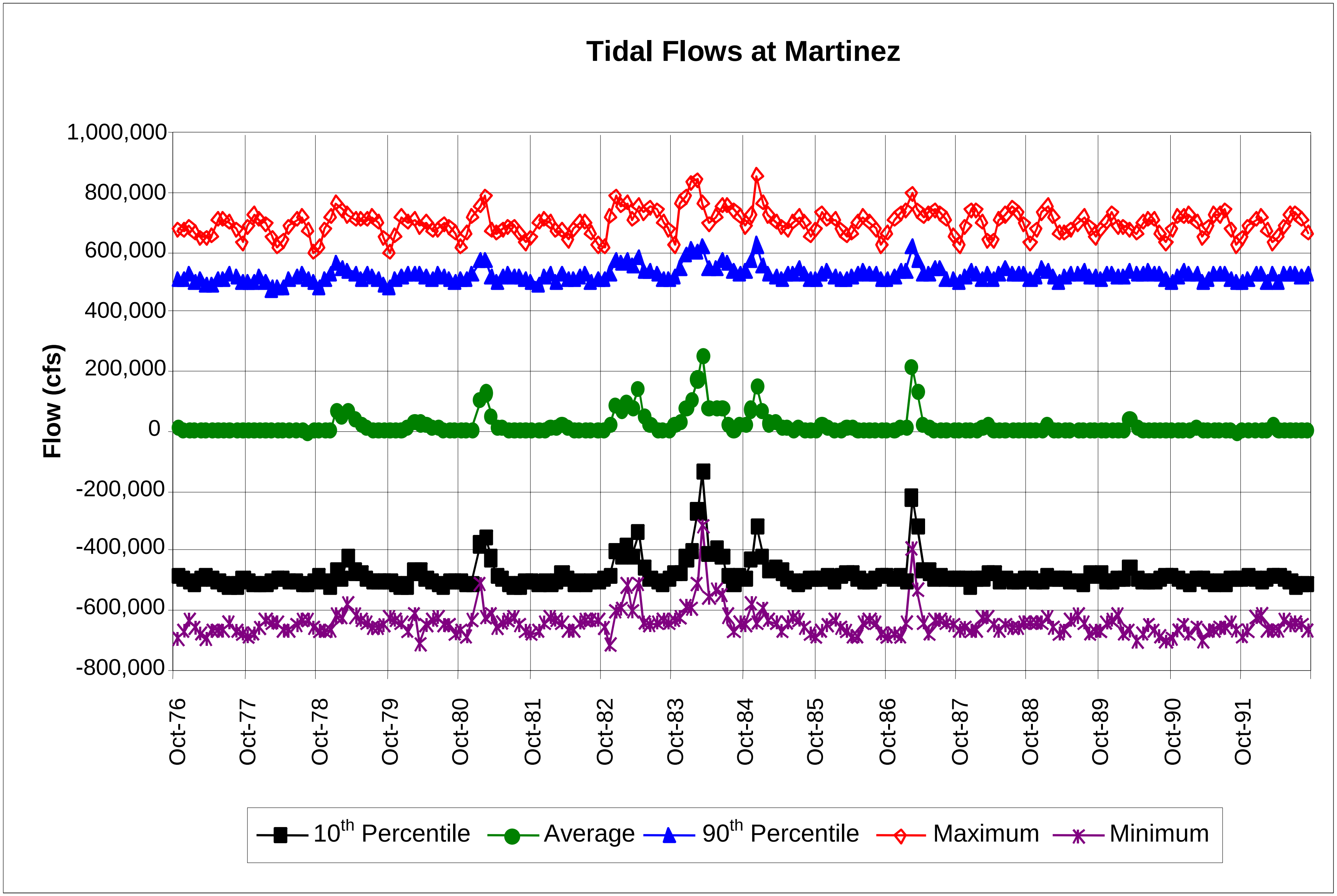

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Figure D-48

Distribution of Simulated Tidal Flow at Martinez, Water Years 1976–1991

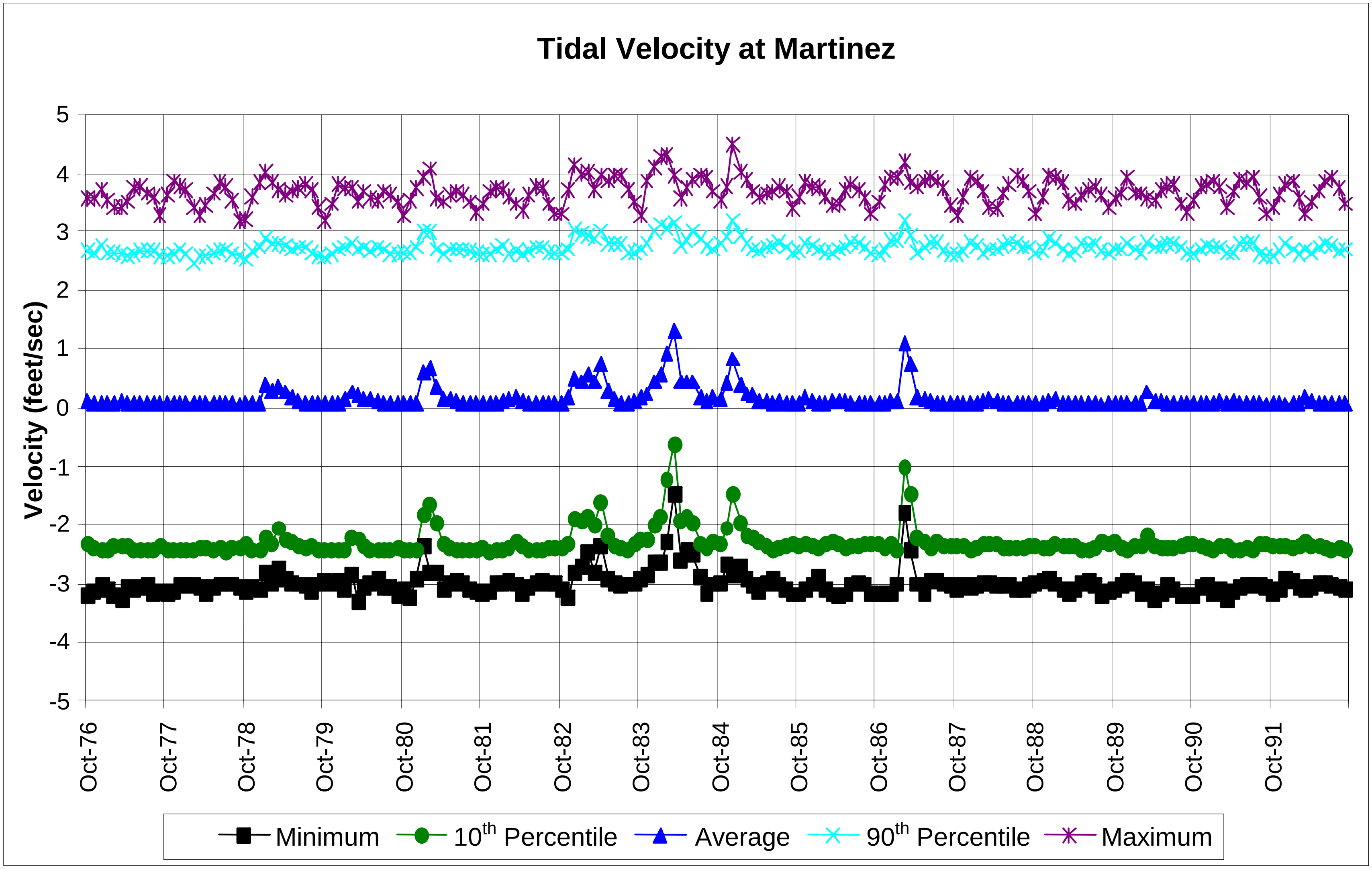

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Figure D-49

Distribution of Simulated Tidal Velocities at Martinez, Water Years 1976–1991

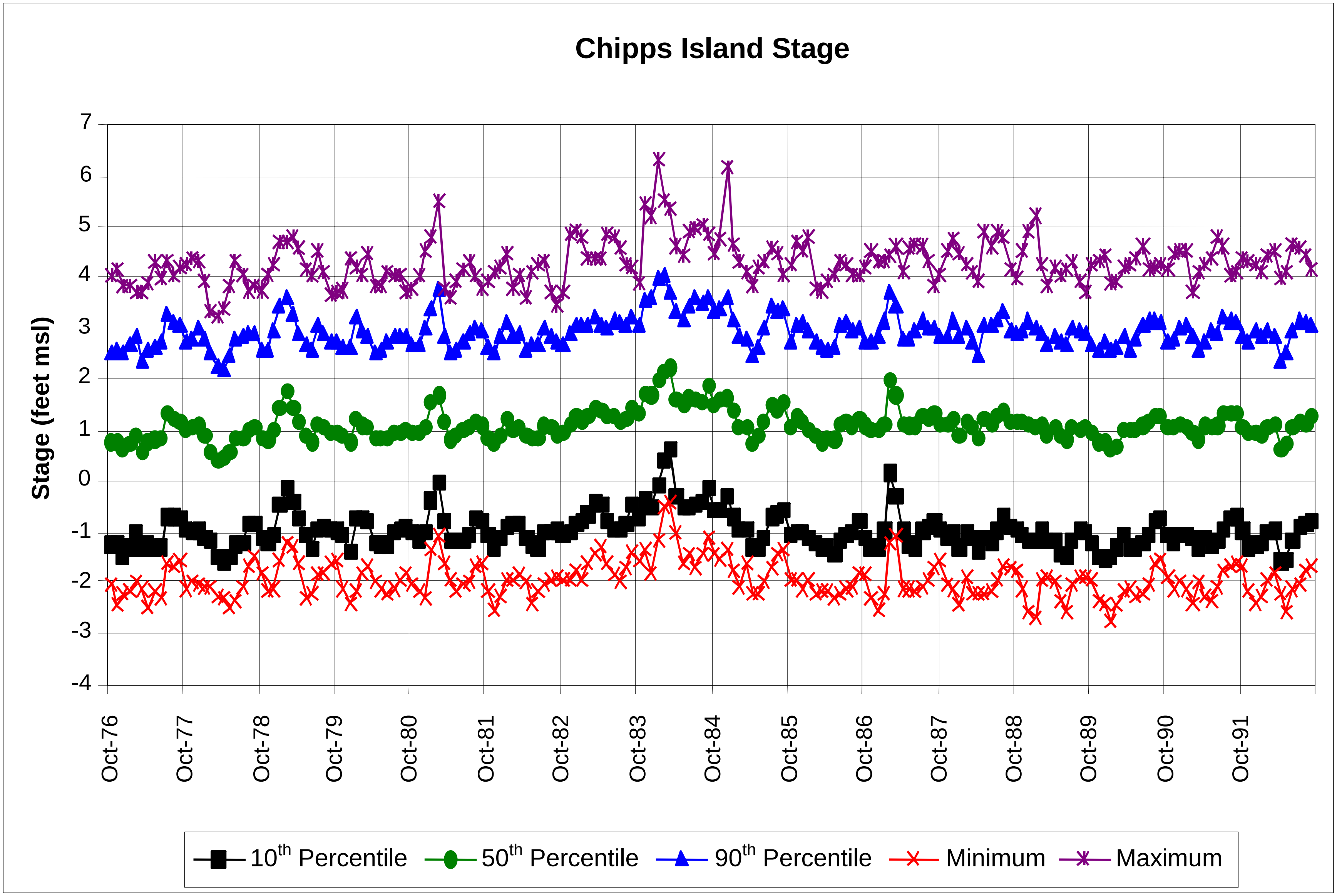

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Figure D-50

Distribution of Simulated Tidal Stage at Chipps Island, Water Years 1976–1991

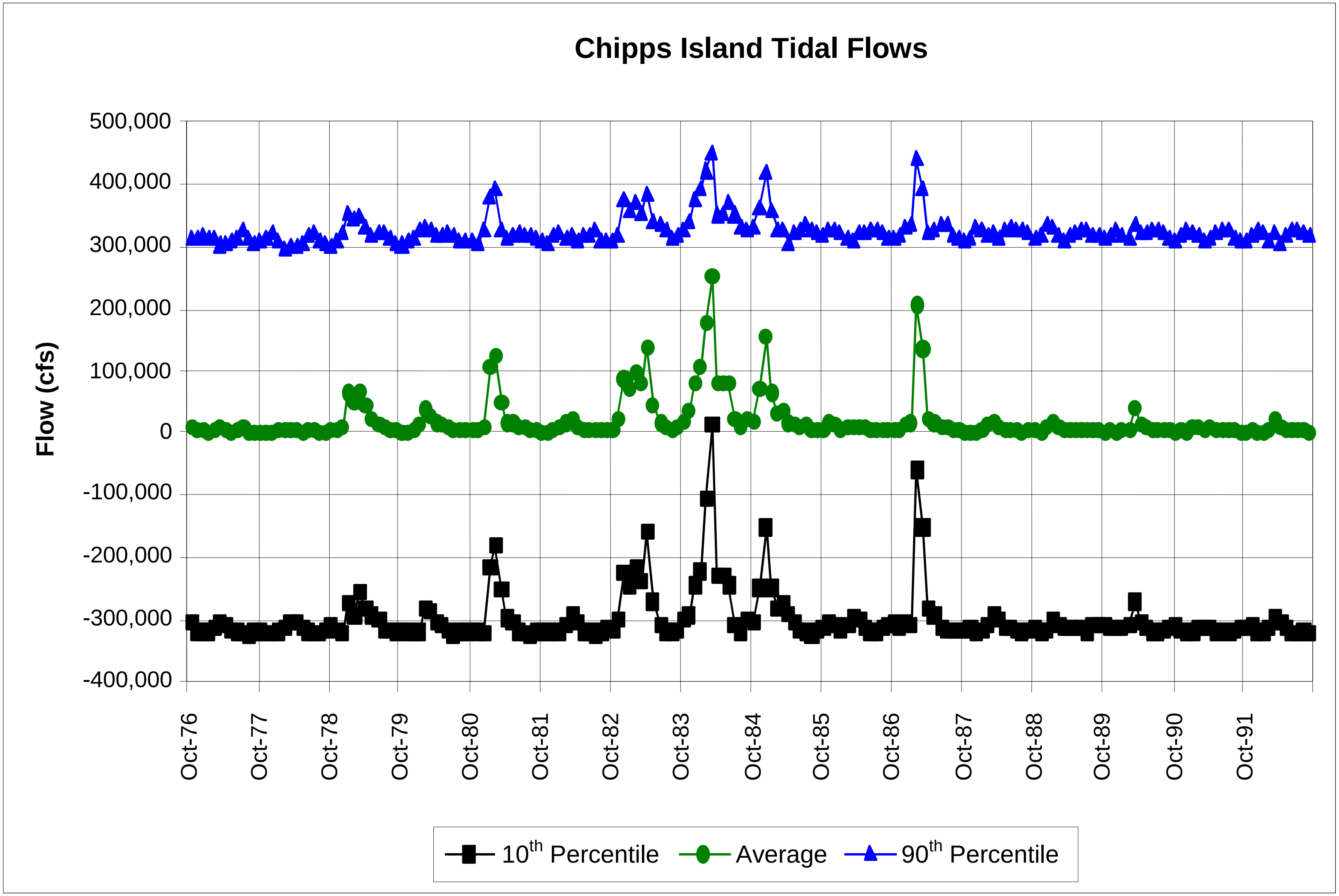

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Figure D-51

Distribution of Simulated Tidal Flows at Chipps Island, Water Years 1976–1991

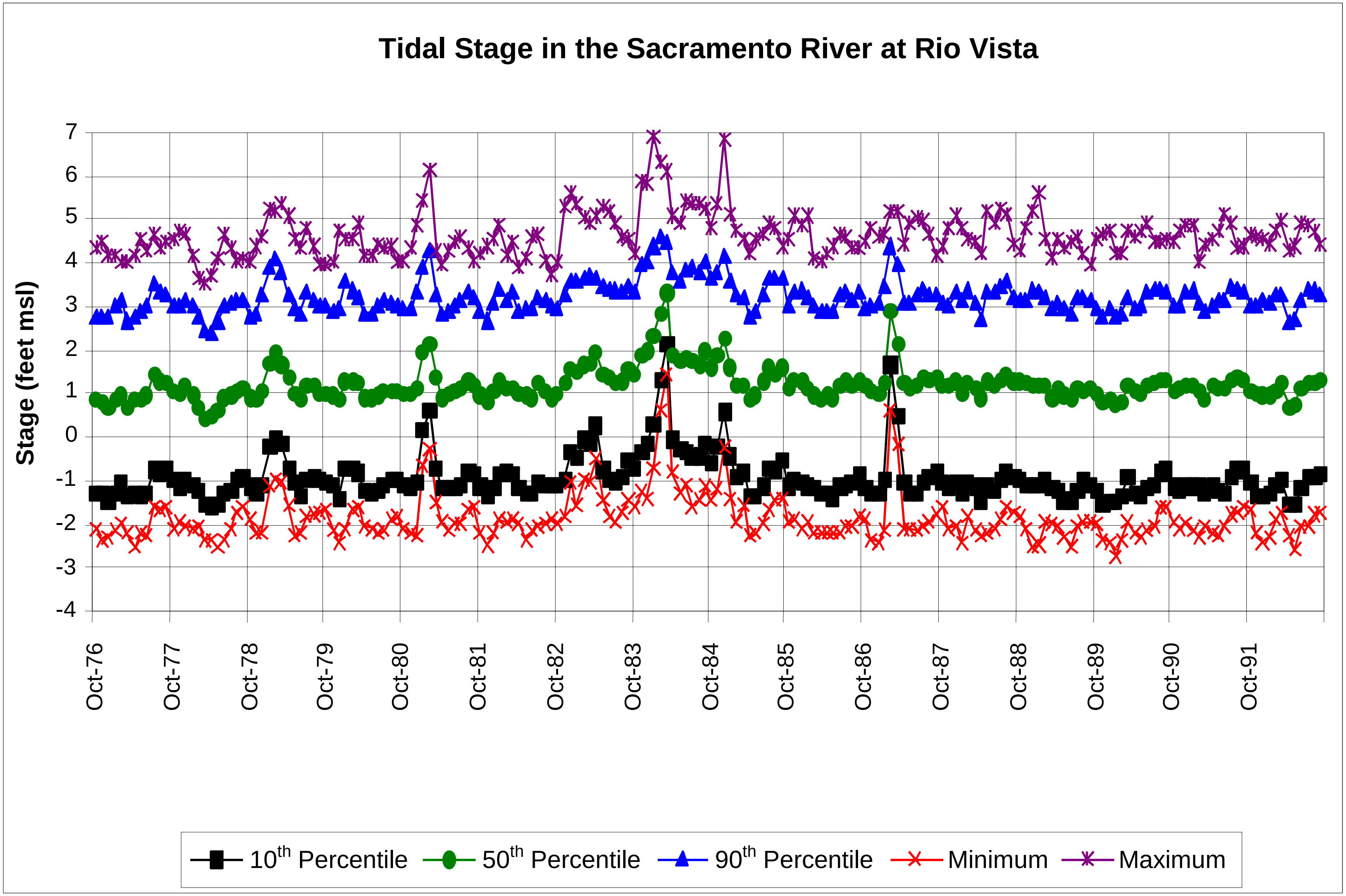

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Figure D-52

Distribution of Simulated Tidal Stage in the Sacramento River at Rio Vista, Water Years 1976–1991

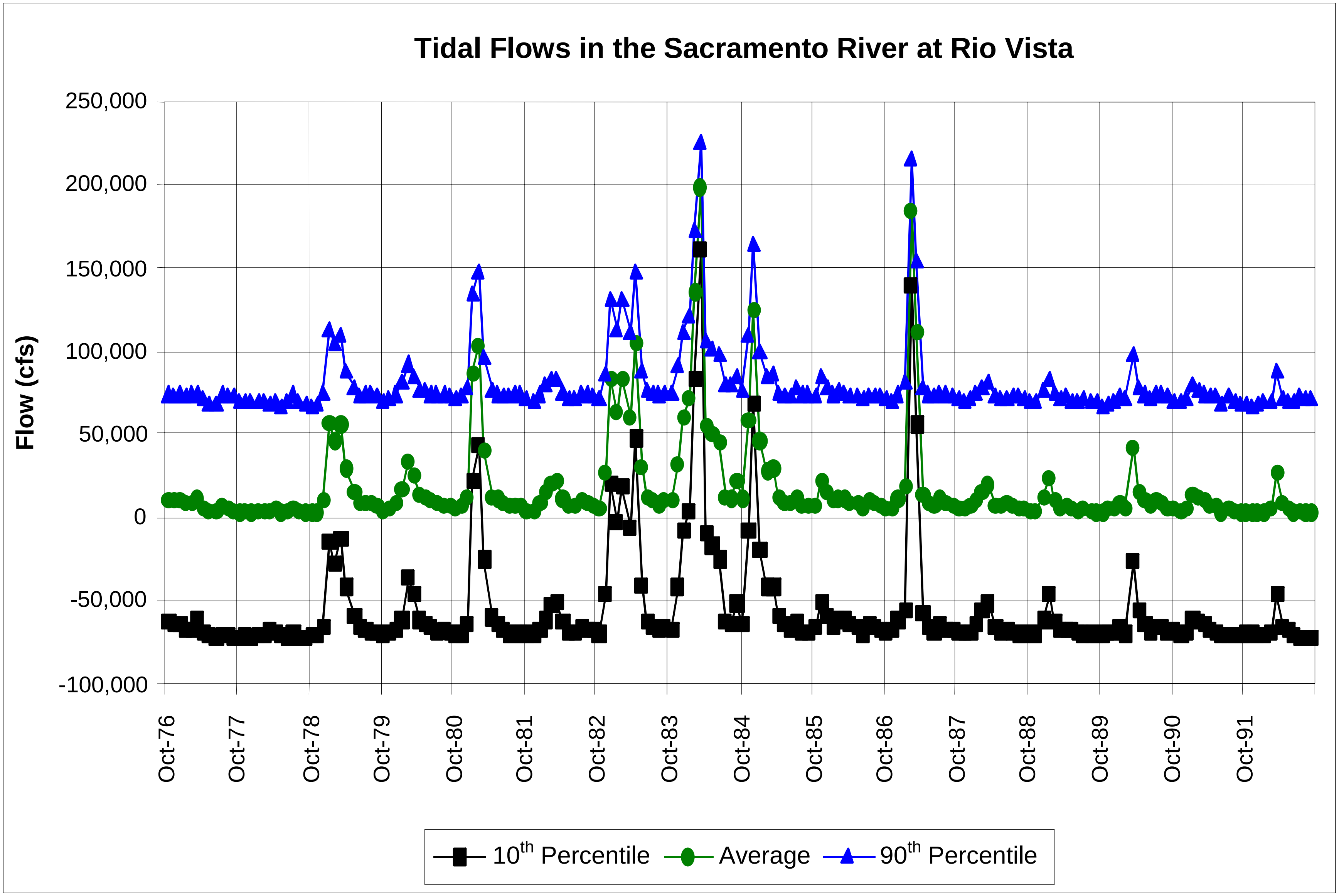

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Figure D-53

Distribution of Simulated Tidal Flow in the Sacramento River at Rio Vista, Water Years 1976–1991

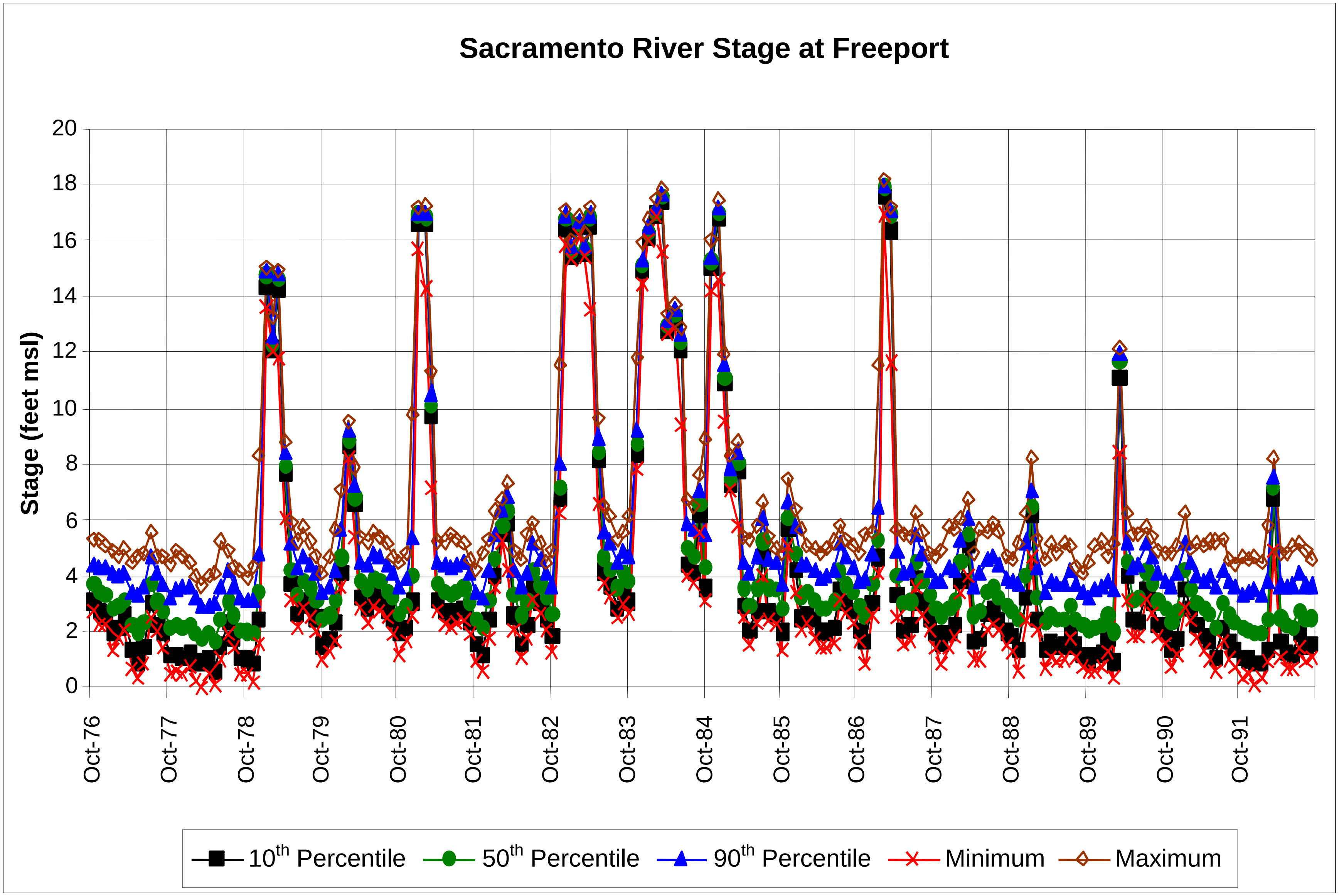

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Figure D-54

Distribution of Simulated River Stage in the Sacramento River at Freeport, Water Years 1976–1991

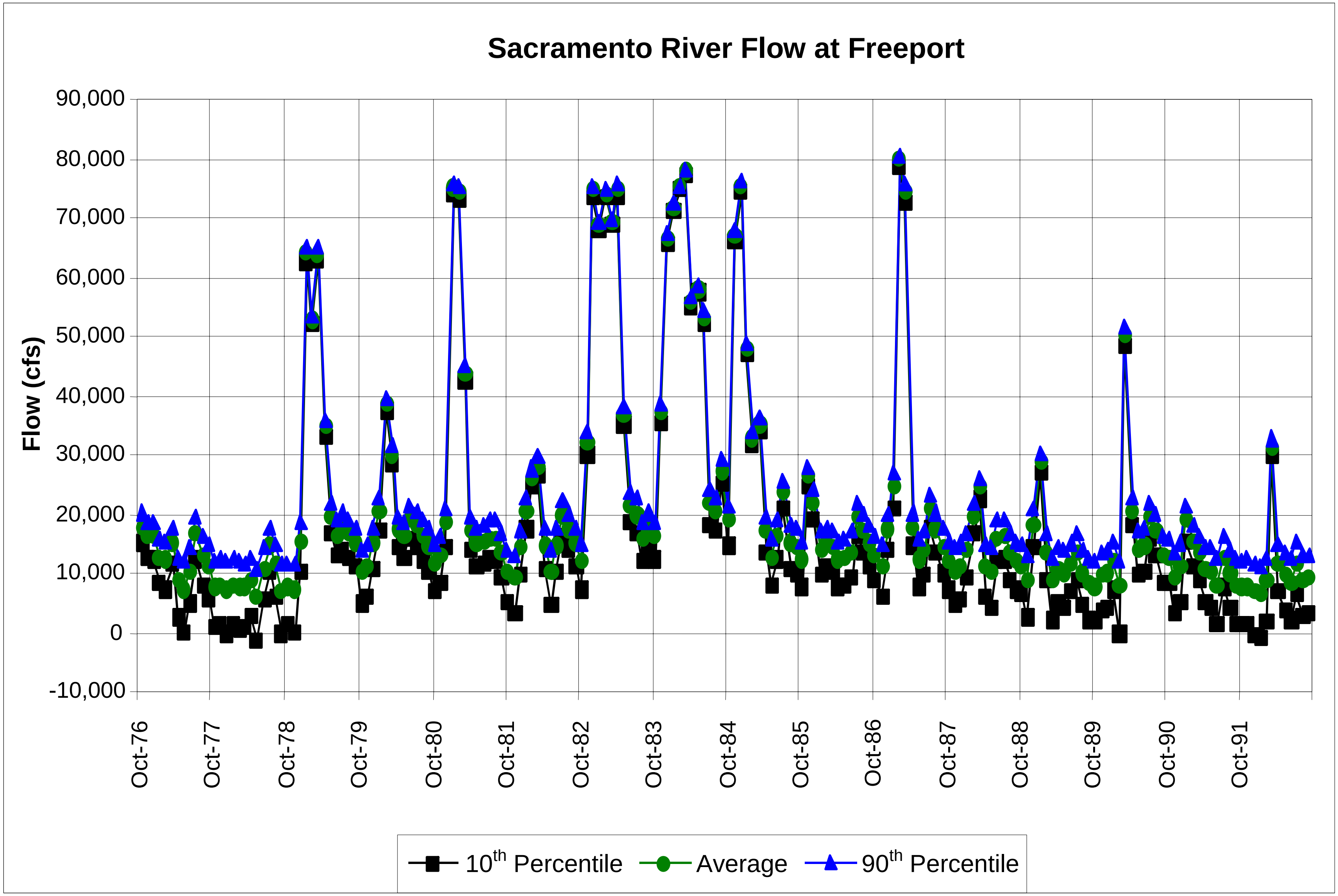

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Figure D-55

Distribution of Simulated River Flow in the Sacramento River at Freeport, Water Years 1976–1991

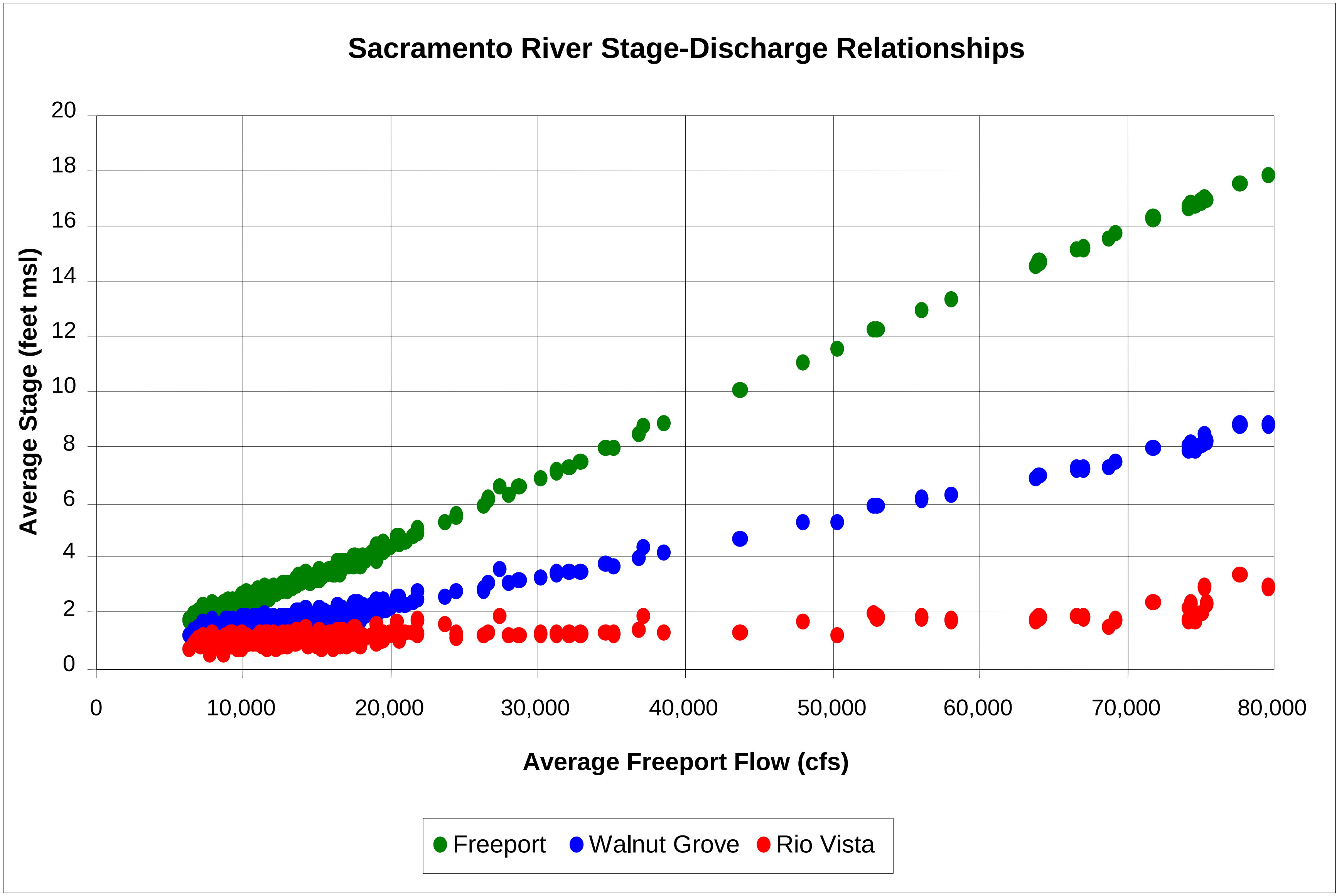

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Figure D-56

Comparison of Sacramento River Flow, Water Years 1976–1991

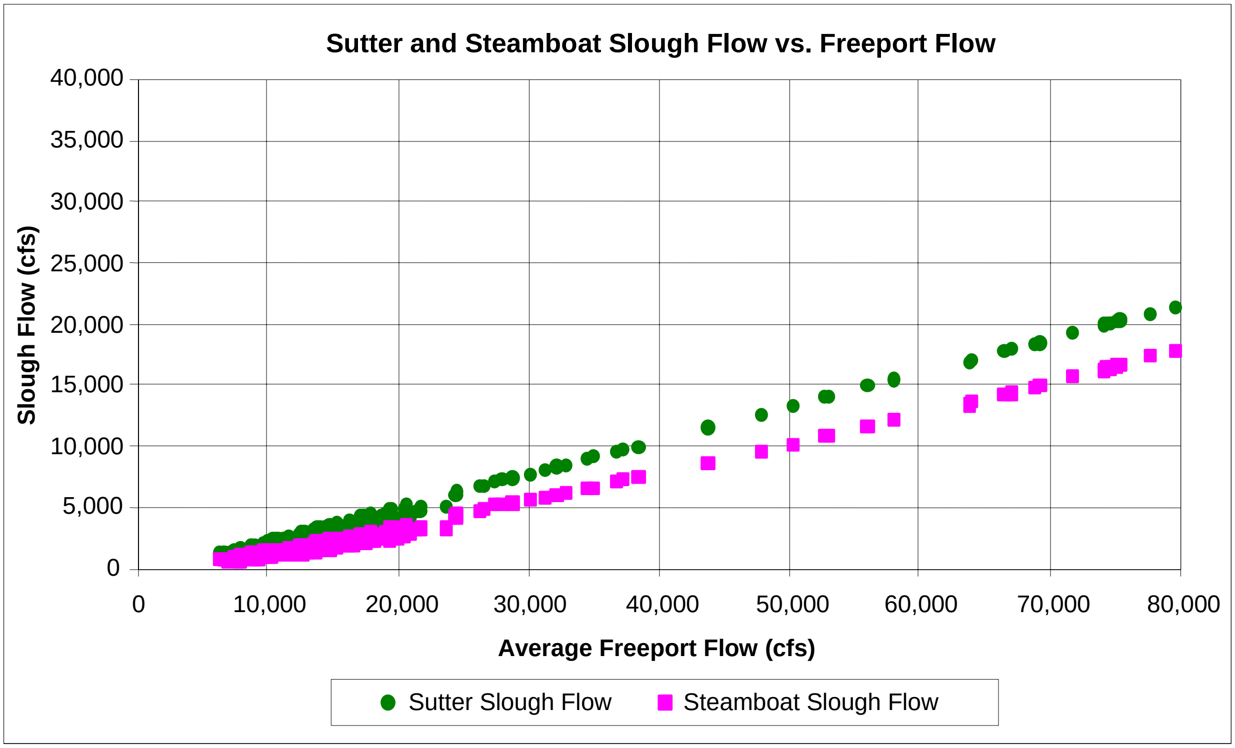

Figure D-57a. Freeport Flow vs. Sutter and Steamboat Sloughs Flow, Water Years 1976–1991

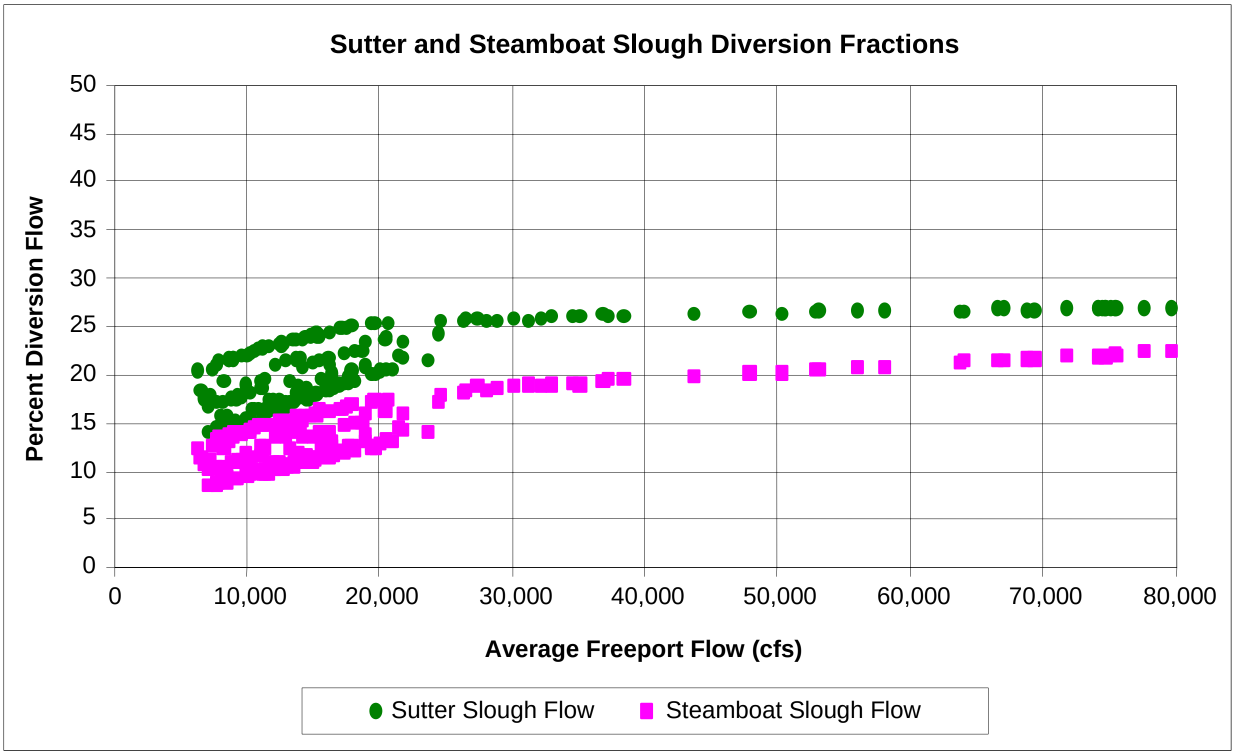

Figure D-57b. Freeport Flow vs. Diversions in Sutter and Steamboat Sloughs, Water Years 1976–1991

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Figures D-57a and D-57b

Distribution of Simulated Flows in Sutter and Steamboat Sloughs

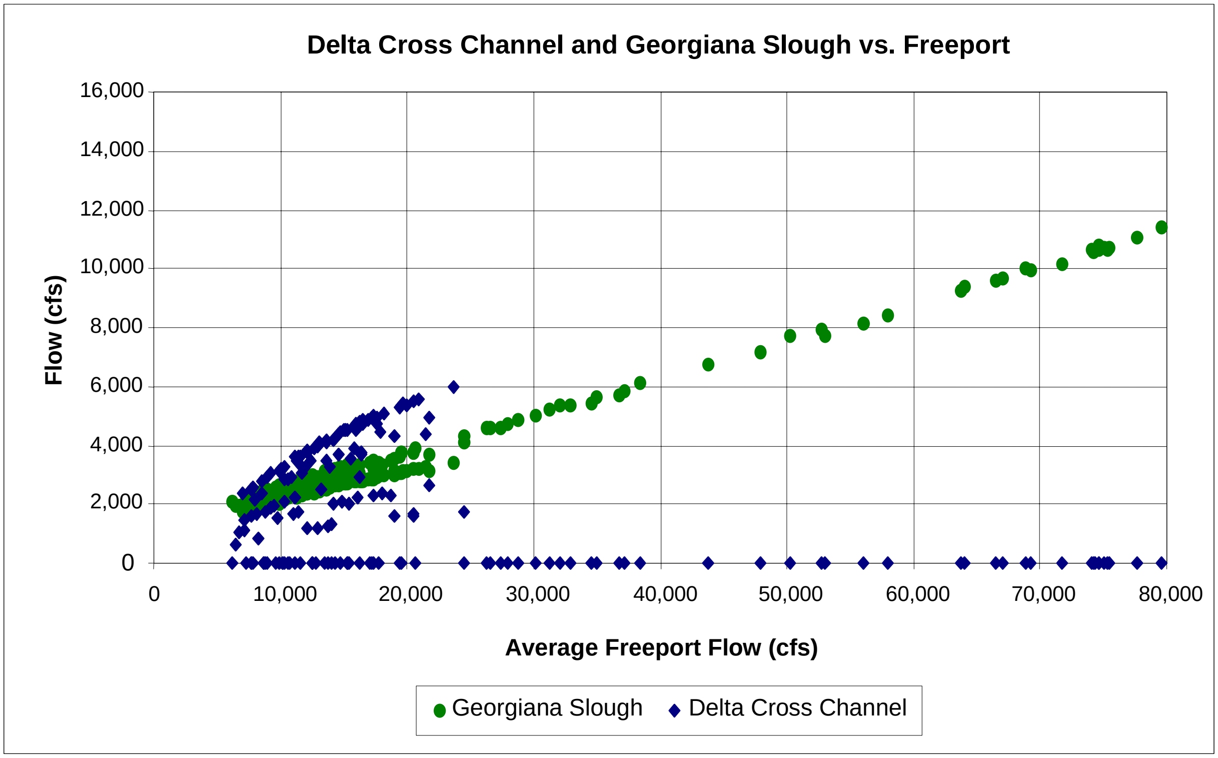

Figure D-58a. Distribution of Simulated Flows in the Delta Cross Channel and Georgiana Slough vs. Average Flow in the Sacramento River at Freeport, Water Years 1976–1991

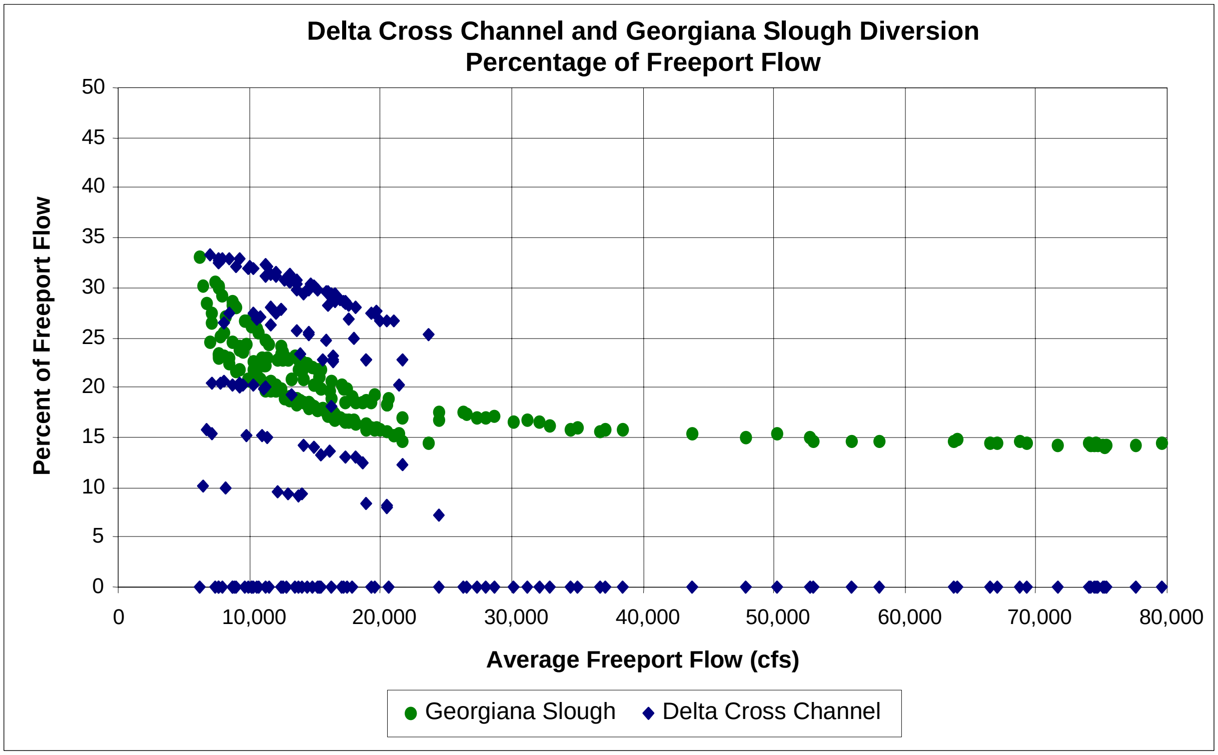

Figure D-58b. Distribution of Simulated Flows in the Delta Cross Channel and Georgiana Slough as a Percentage of Average Flow in the Sacramento River at Freeport, Water Years 1976–1991

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Figures D-58a and D-58b

Distribution of Simulated Flows in the Delta Cross Channel and Georgiana Slough

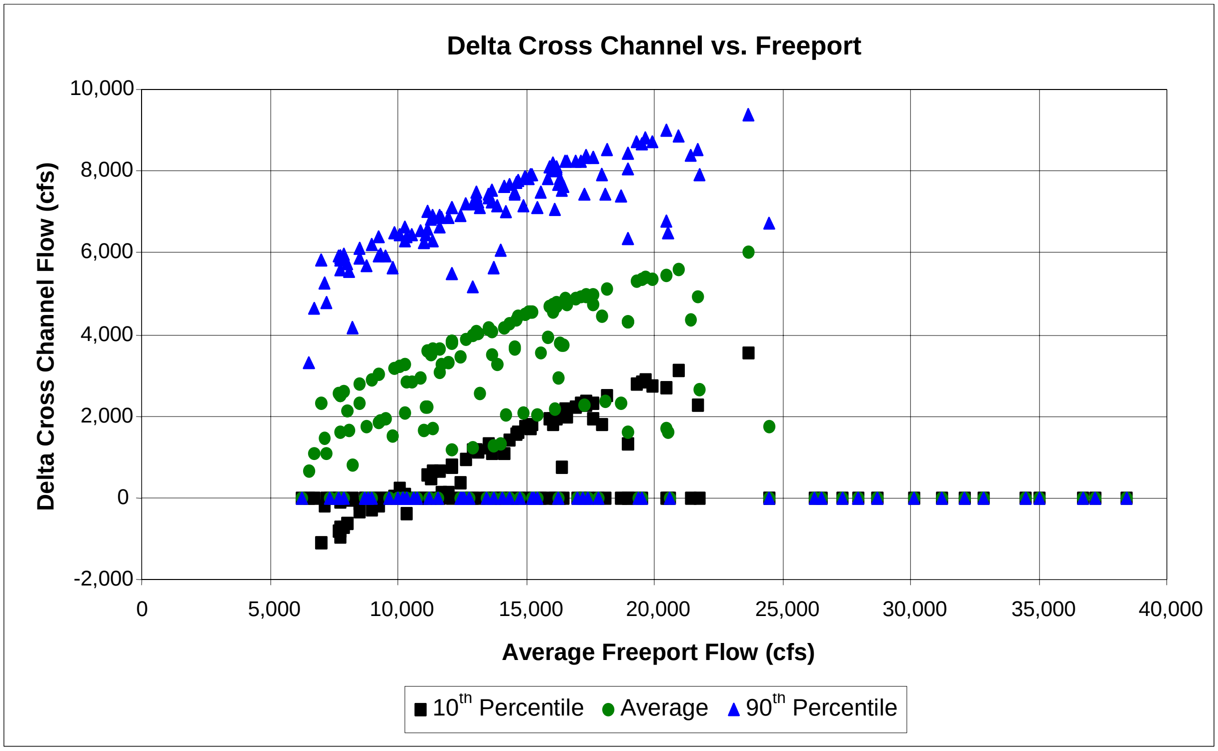

Figure D-59a. Distribution of Simulated Flow in the Delta Cross Channel vs. Average Flow in the Sacramento River at Freeport, Water Years 1976–1991

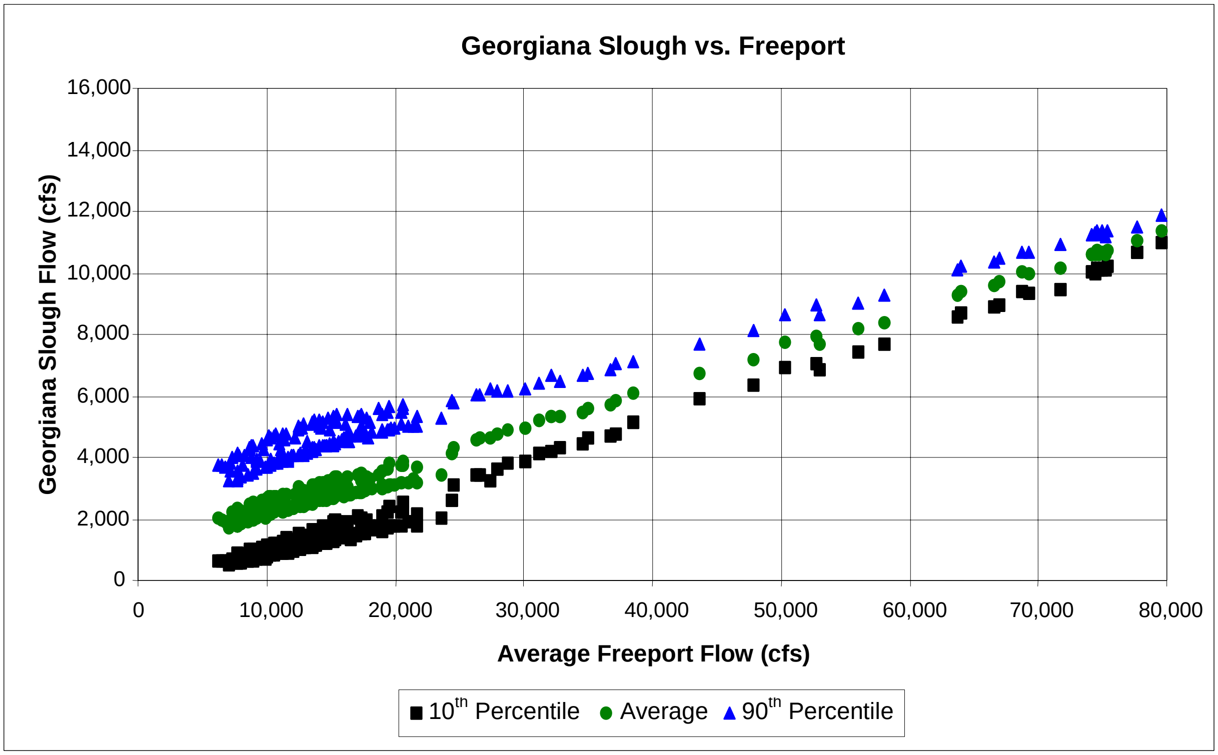

Figure D-59b. Distribution of Simulated Flow in Georgiana Slough vs. Average Flow in the Sacramento River at Freeport, Water Years 1976–1991

Figures D-59a and D-59b

Distribution of Simulated Flows in the Delta Cross Channel and Georgiana Slough

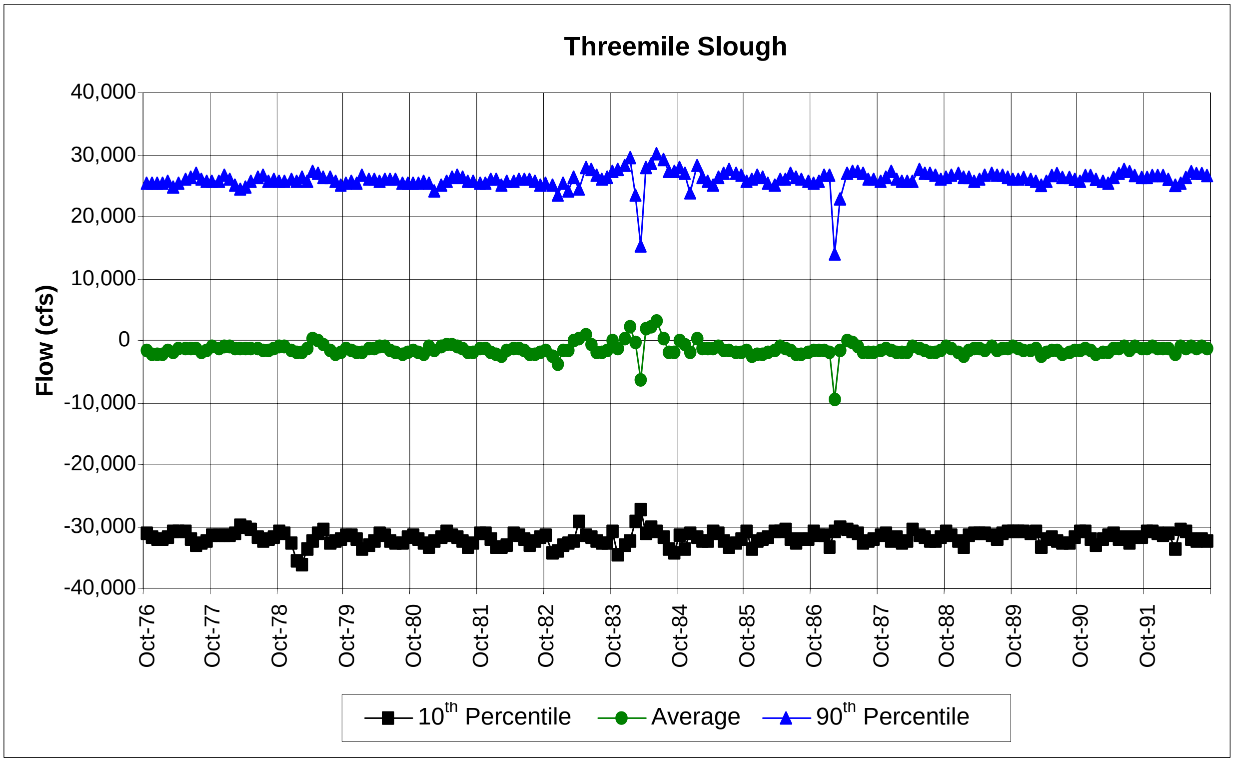

Figure D-60a. Distribution of Simulated Flow at Threemile Slough, Water Years 1976–1991

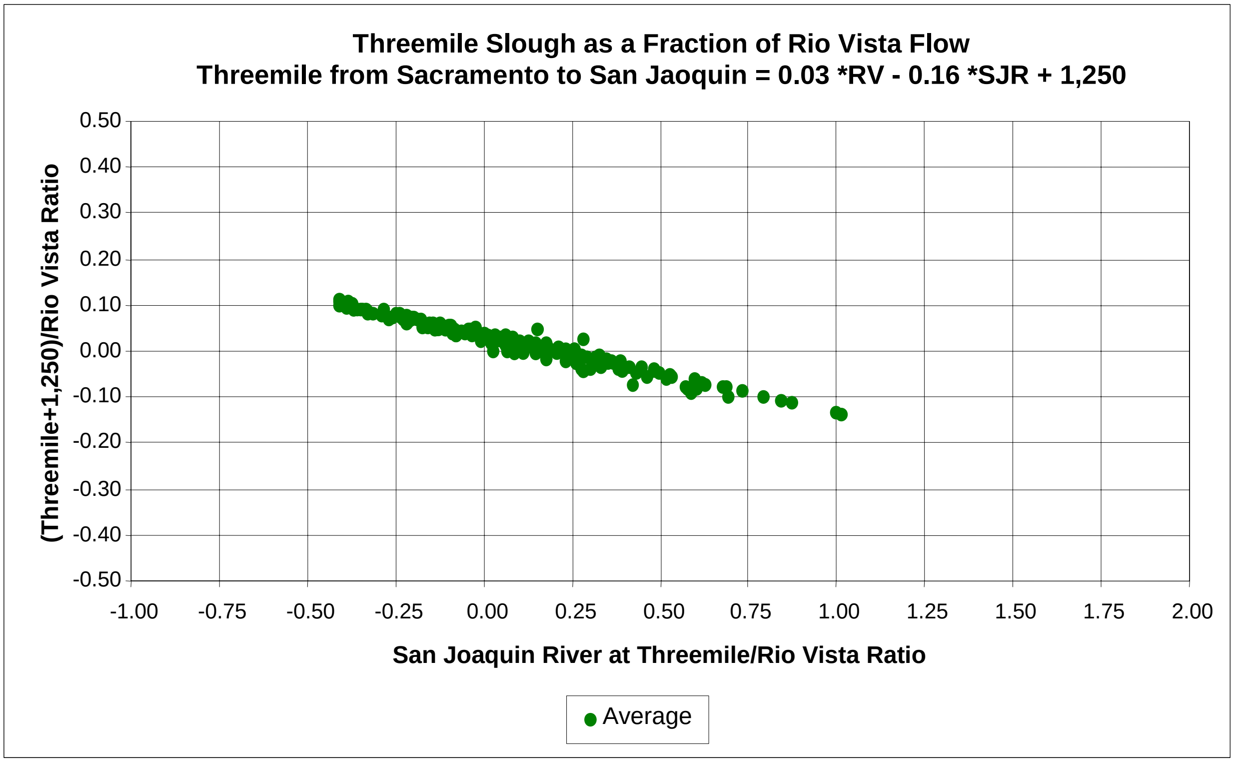

Figure D-60b. Threemile Slough as a Fraction of Average Rio Vista Flow, Water Years 1976–1991

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Figures D-60a and D-60b

Distribution of Simulated Flows in Threemile Slough

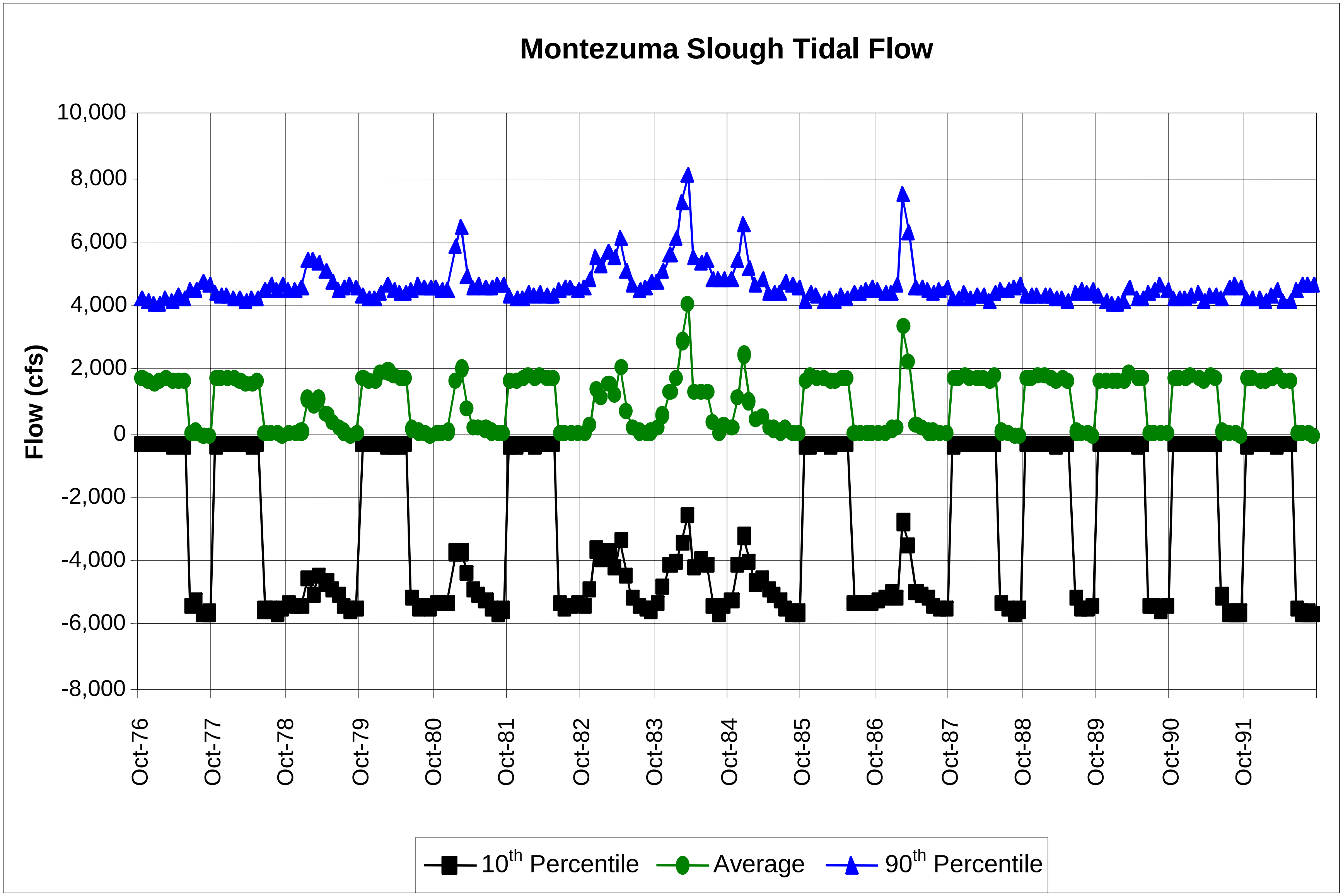

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Figure D-61

Distribution of Simulated Flow at Montezuma Slough, Water Years 1976–1991

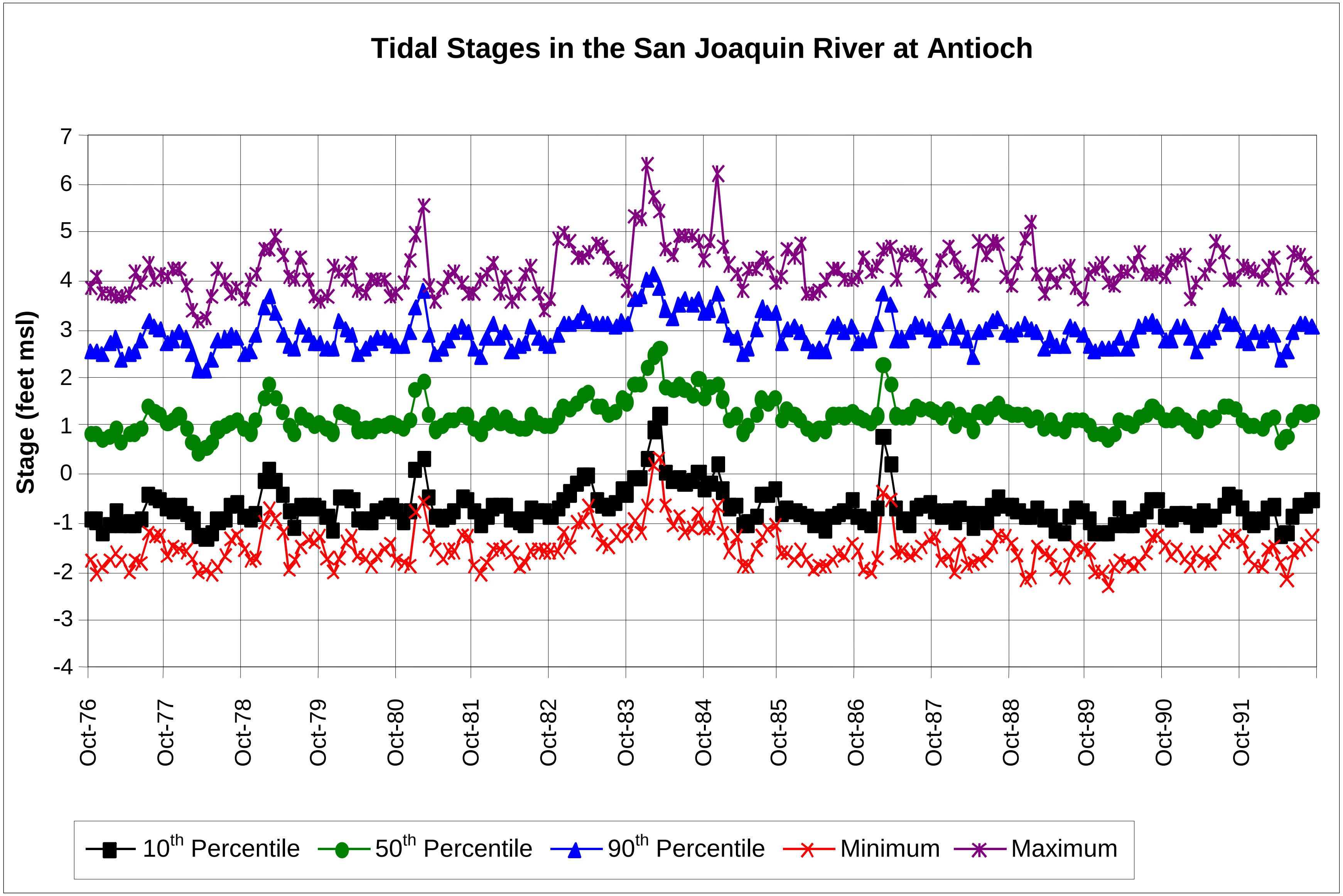

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Figure D-62

Distribution of Simulated Tidal Stage in the San Joaquin River at Antioch, Water Years 1976–1991

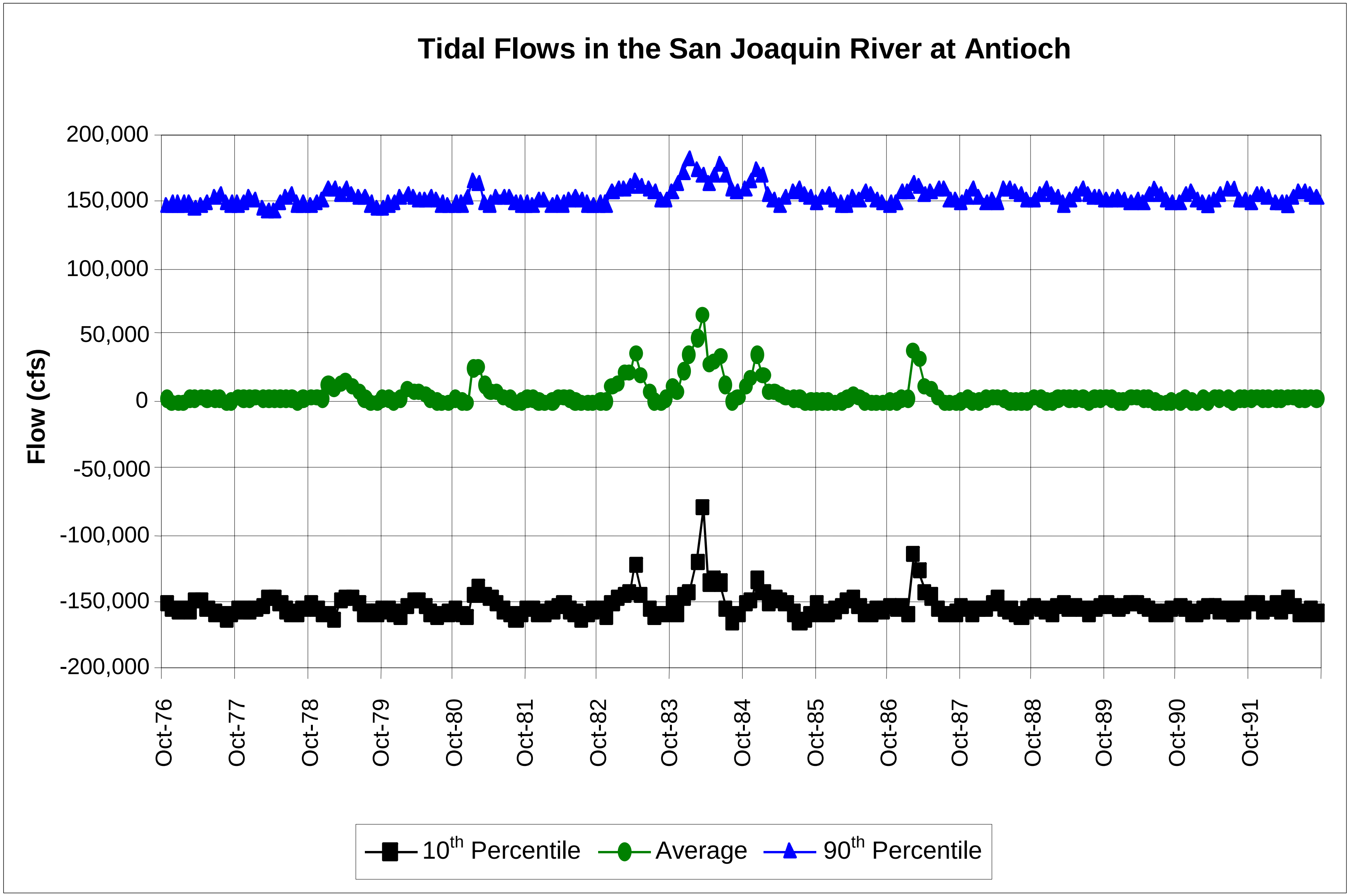

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Figure D-63

Distribution of Simulated Tidal Flow in the San Joaquin River at Antioch, Water Years 1976–1991

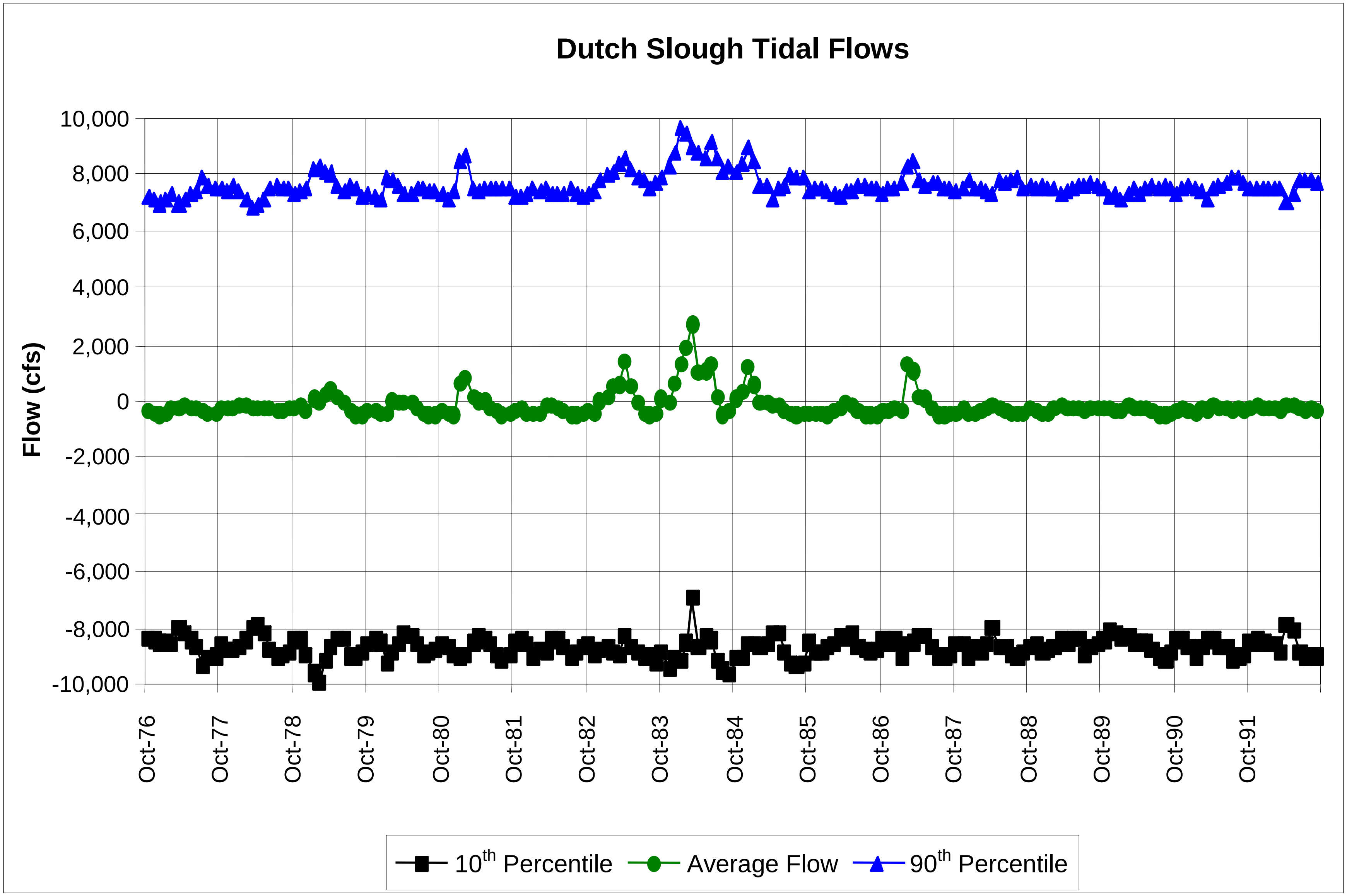

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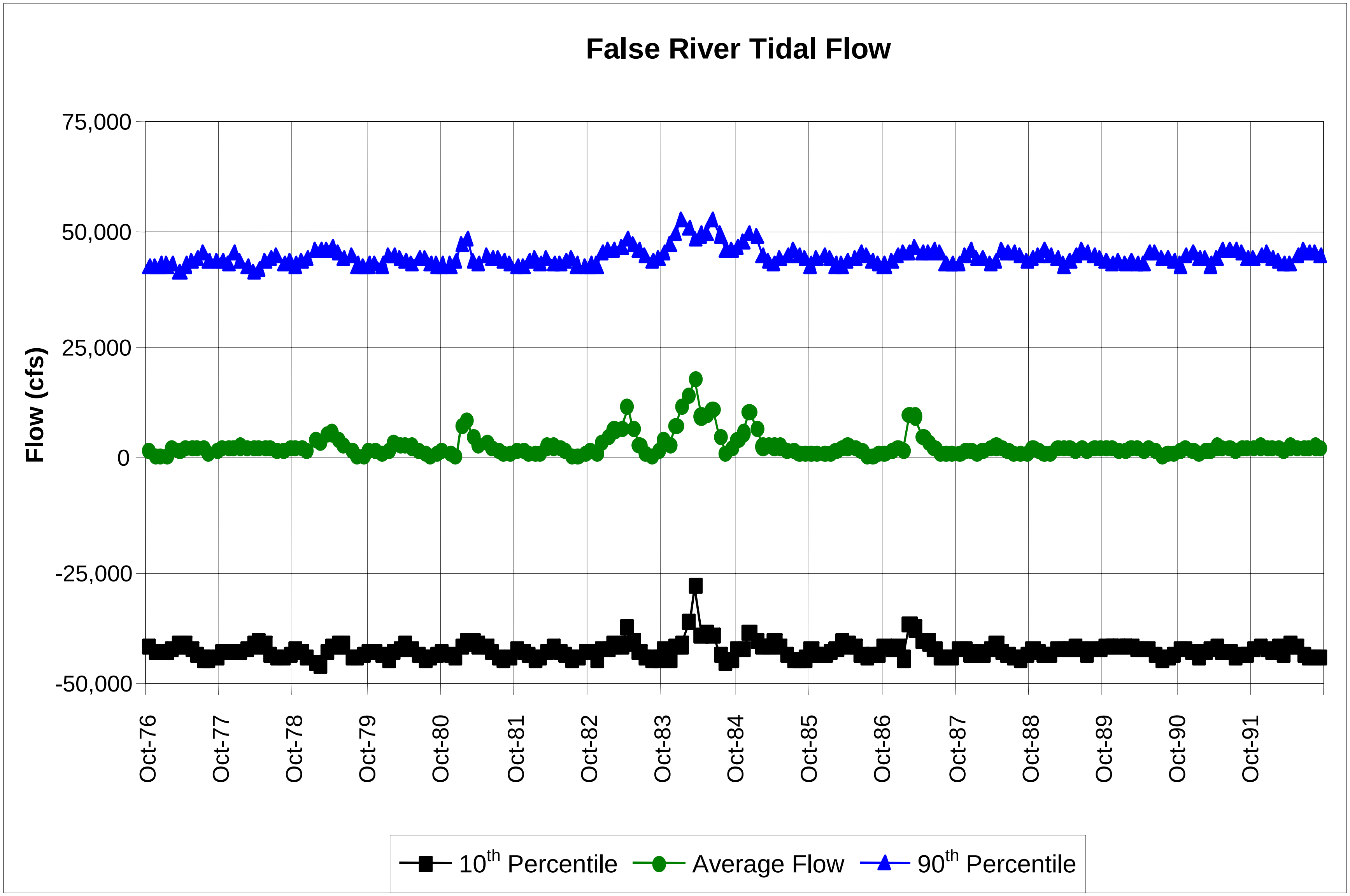
Figure D-64

Distribution of Simulated Tidal Flow at Dutch Slough, Water Years 1976–1991



02053.02 101

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Figure D-65

Distribution of Simulated Tidal Flow in False River, Water Years 1976–1991

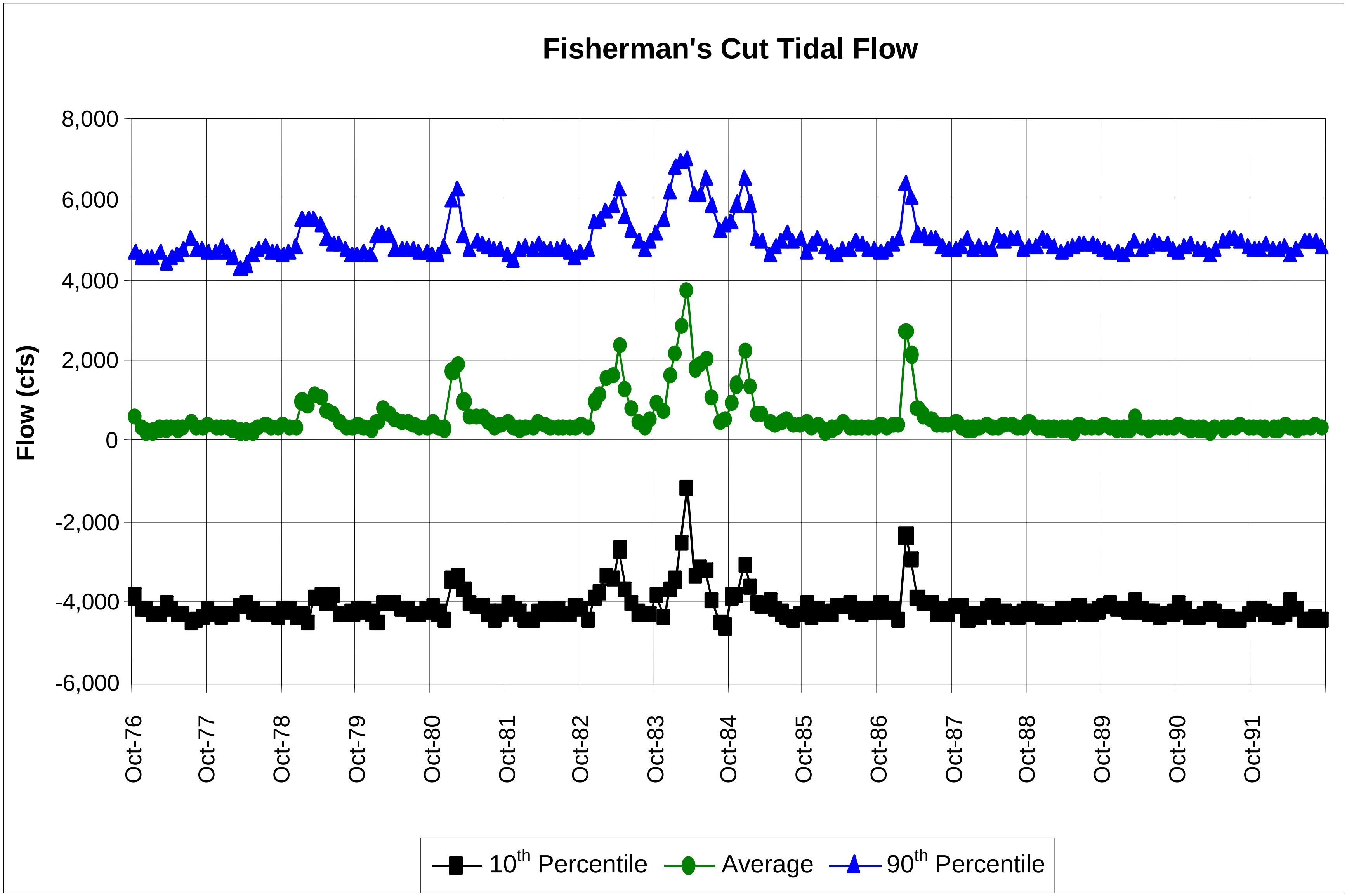

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Figure D-66

Distribution of Simulated Tidal Flow at Fisherman's Cut, Water Years 1976–1991

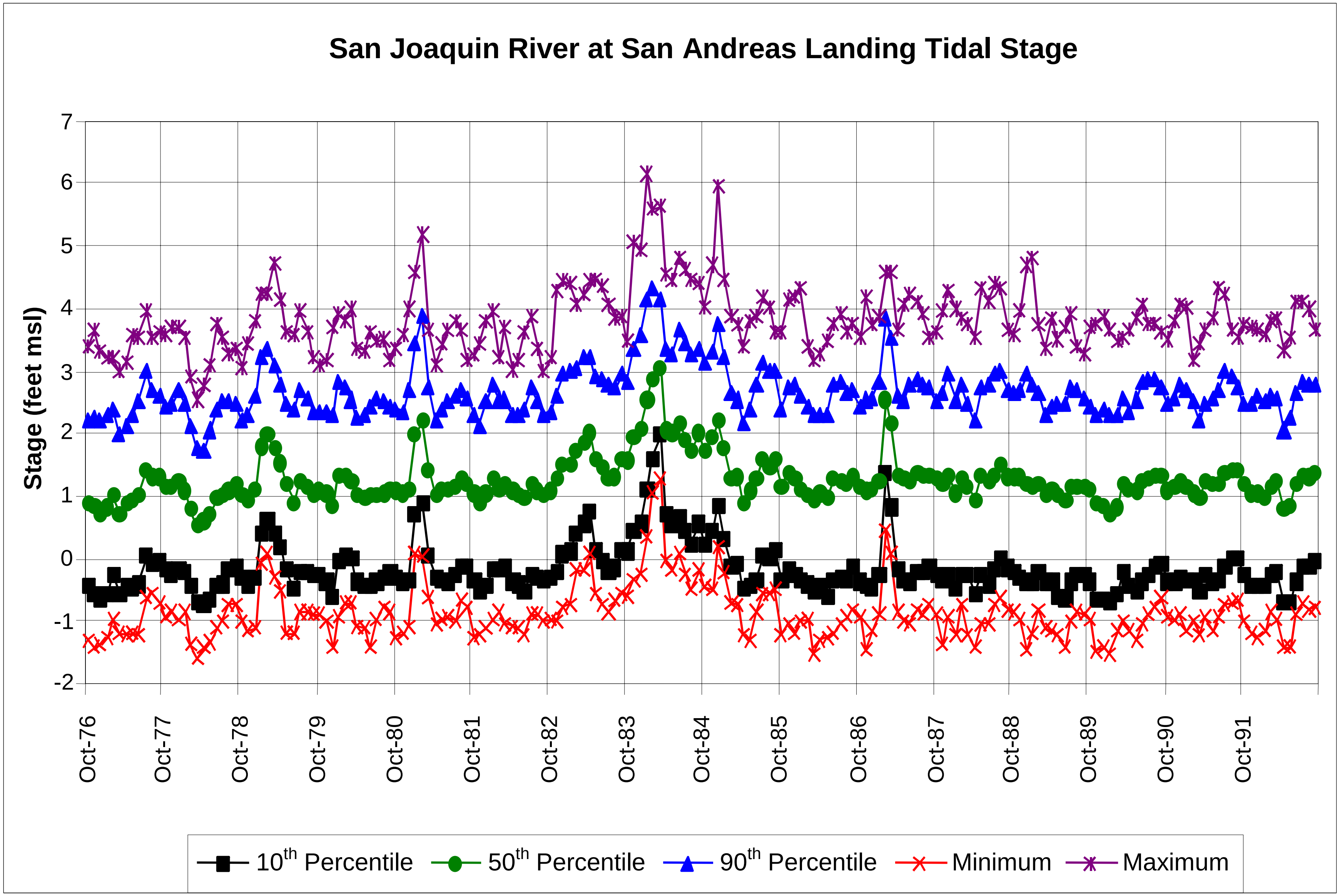

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Figure D-67

Distribution of Simulated Tidal Stage in the San Joaquin River at San Andreas Landing, Water Years 1976–1991

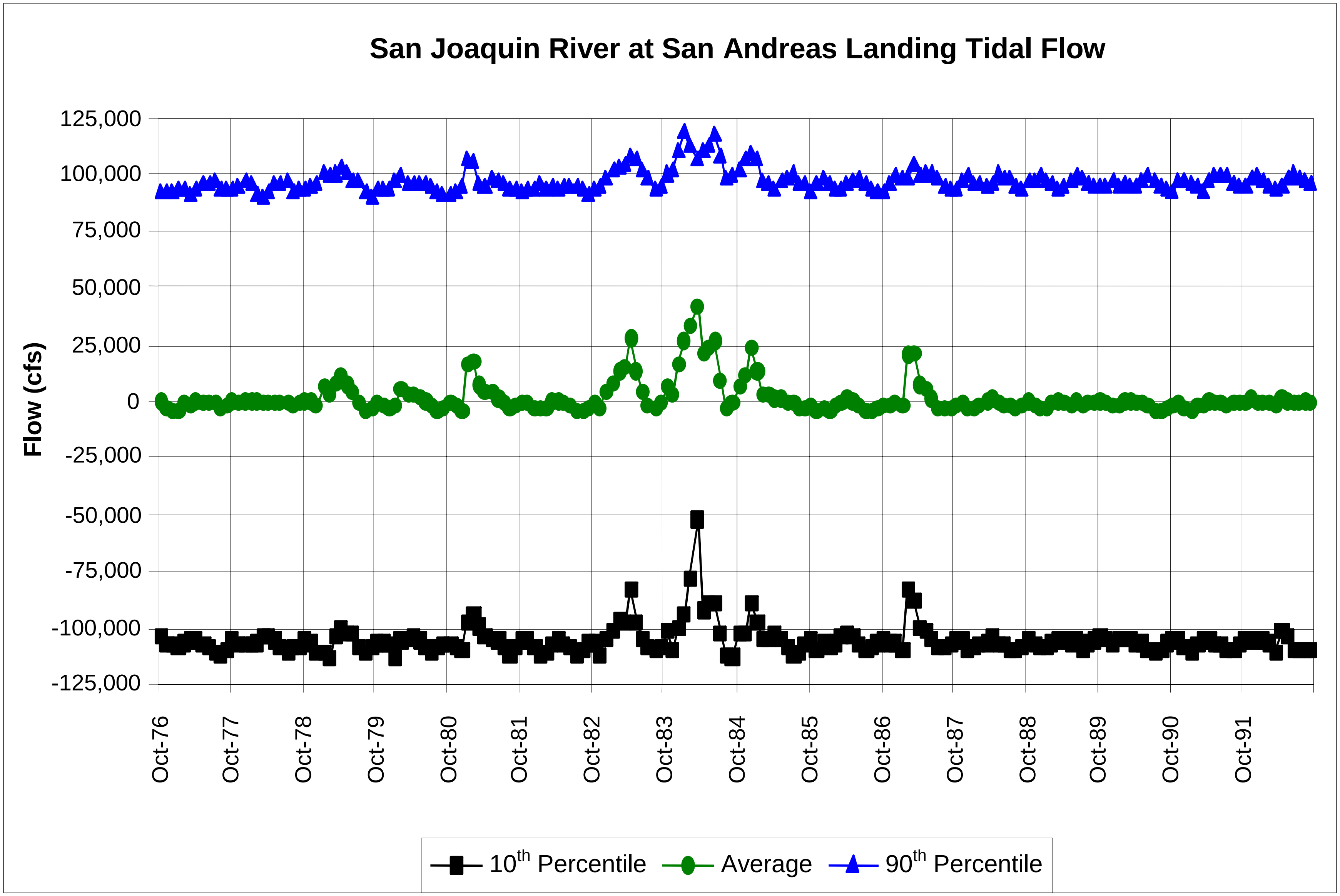

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Figure D-68

Distribution of Simulated Tidal Flow in the San Joaquin River at San Andreas Landing, Water Years 1976–1991

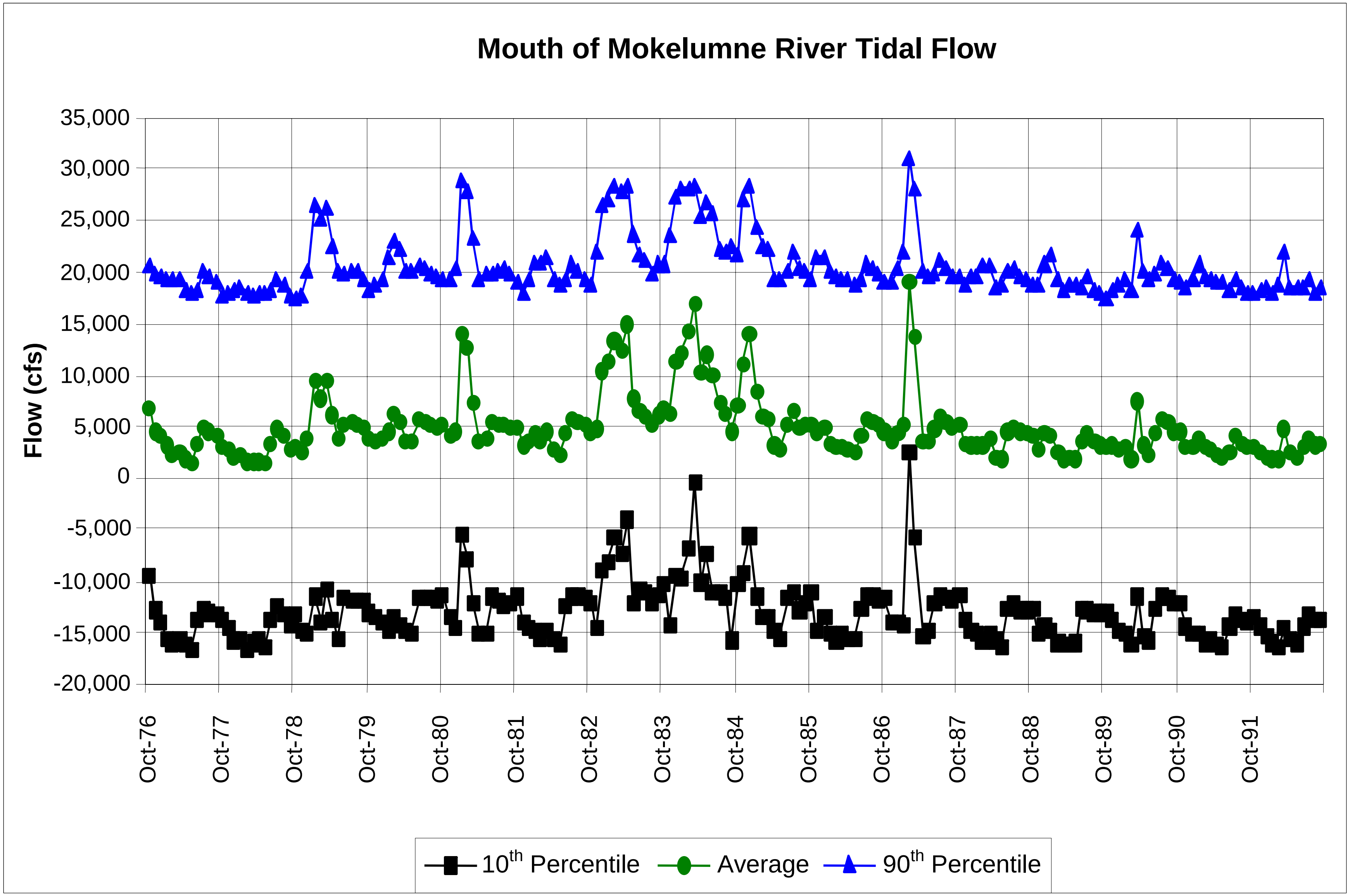

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Figure D-69

Distribution of Simulated Tidal Flow at the Mouth of the Mokelumne River, Water Years 1976–1991

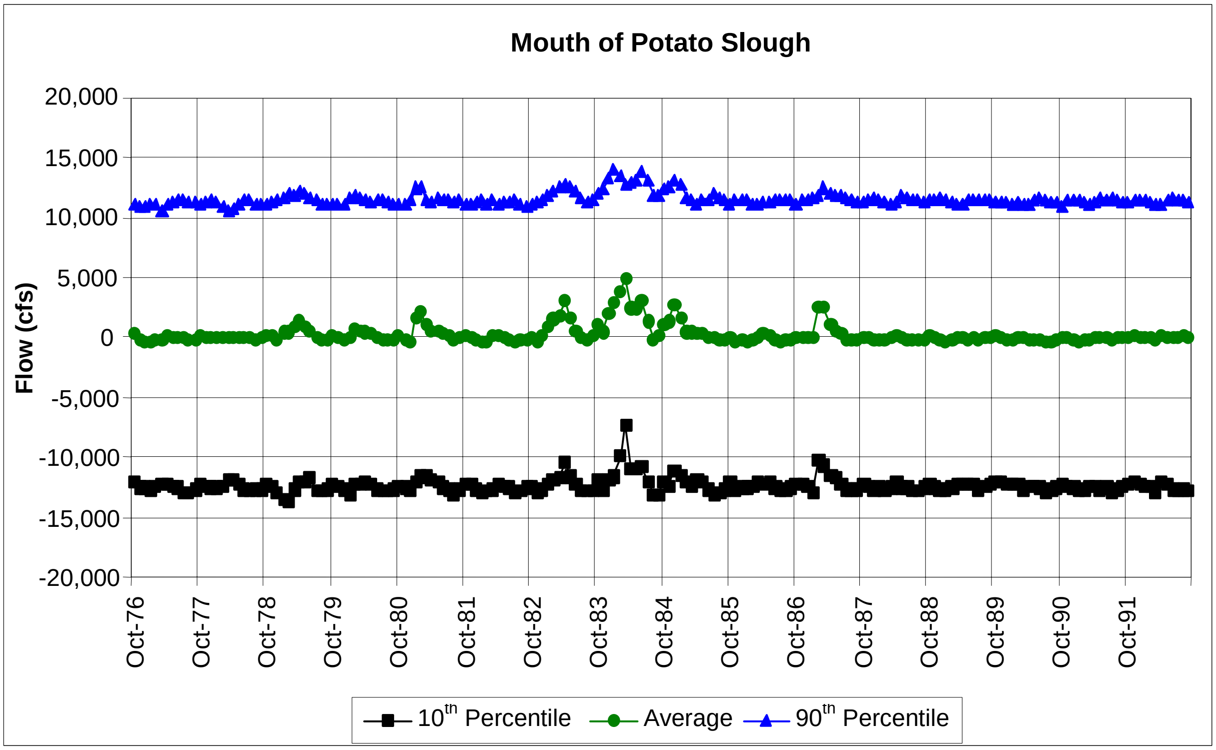

Figure D-70a. Distribution of Simulated Tidal Flow at the Mouth of Potato Slough, Water Years 1976–1991

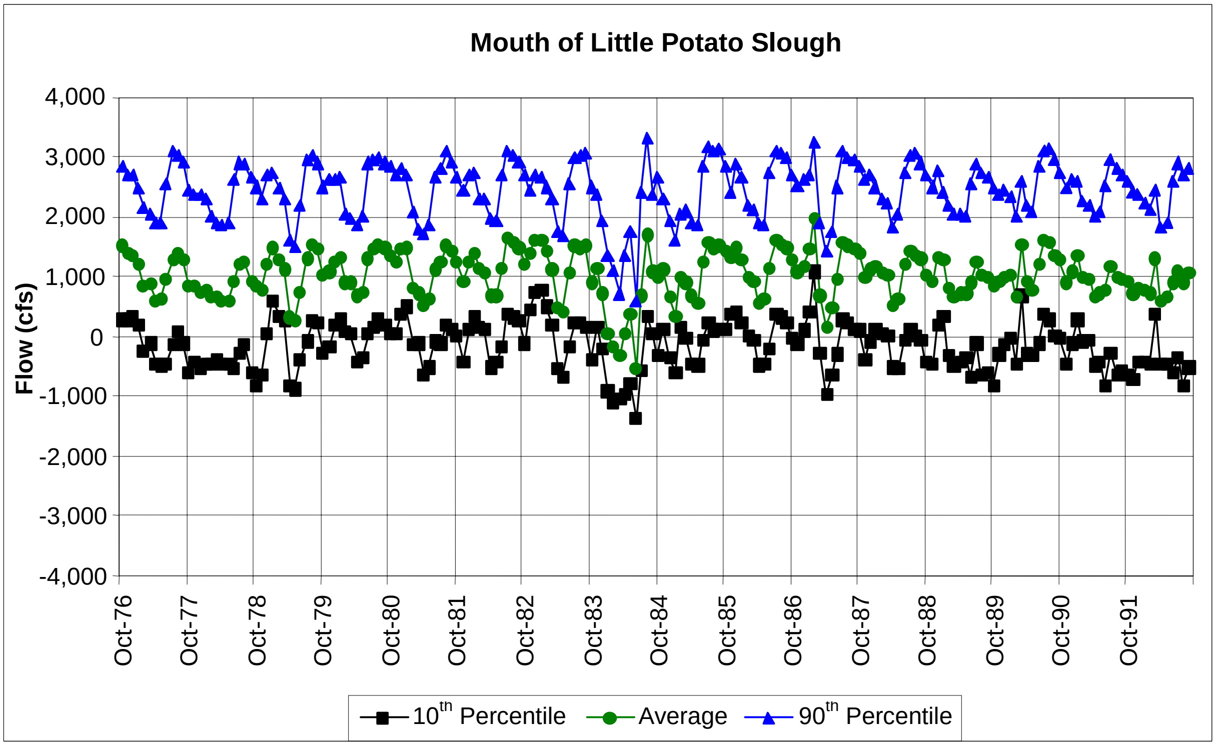

Figure D-70b. Distribution of Simulated Tidal Flow at the Mouth of Little Potato Slough, Water Years 1976–1991

Figures D-70a and D-70b

Distribution of Simulated Tidal Flow at the Mouth of Potato and Little Potato Sloughs

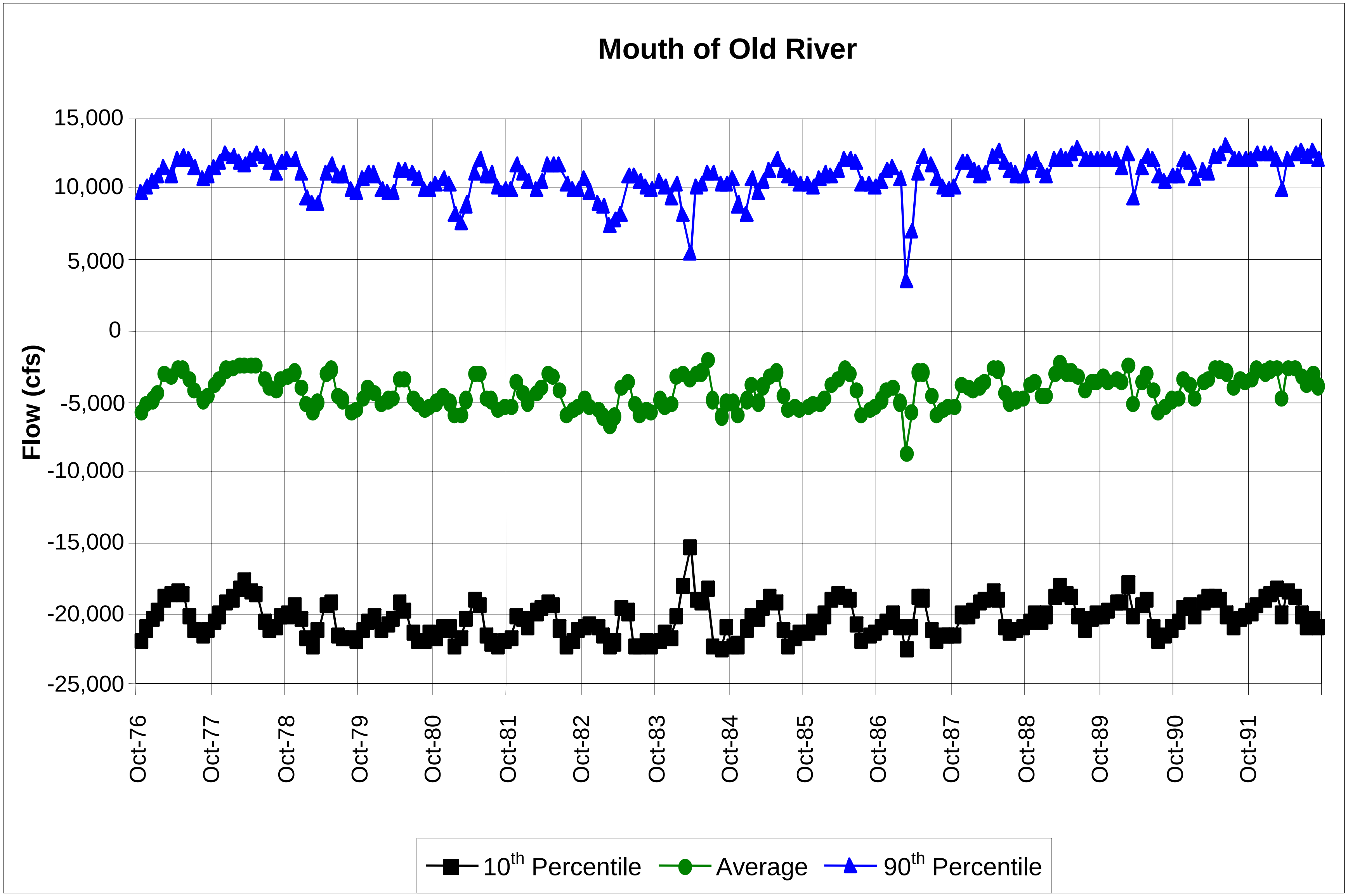

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Figure D-71

Distribution of Simulated Tidal Flow at the Mouth of Old River, Water Years 1976–1991

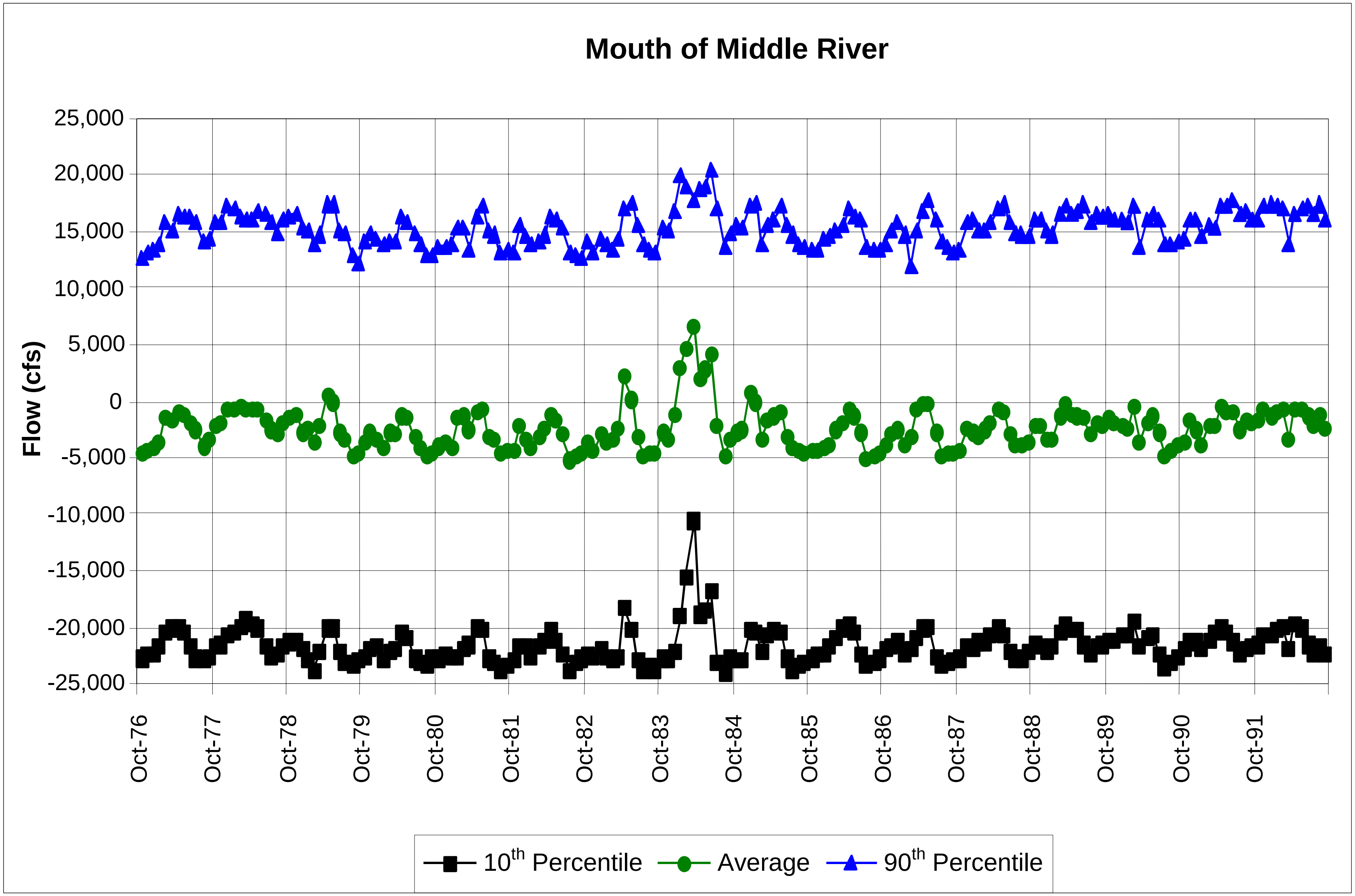

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Figure D-72

Distribution of Simulated Tidal Flow at the Mouth of Middle River, Water Years 1976–1991

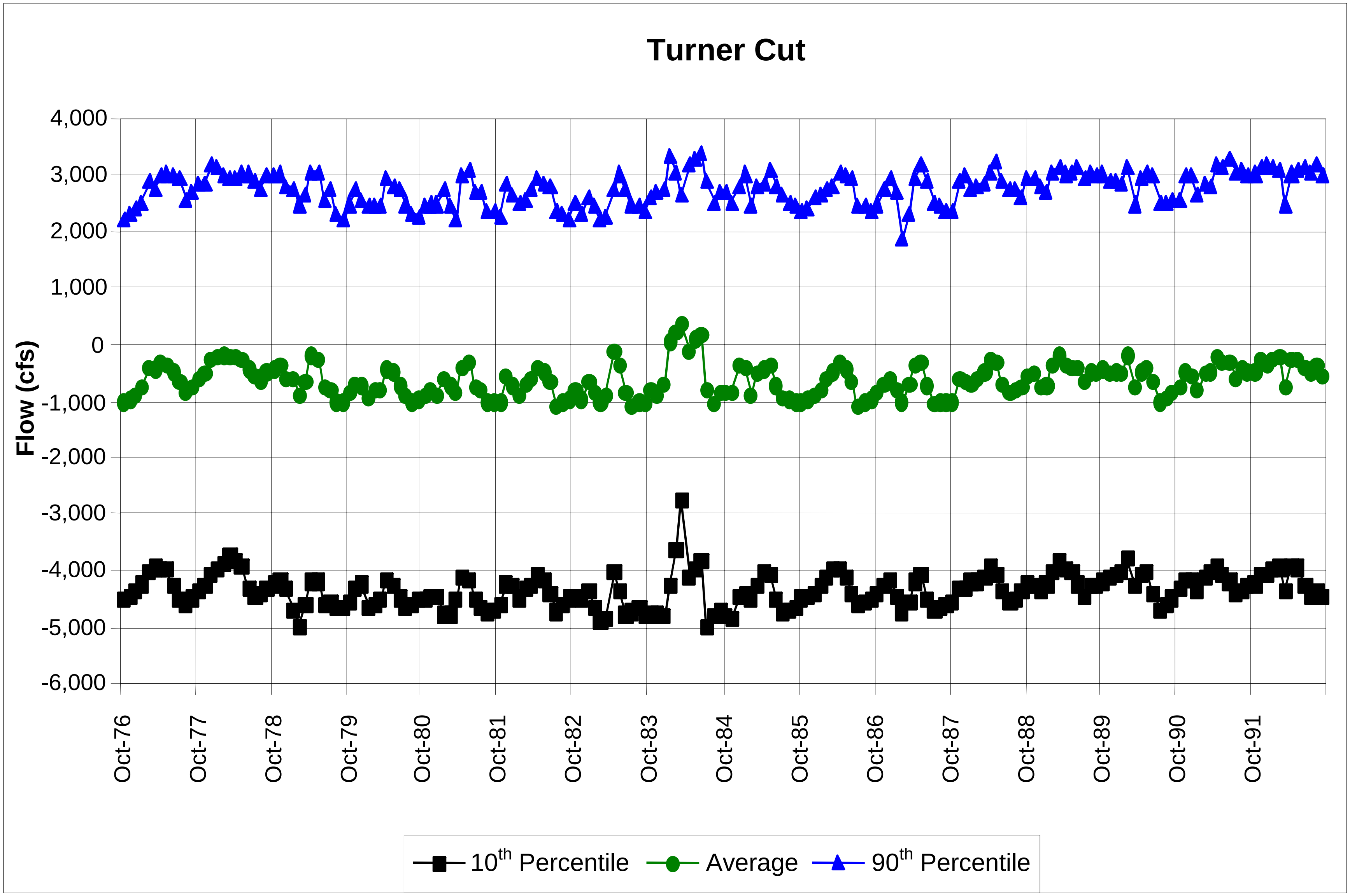

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Figure D-73

Distribution of Simulated Tidal Flow at Turner Cut, Water Years 1976–1991

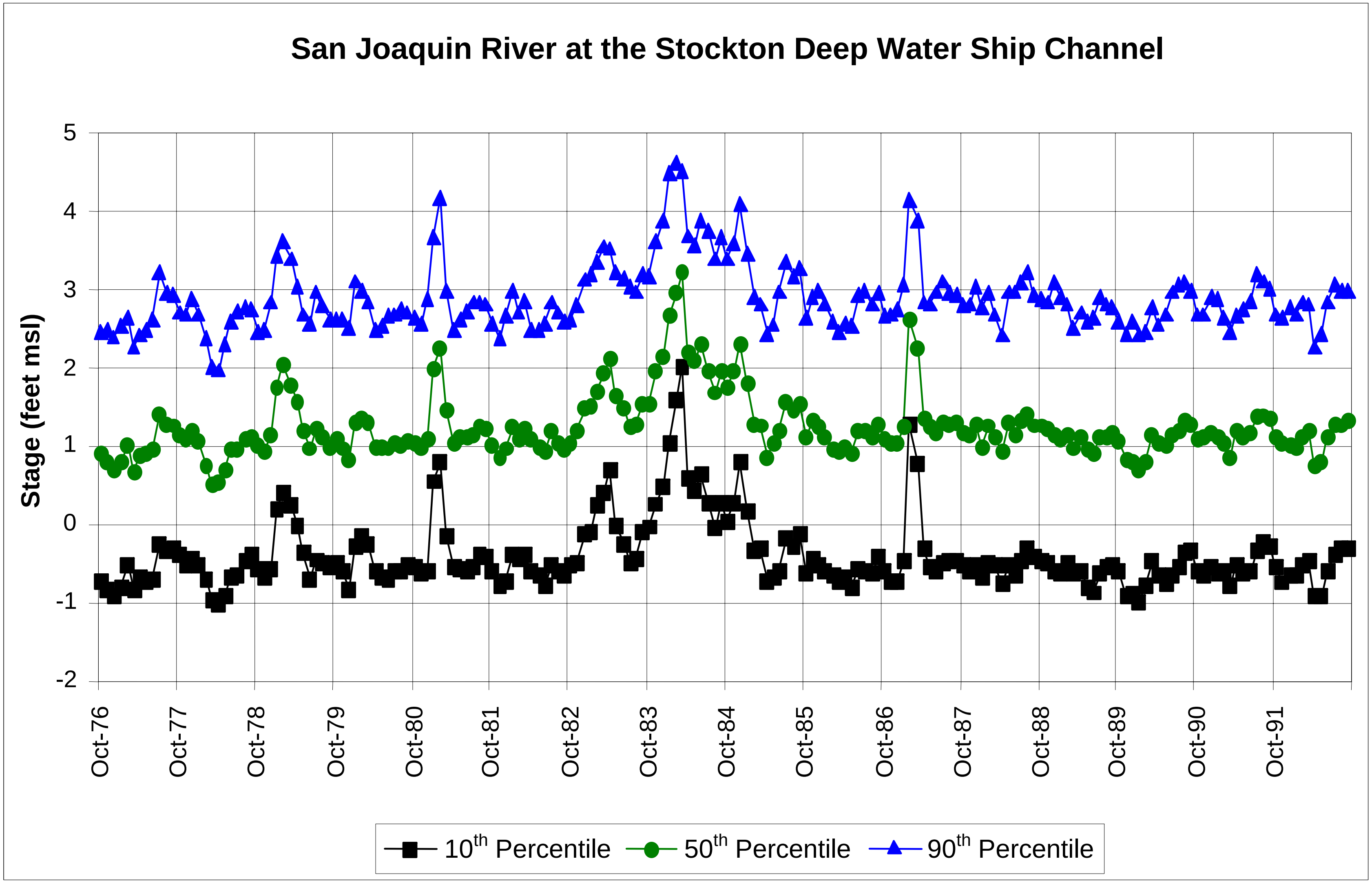

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Figure D-74

Distribution of Simulated Tidal Stage in the San Joaquin River at Stockton (Rough & Ready Island), Water Years 1976–1991

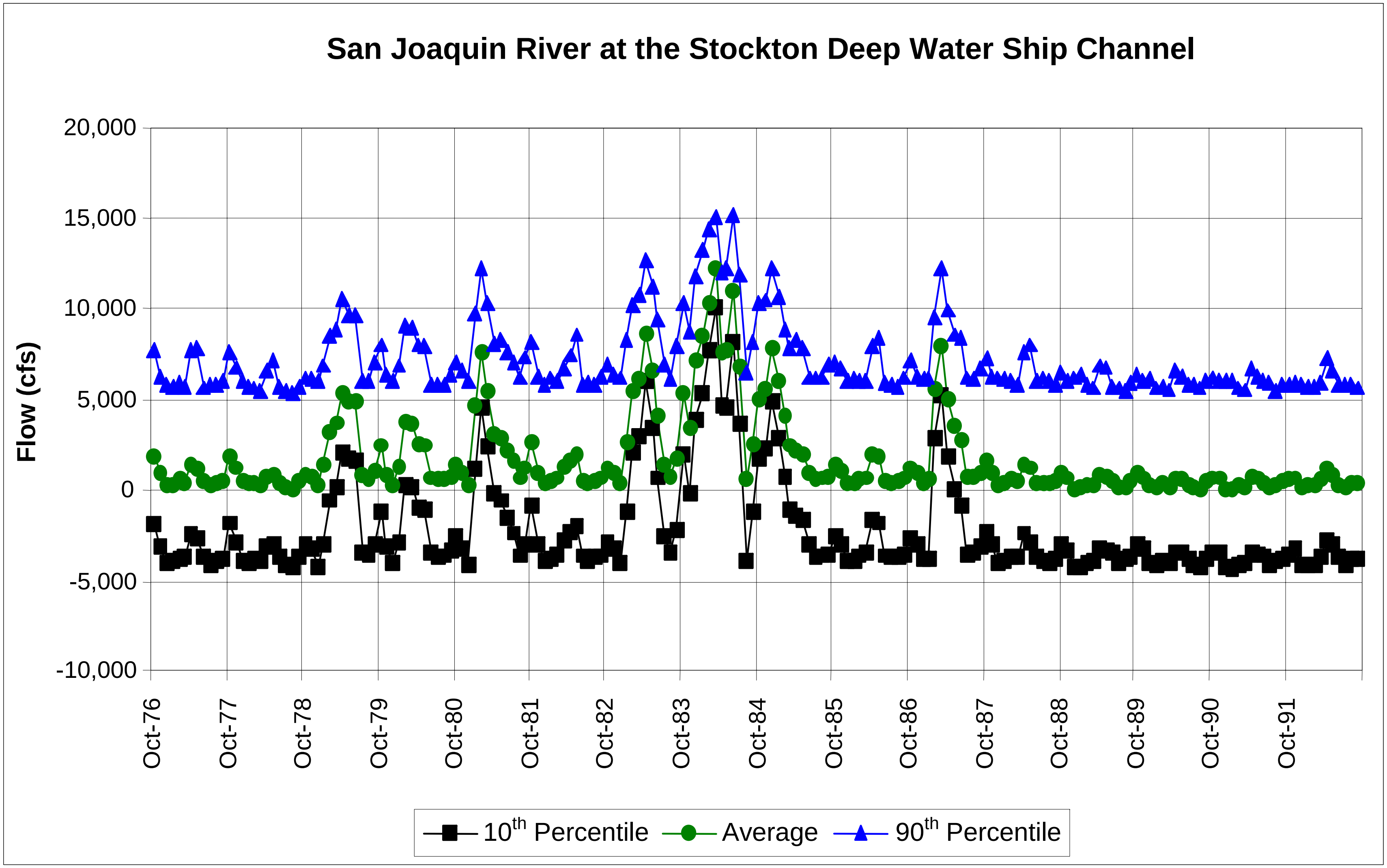

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Figure D-75

Distribution of Simulated Tidal Flow in the San Joaquin River at Stockton (Rough & Ready Island), Water Years 1976–1991

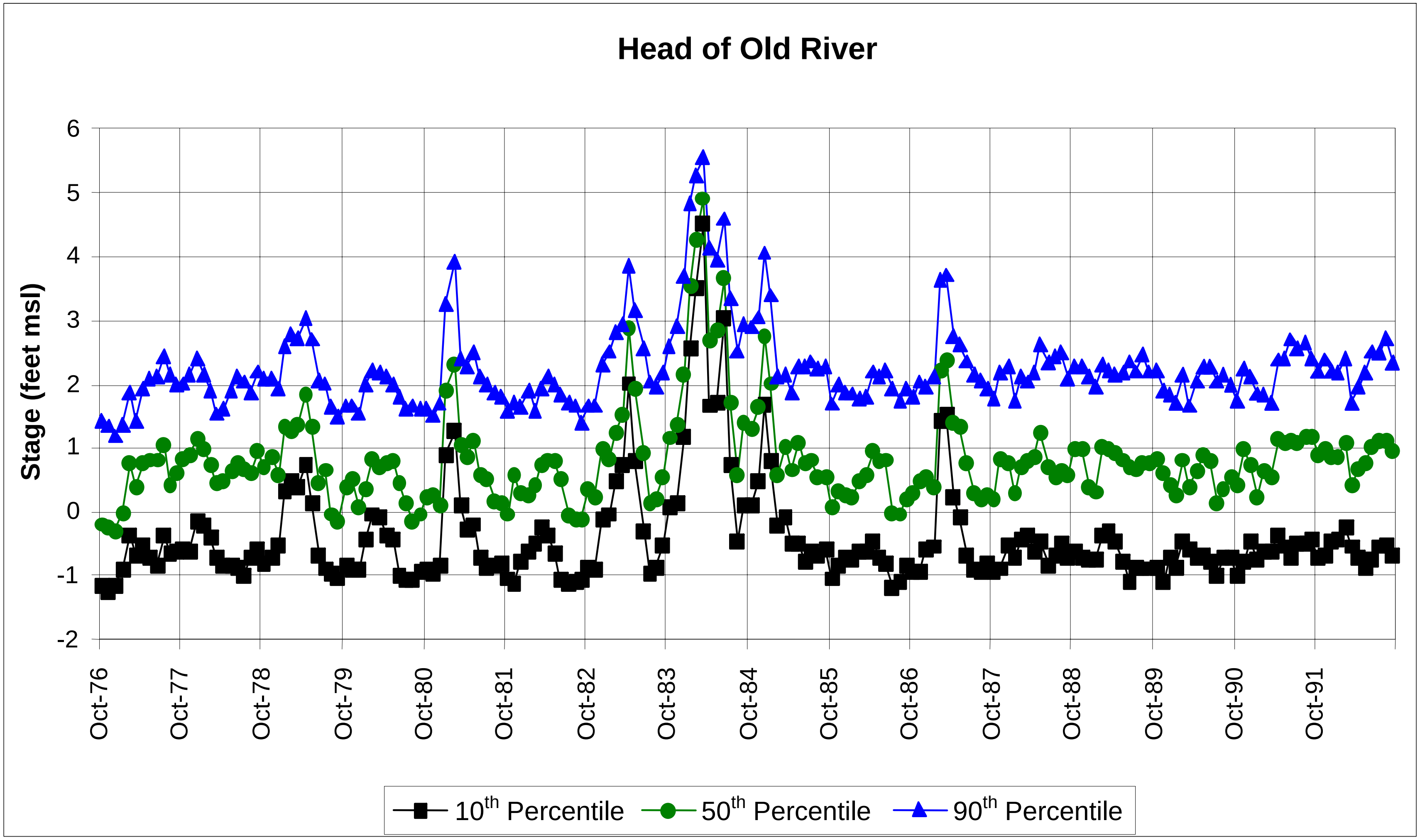

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Figure D-76

Distribution of Simulated Tidal Stage at the Head of Old River, Water Years 1976–1991

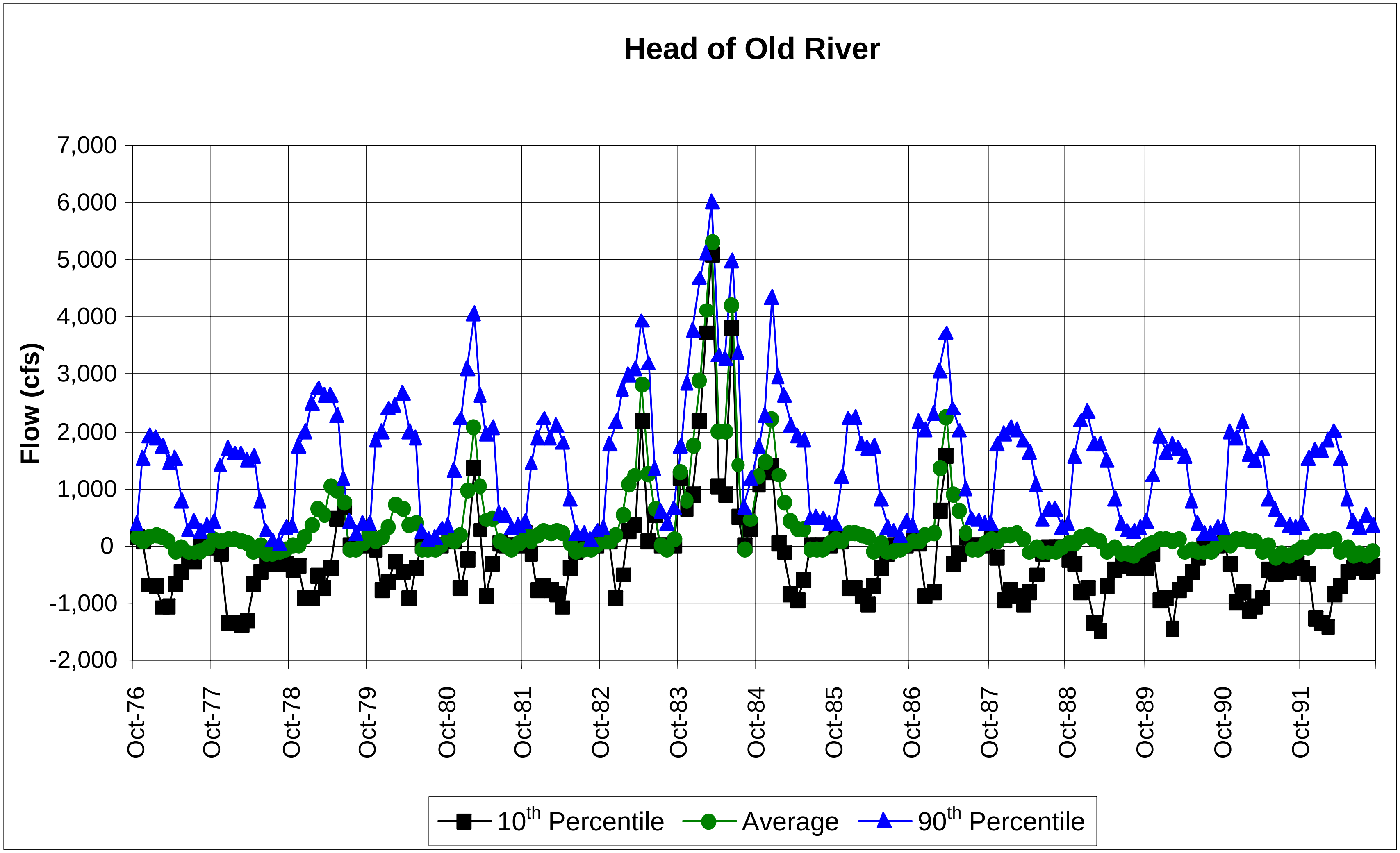

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Figure D-77

Distribution of Simulated Tidal Flow at the Head of Old River, Water Years 1976–1991

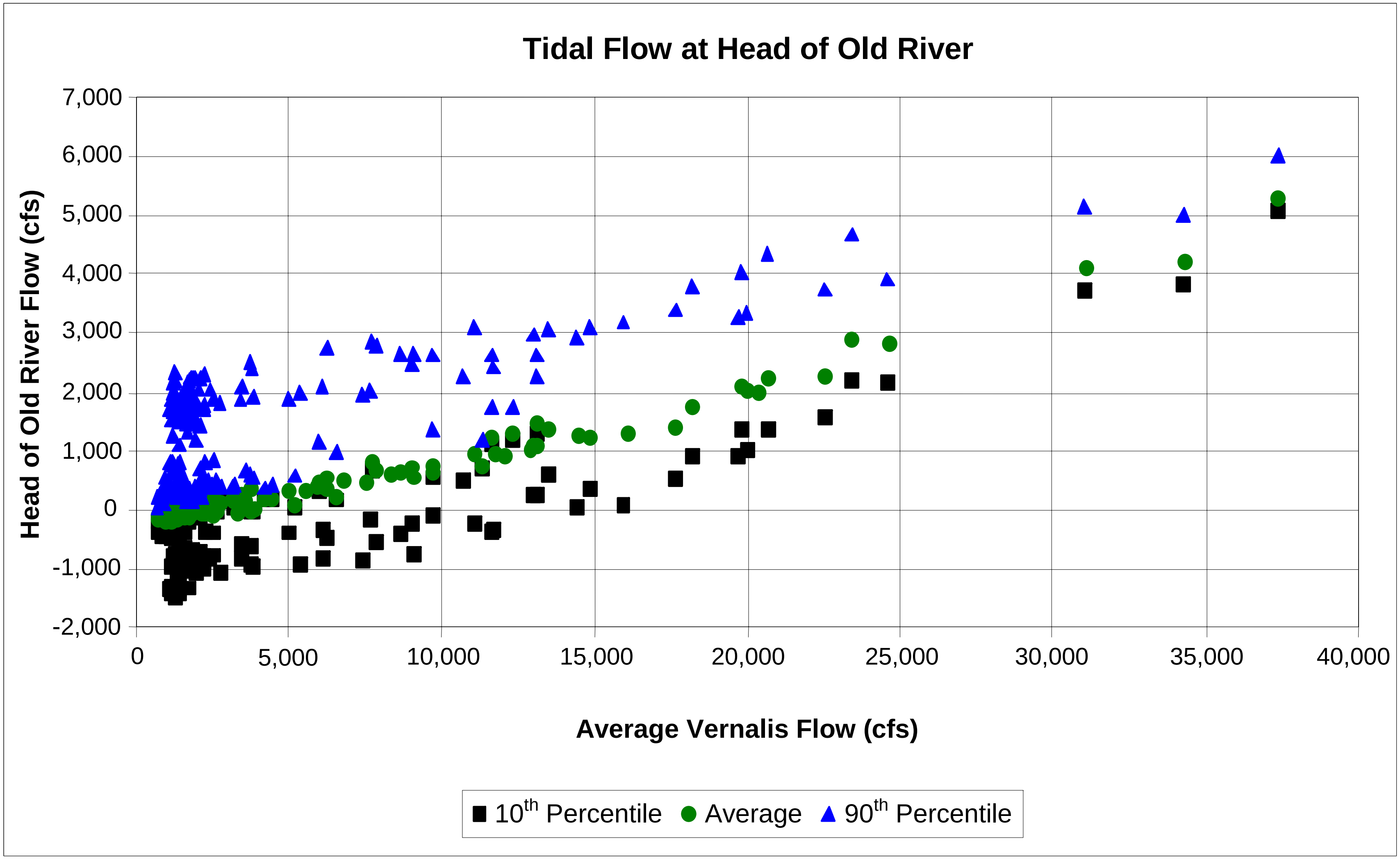

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Figure D-78

Distribution of Simulated Tidal Flow at the Head of Old River vs. San Joaquin River at Vernalis Flow, Water Years 1976–1991

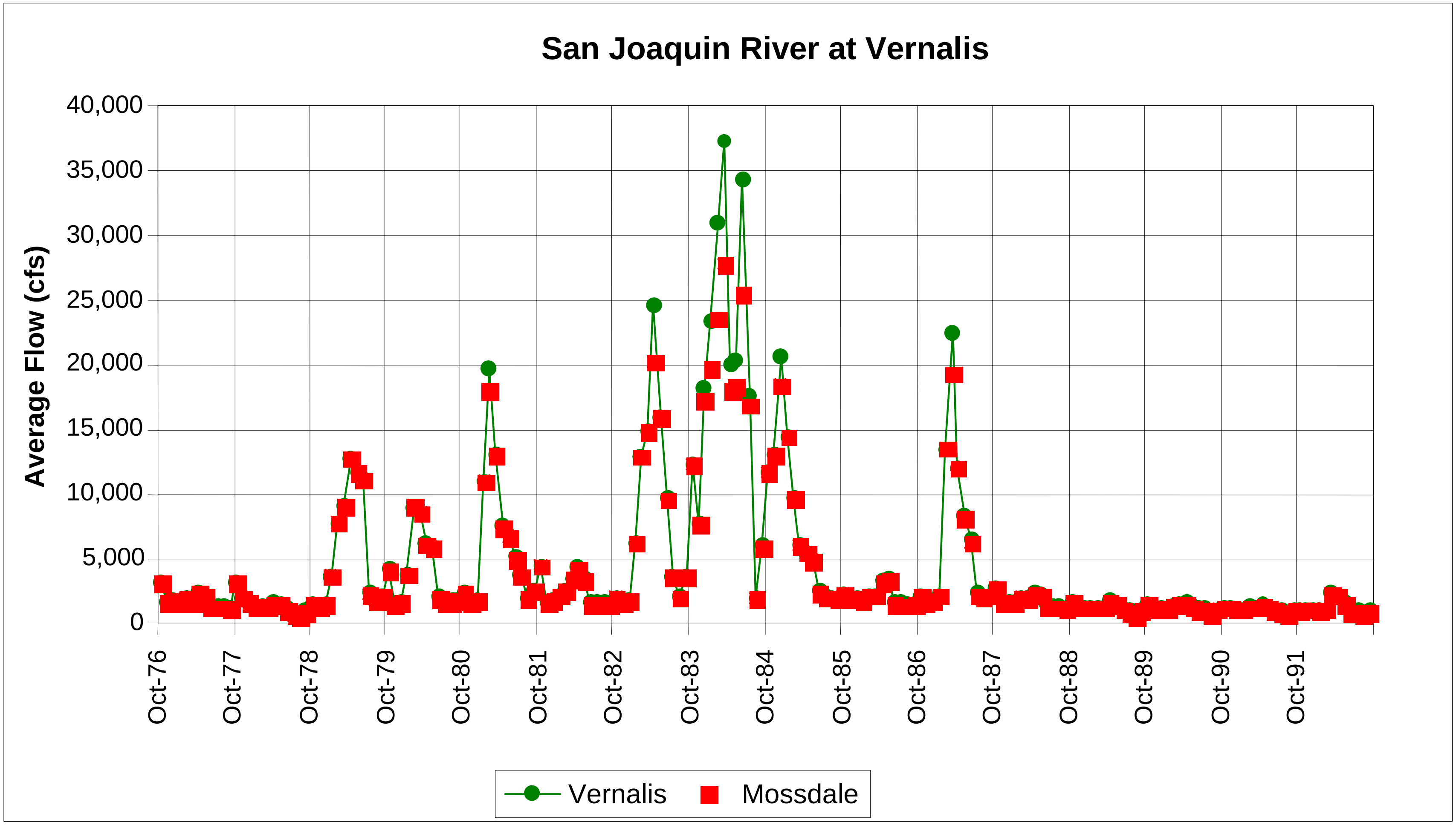

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Figure D-79

Simulated Monthly Average Flow in the San Joaquin River at Vernalis and Mossdale, Water Years 1976–1991

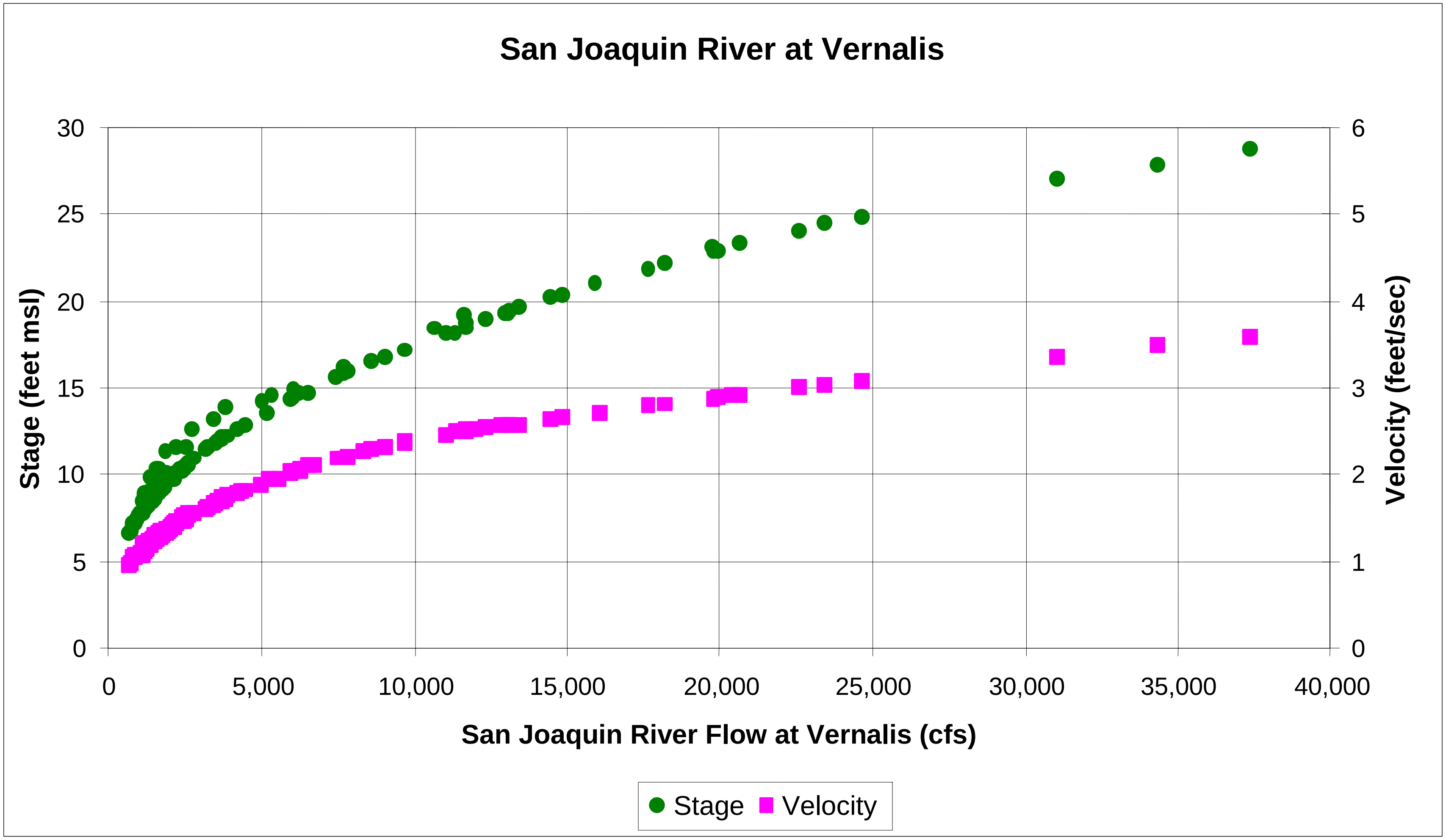

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Figure D-80

Simulated Stage and Velocity in the San Joaquin River at Vernalis, Water Years 1976–1991

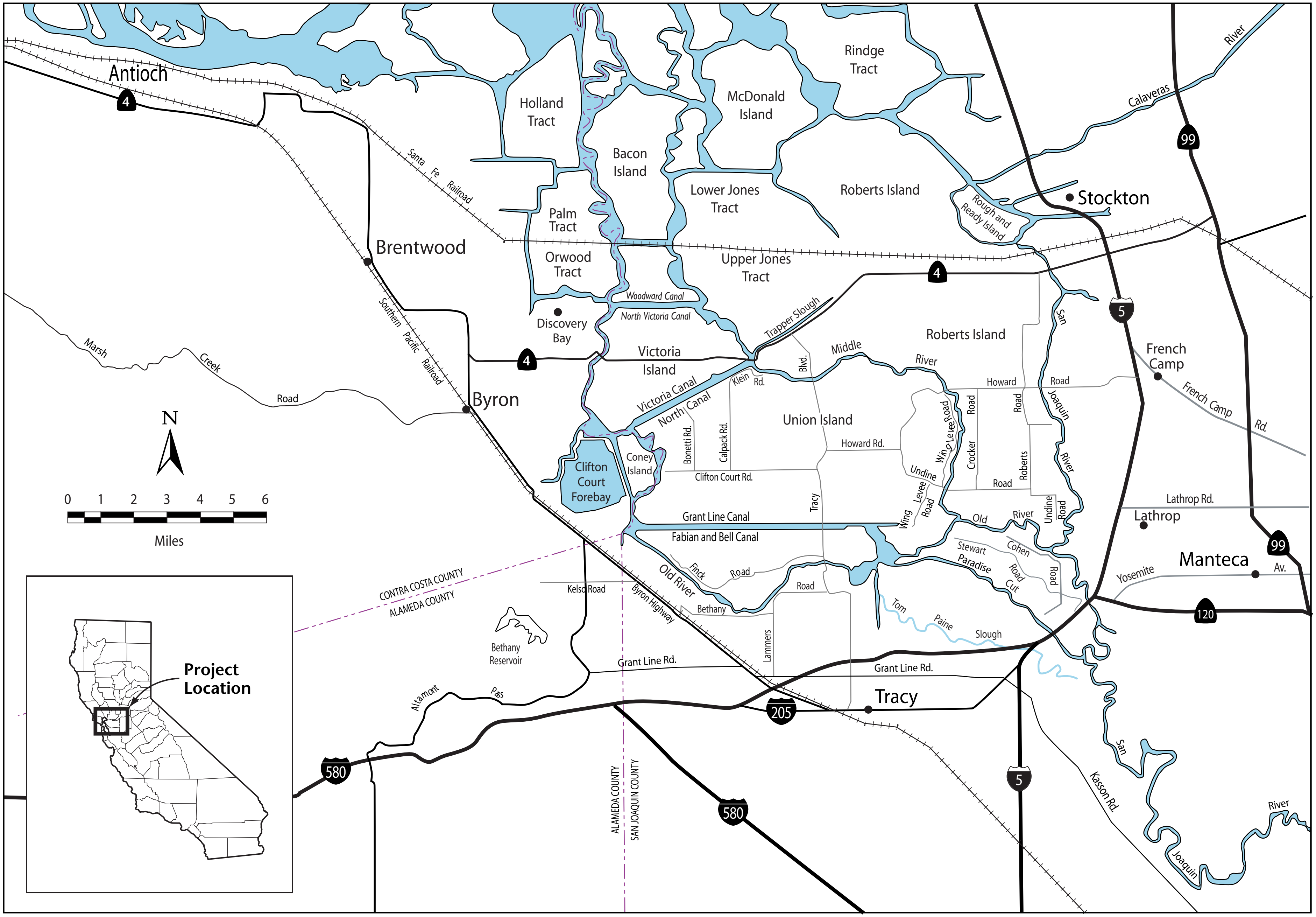

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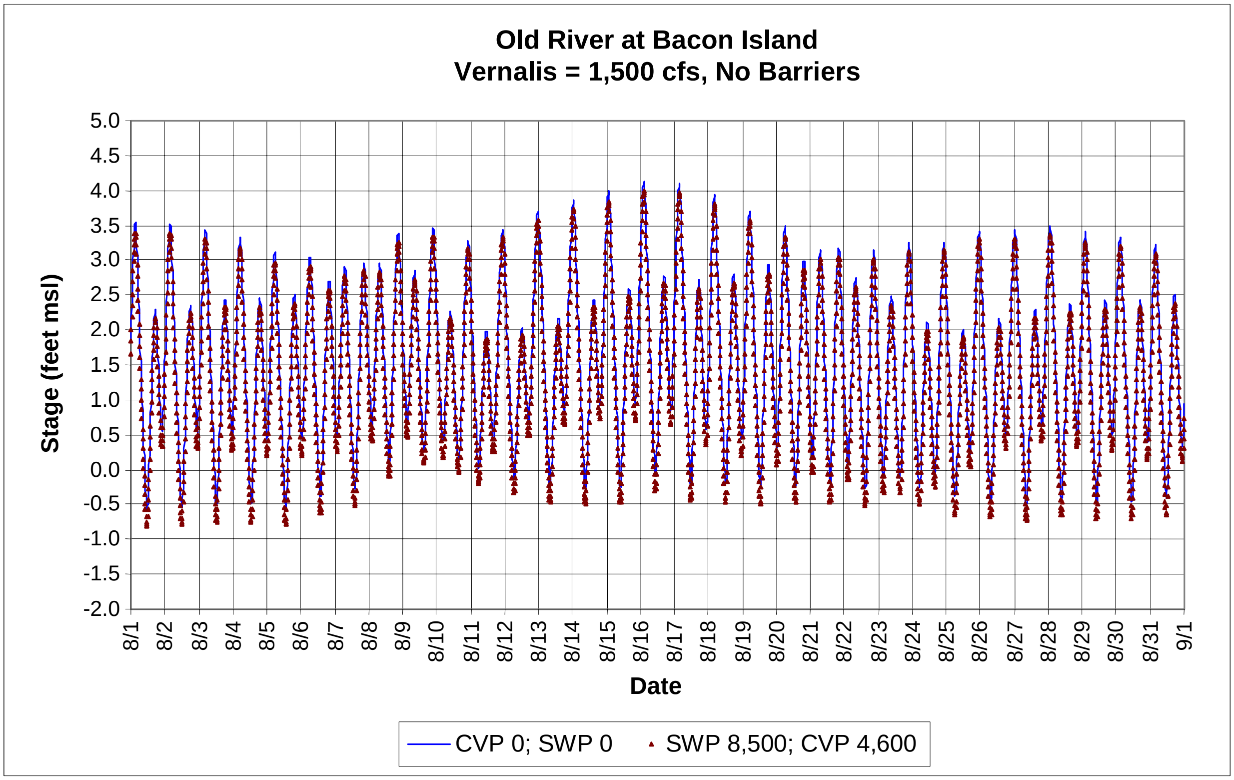
Figure D-81
South Delta Location Map



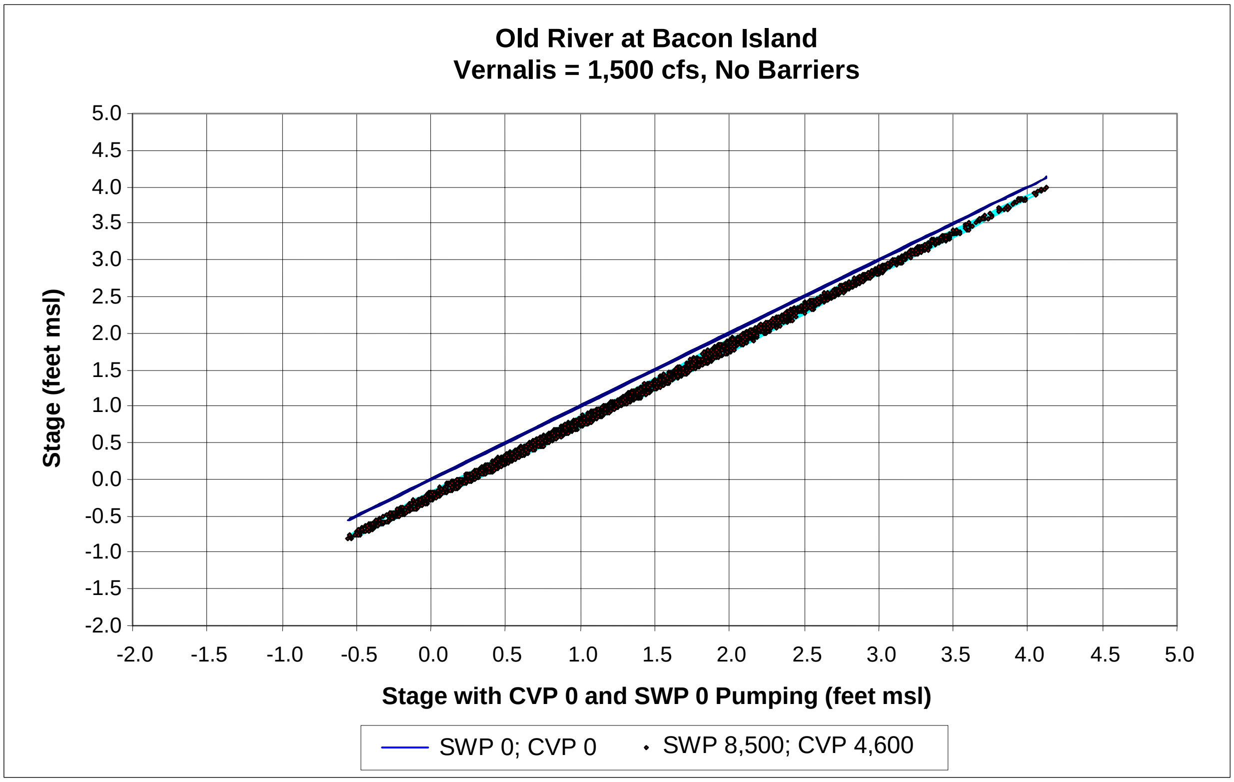


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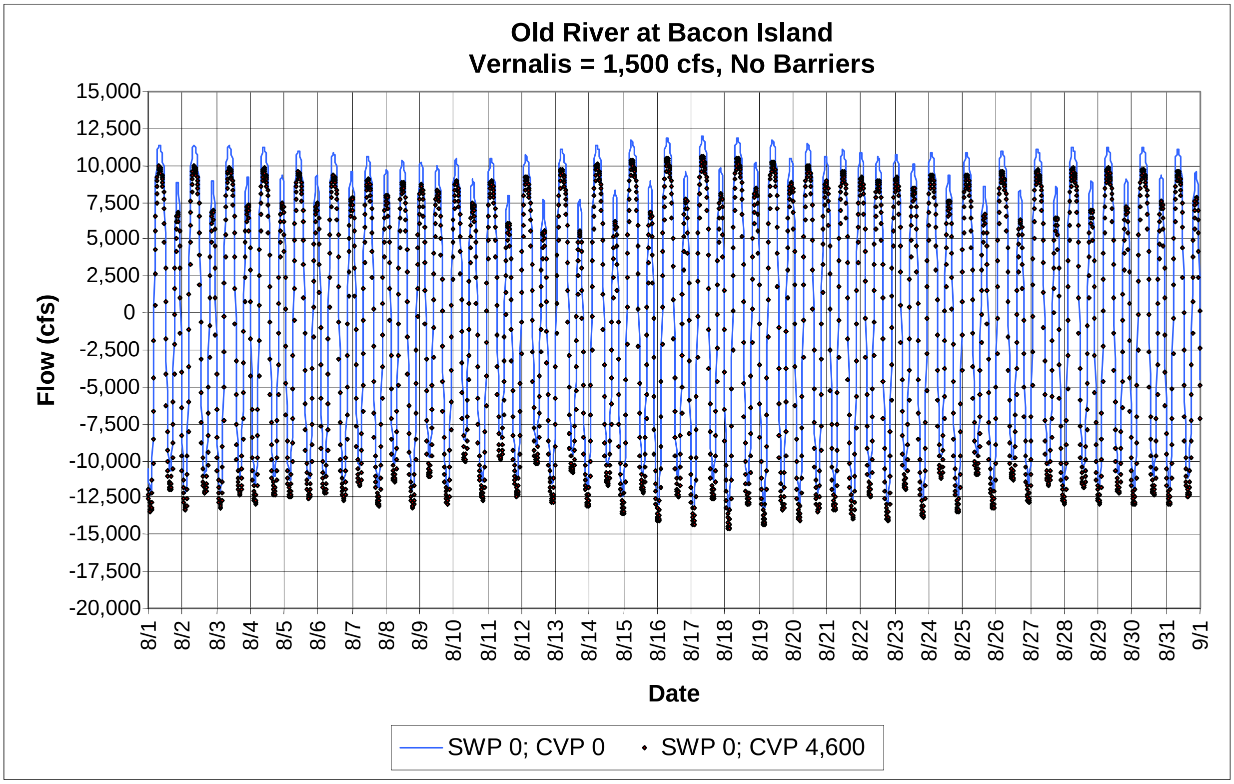
Figure D-82

Simulated Water Surface Elevation (Stage) in Old River at Bacon Island for Various Pumping Combinations



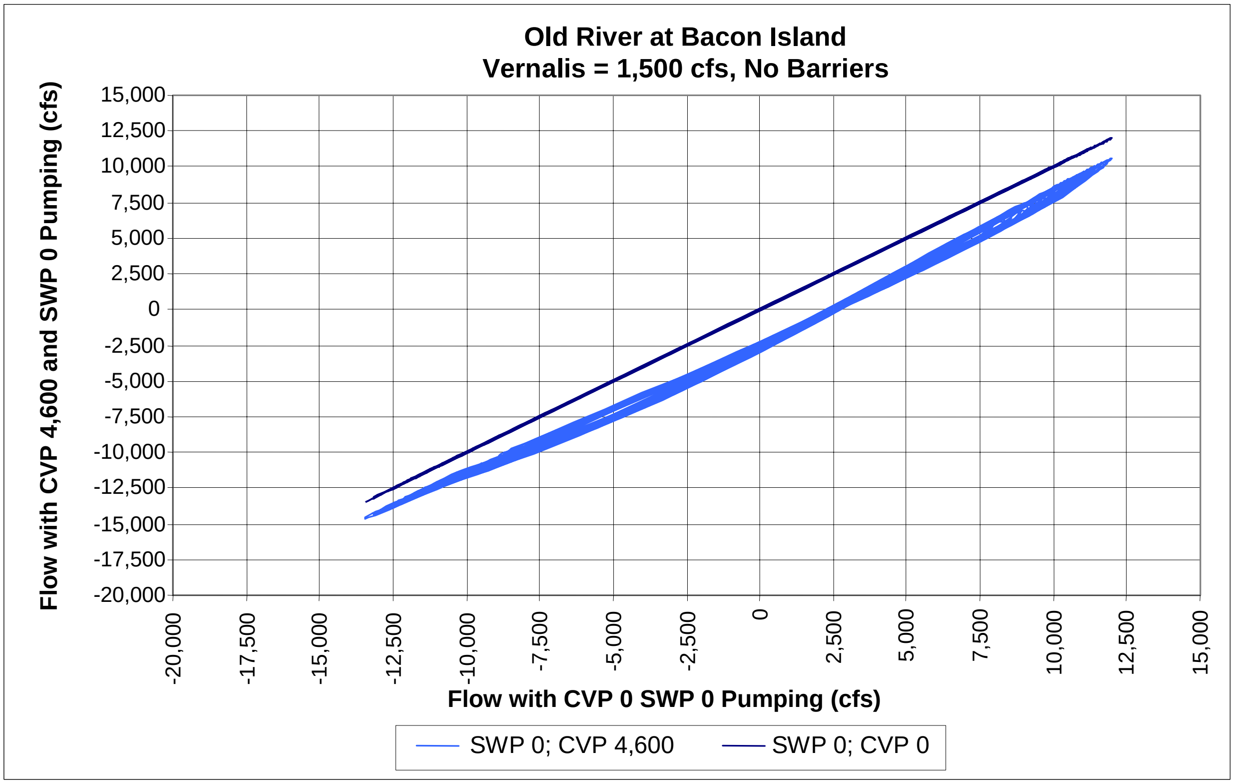


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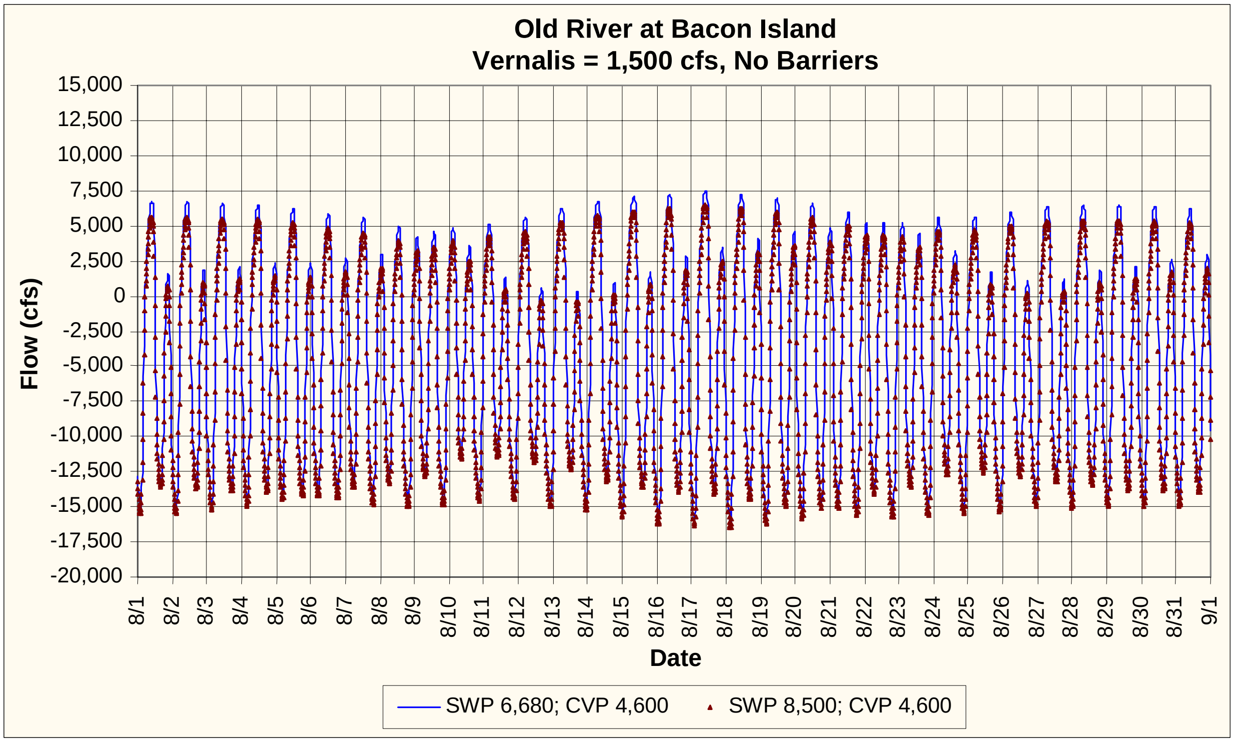
Figure D-83

Simulated Flow in Old River at Bacon Island with CVP Pumping Only



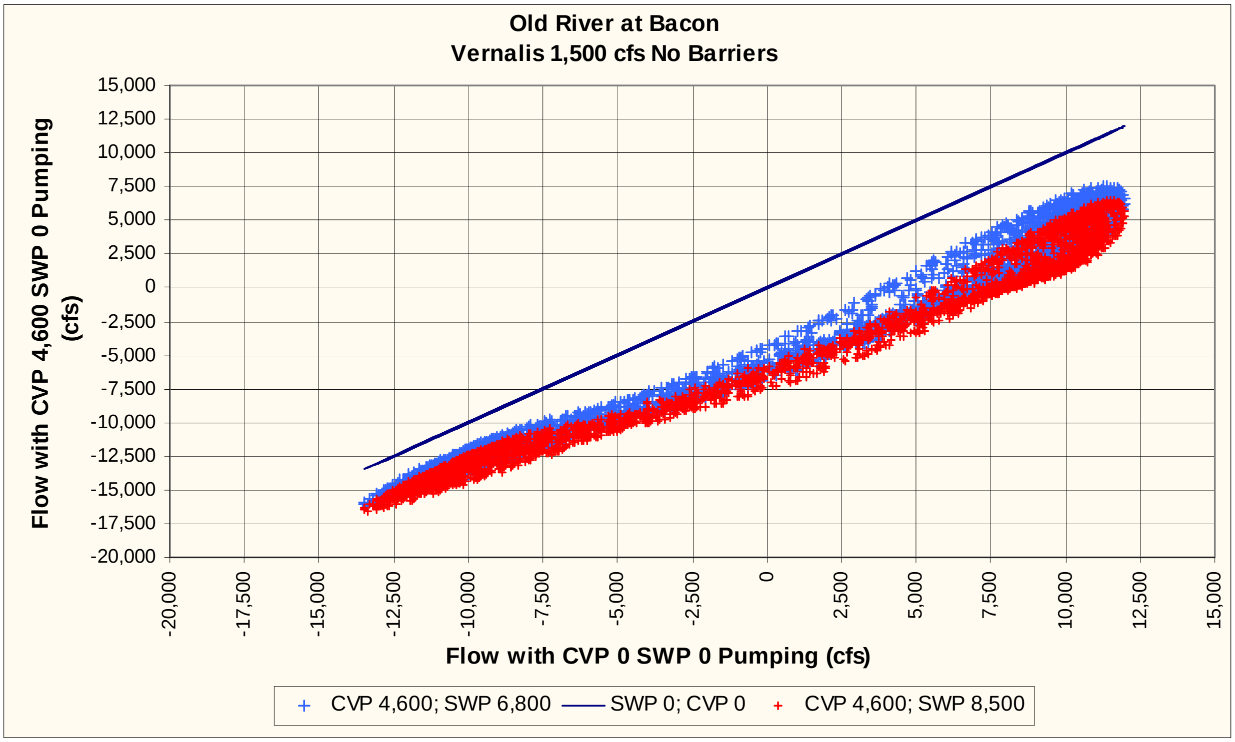


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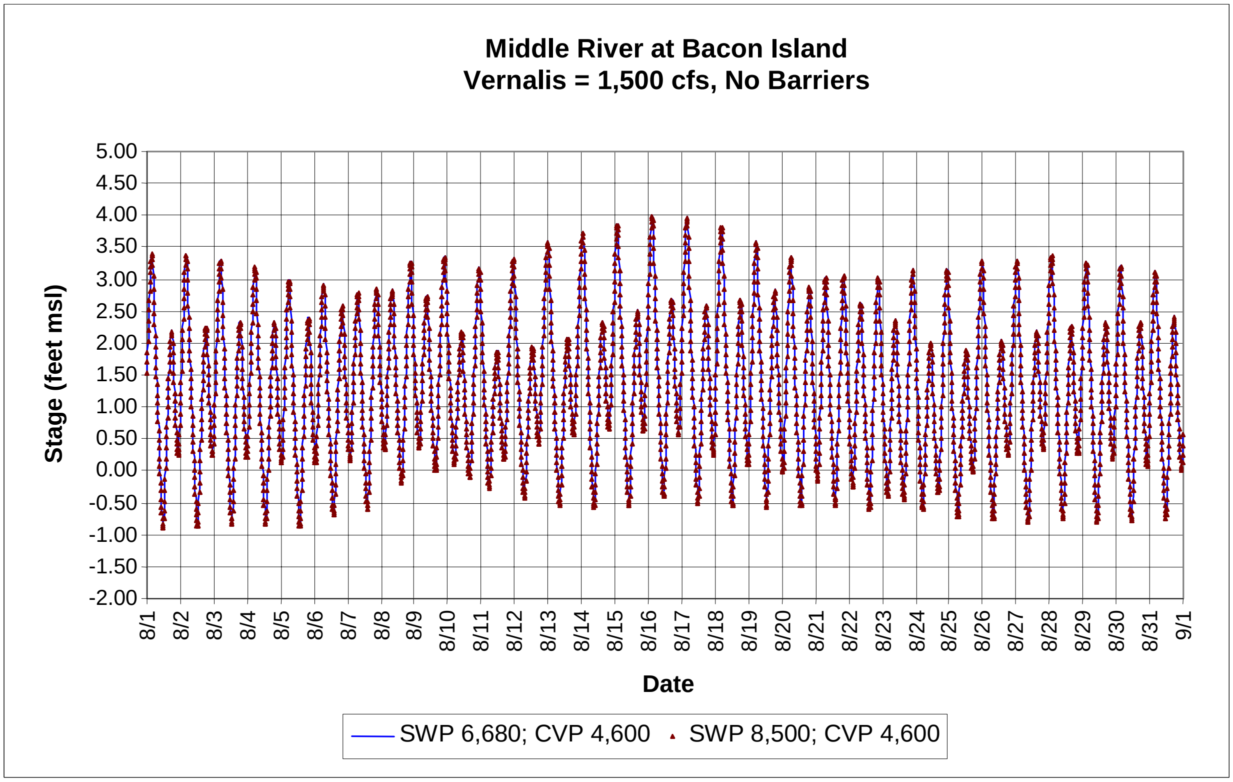
Figure D-84

Simulated Flow in Old River at Bacon Island with CVP and SWP Pumping



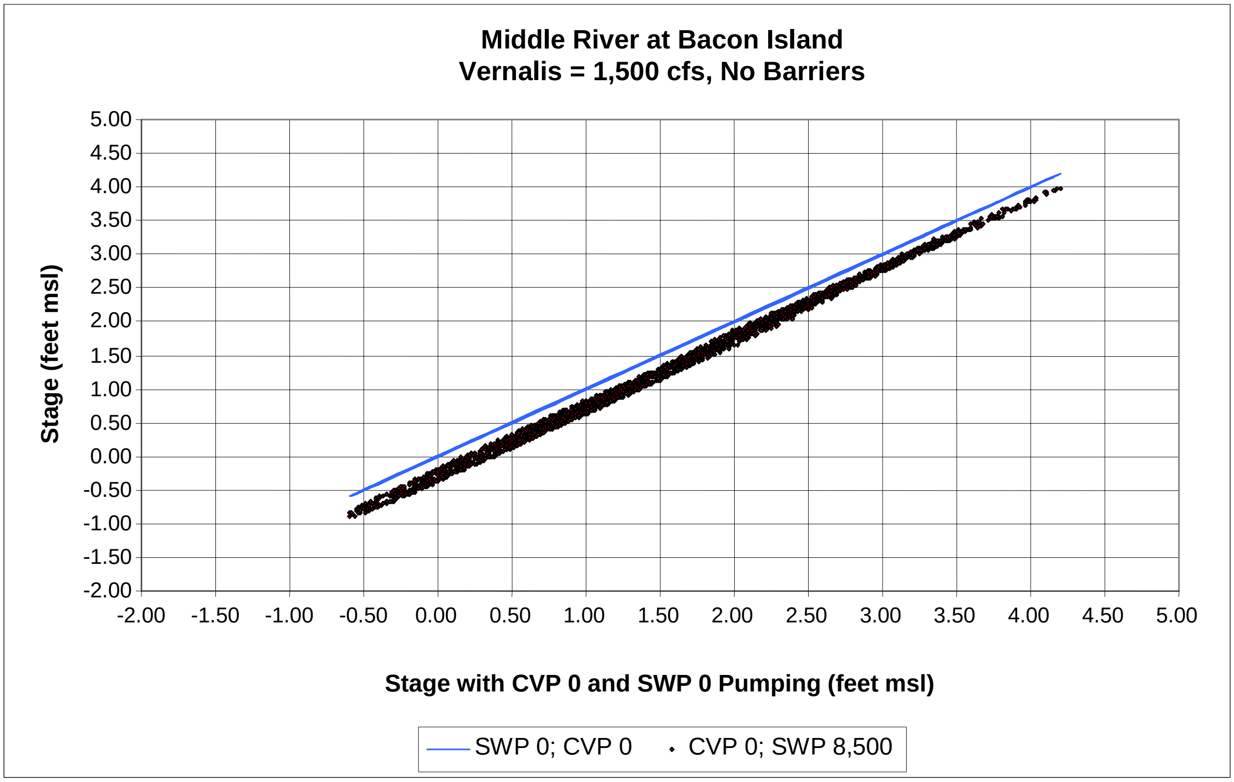


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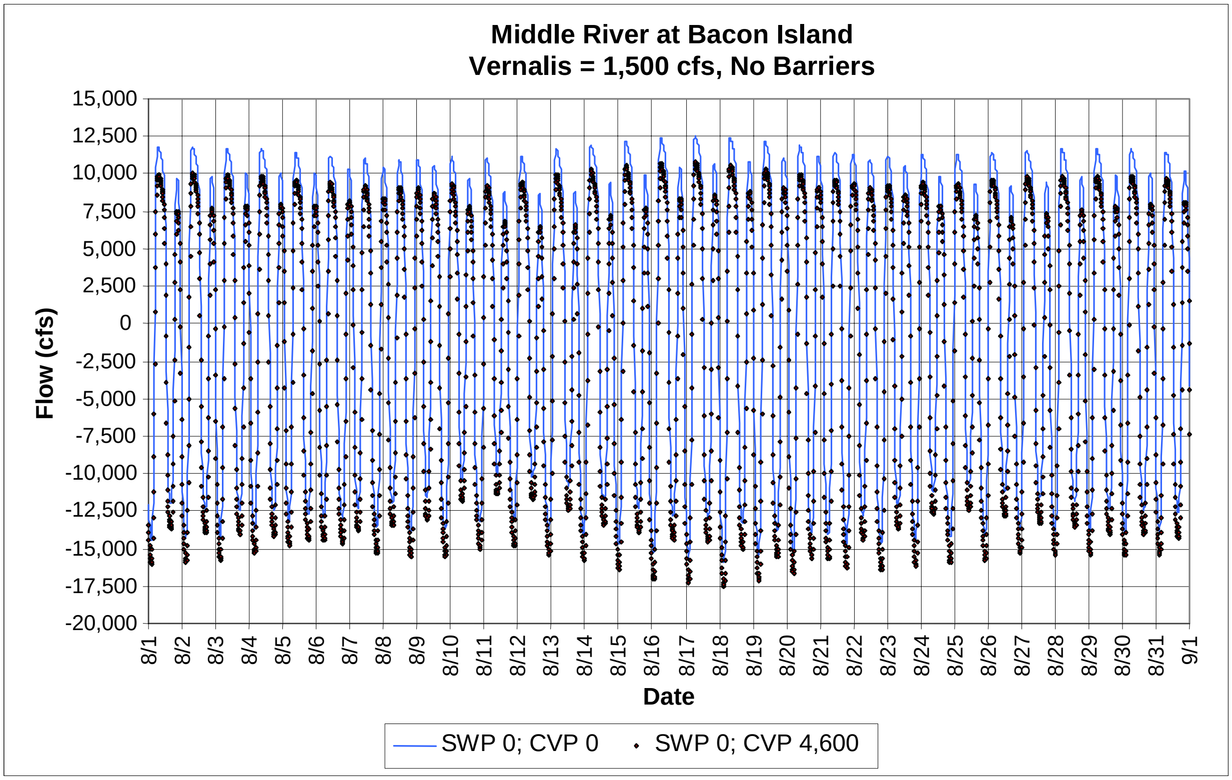
Figure D-85

Simulated Water Surface Elevation (Stage) in Middle River at Bacon Island



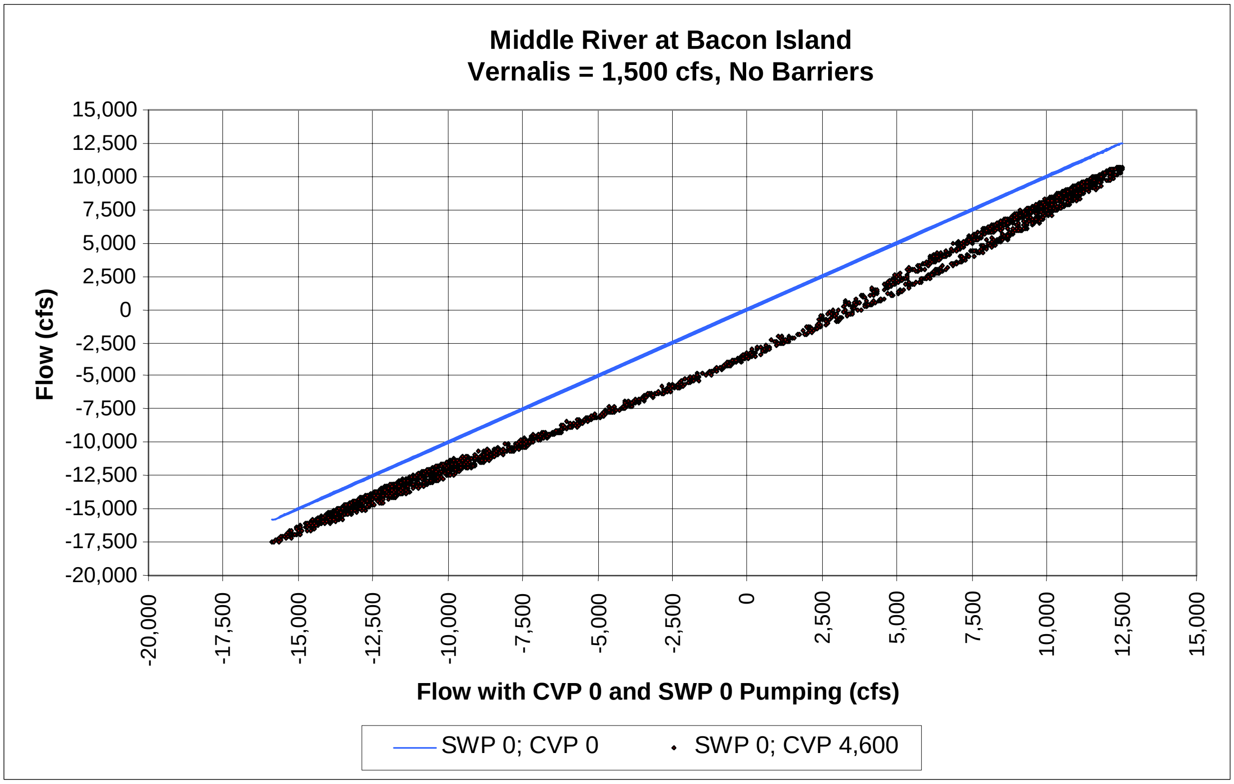


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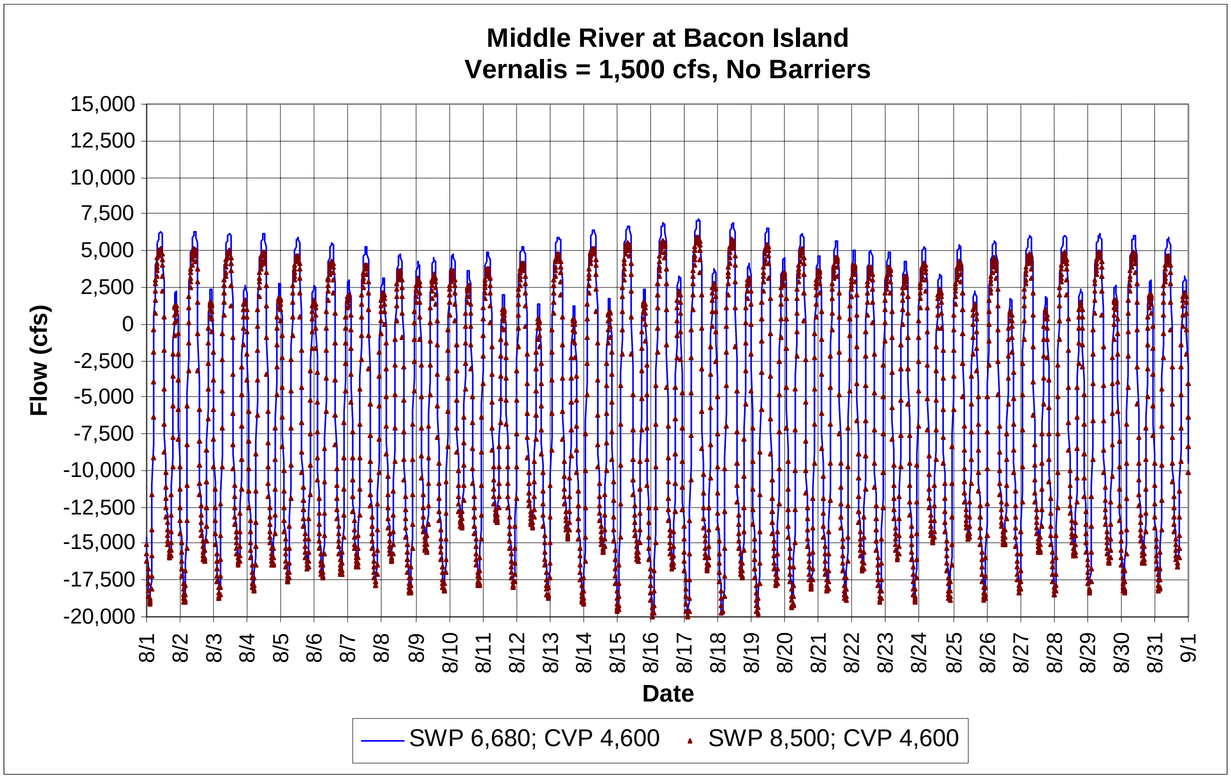
Figure D-86

Simulated Flow in Middle River at Bacon Island with CVP Pumping Only



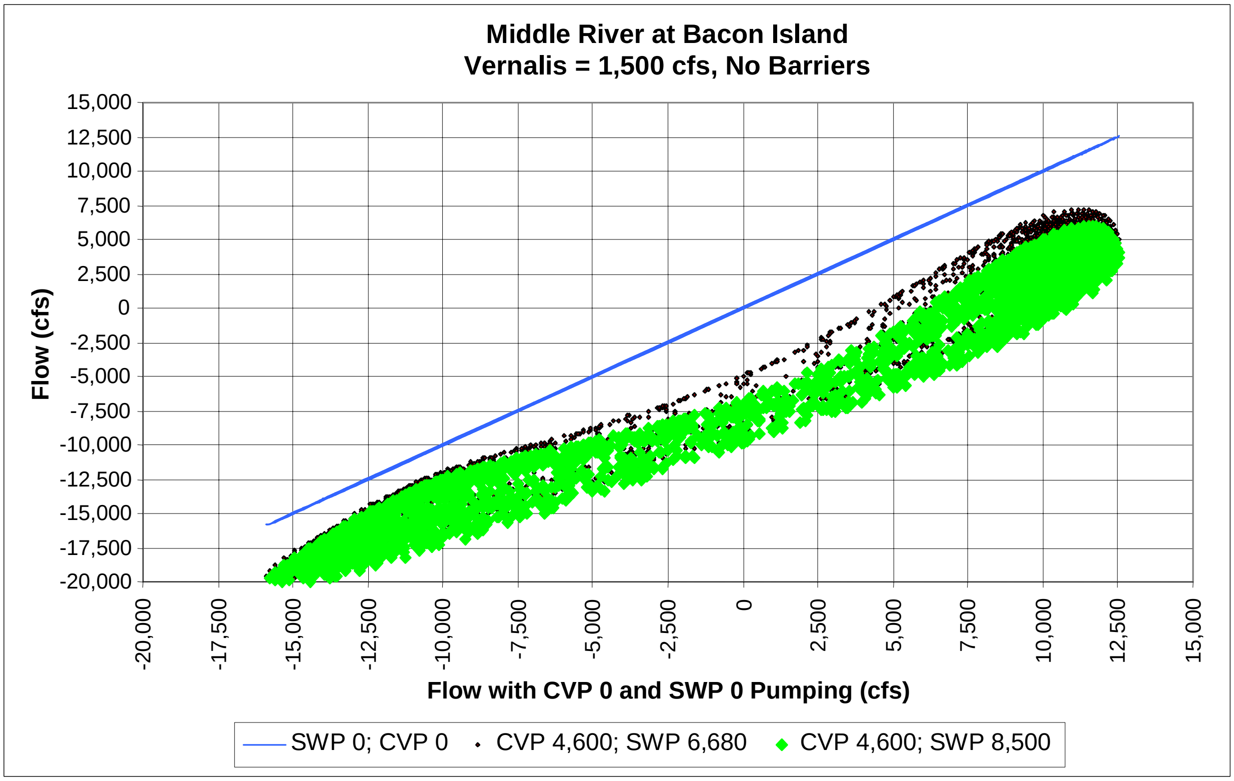


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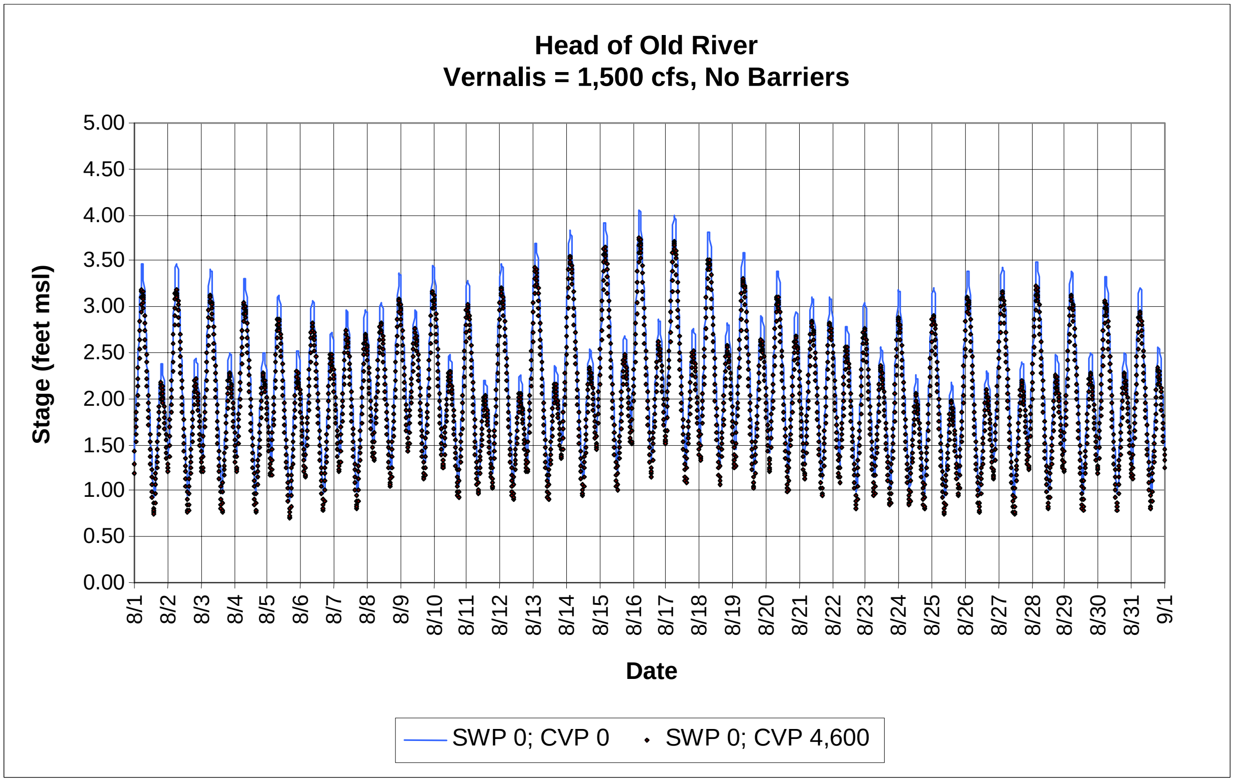
Figure D-87

Simulated Flow in Middle River at Bacon Island with CVP and SWP Pumping



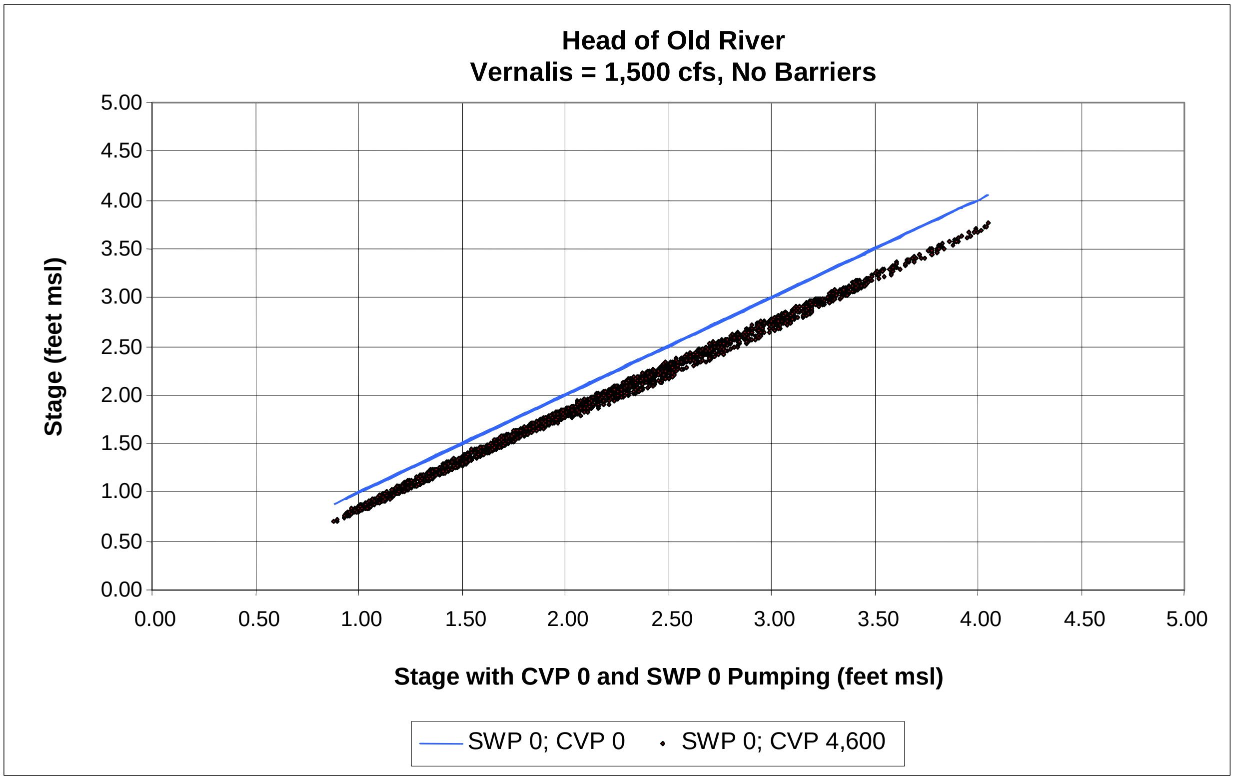


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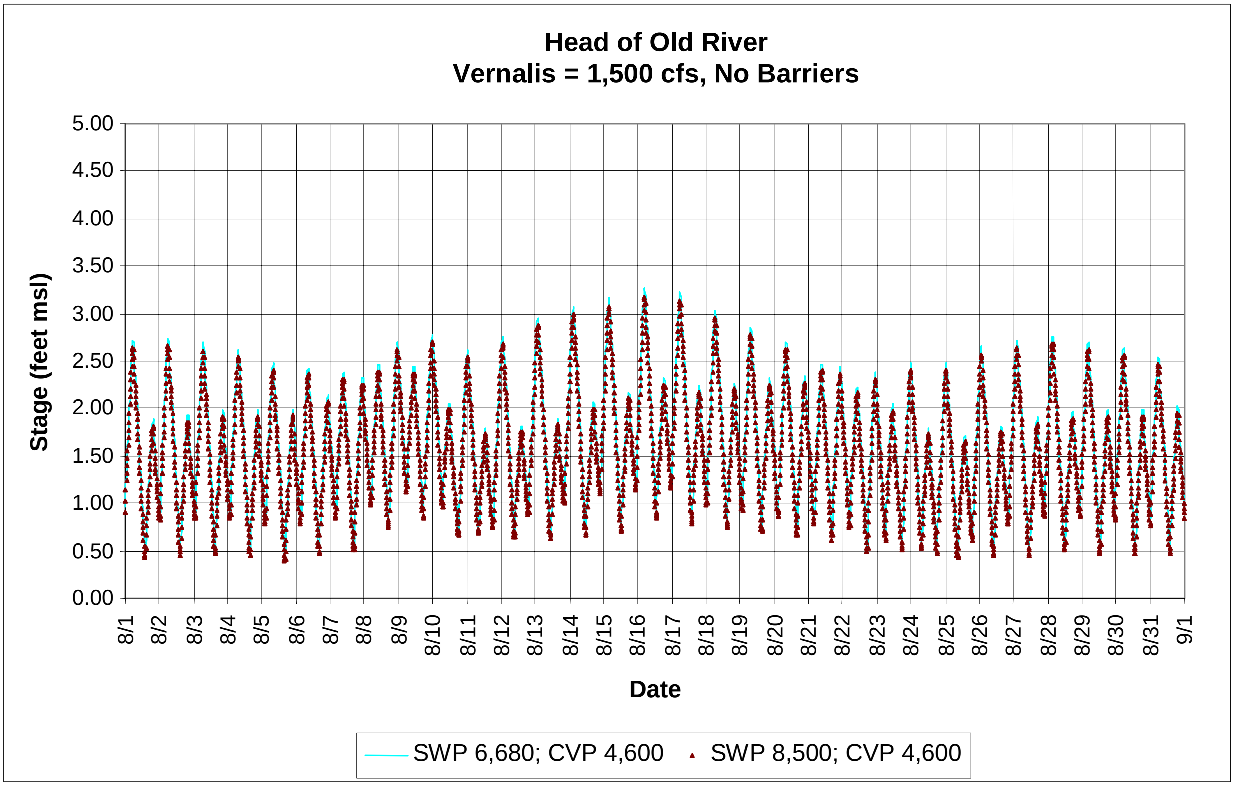
Figure D-88

Simulated Water-Surface Elevation (Stage) at Head of Old River with CVP Pumping Only



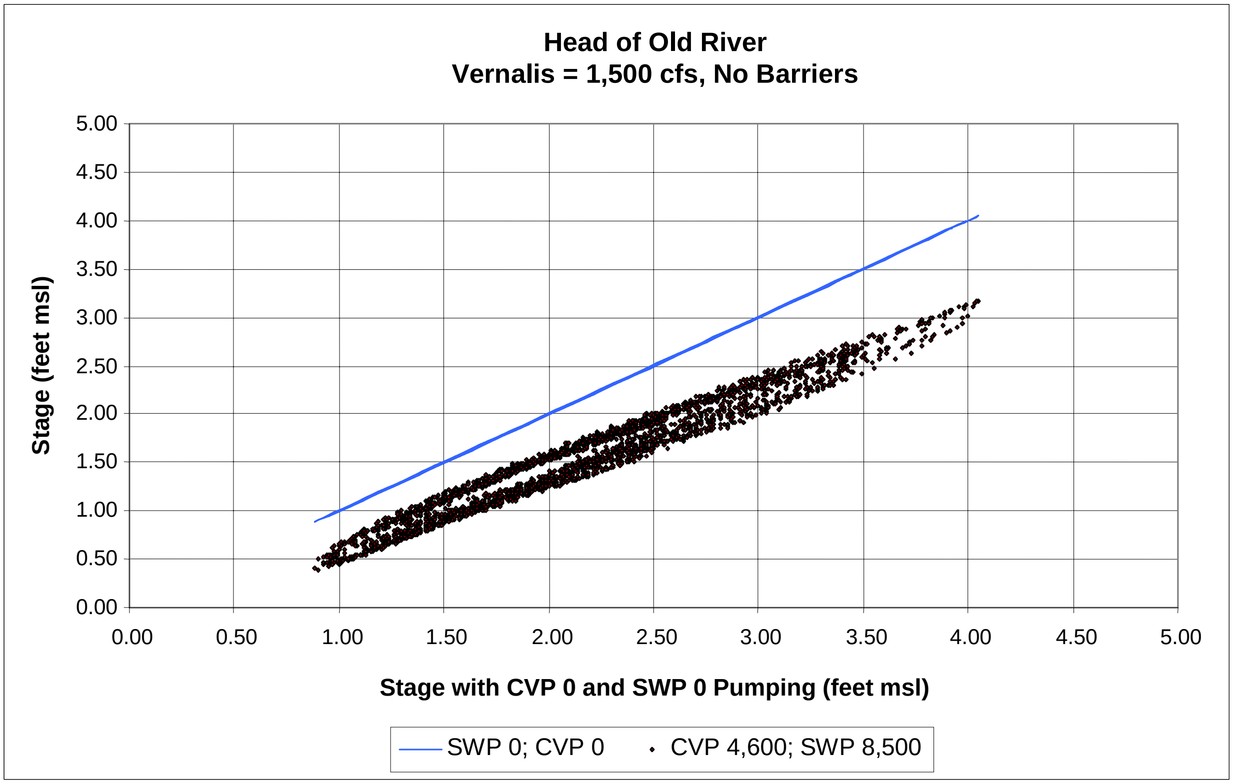


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Figure D-89

Simulated Water-Surface Elevation (Stage) at Head of Old River with CVP and SWP Pumping

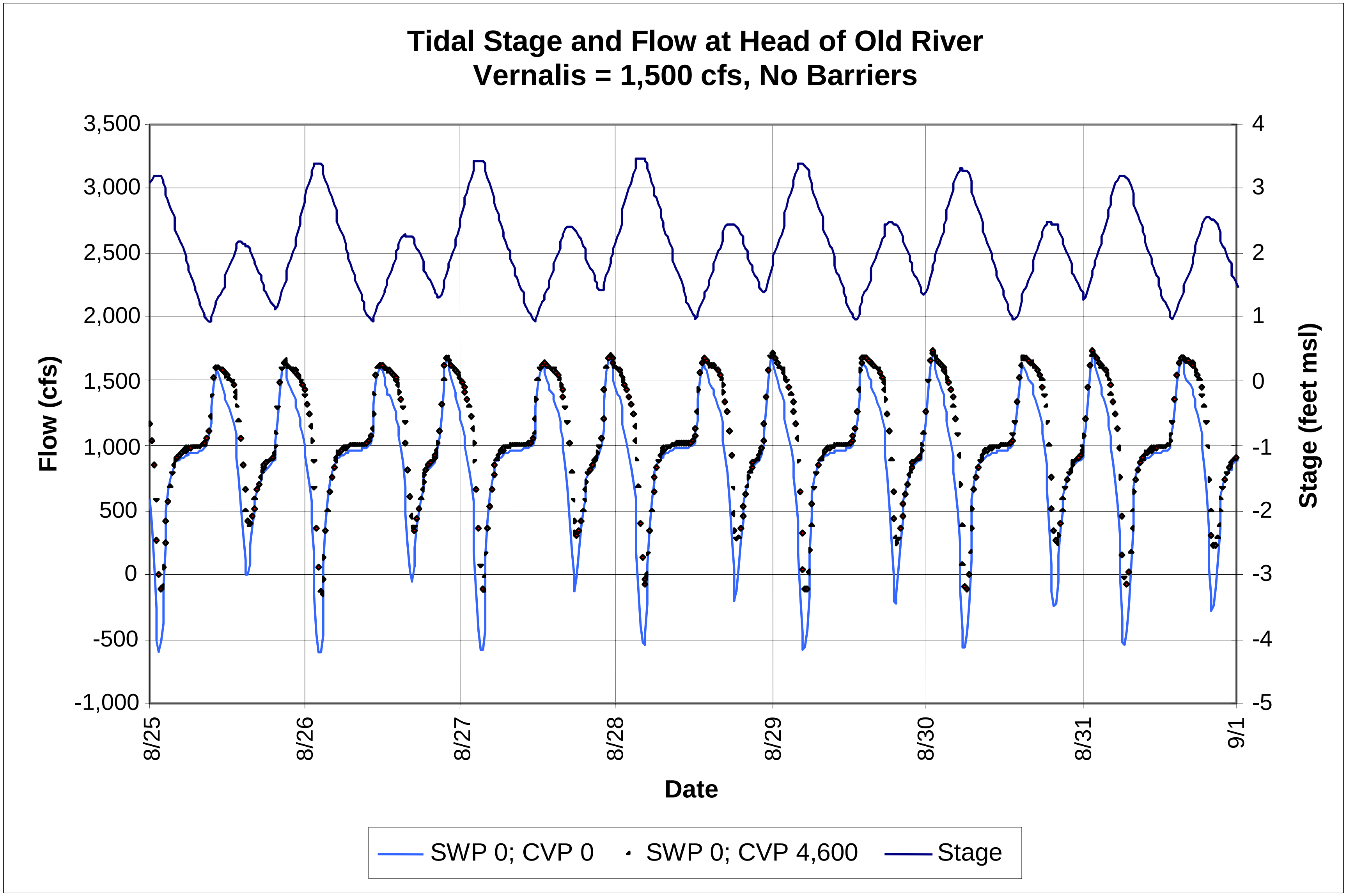

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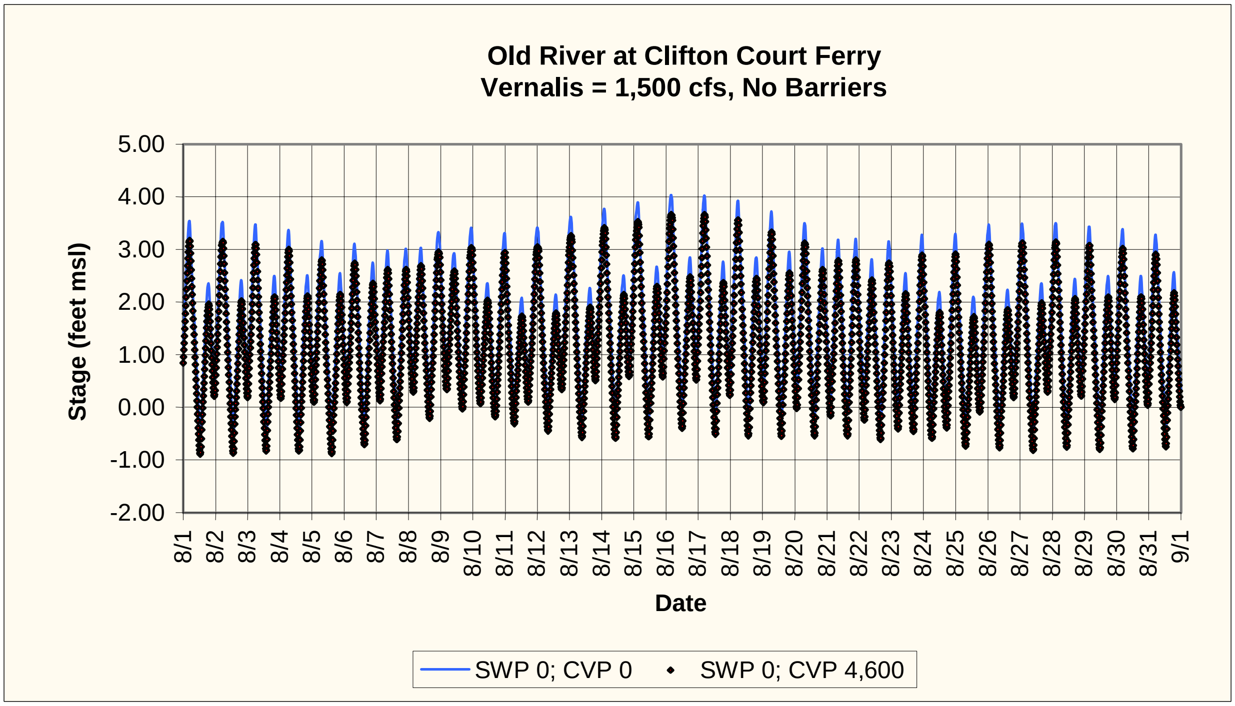
Figure D-90

Simulated Flow at Head of Old River with CVP Pumping Only



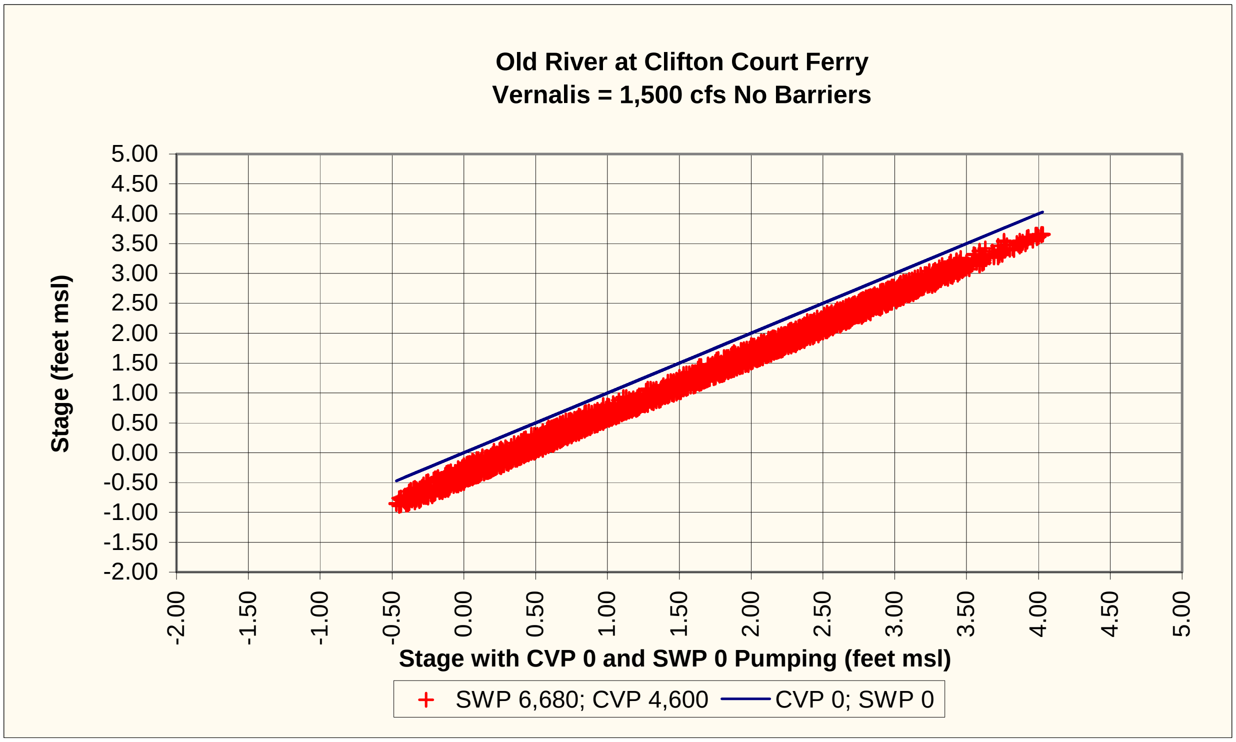


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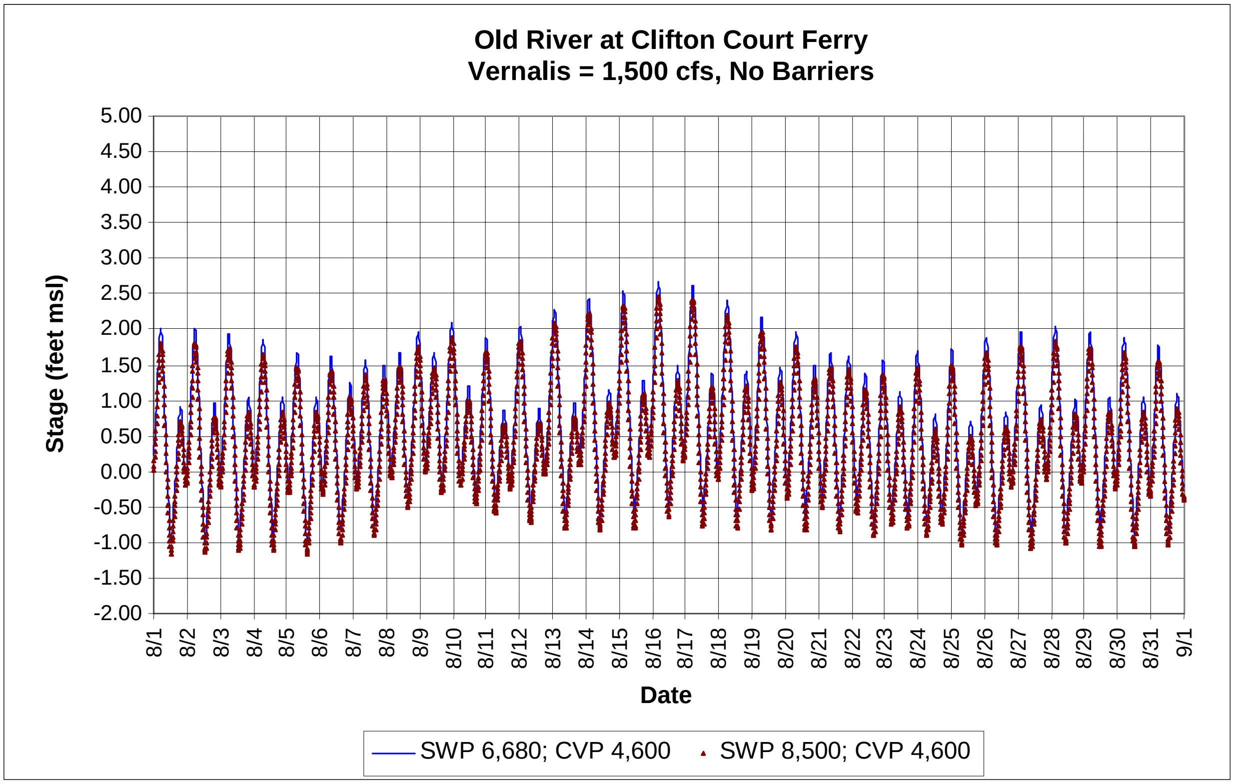
Figure D-91

Simulated Water Surface Elevation (Stage) in Old River at Clifton Court Ferry with CVP Pumping Only



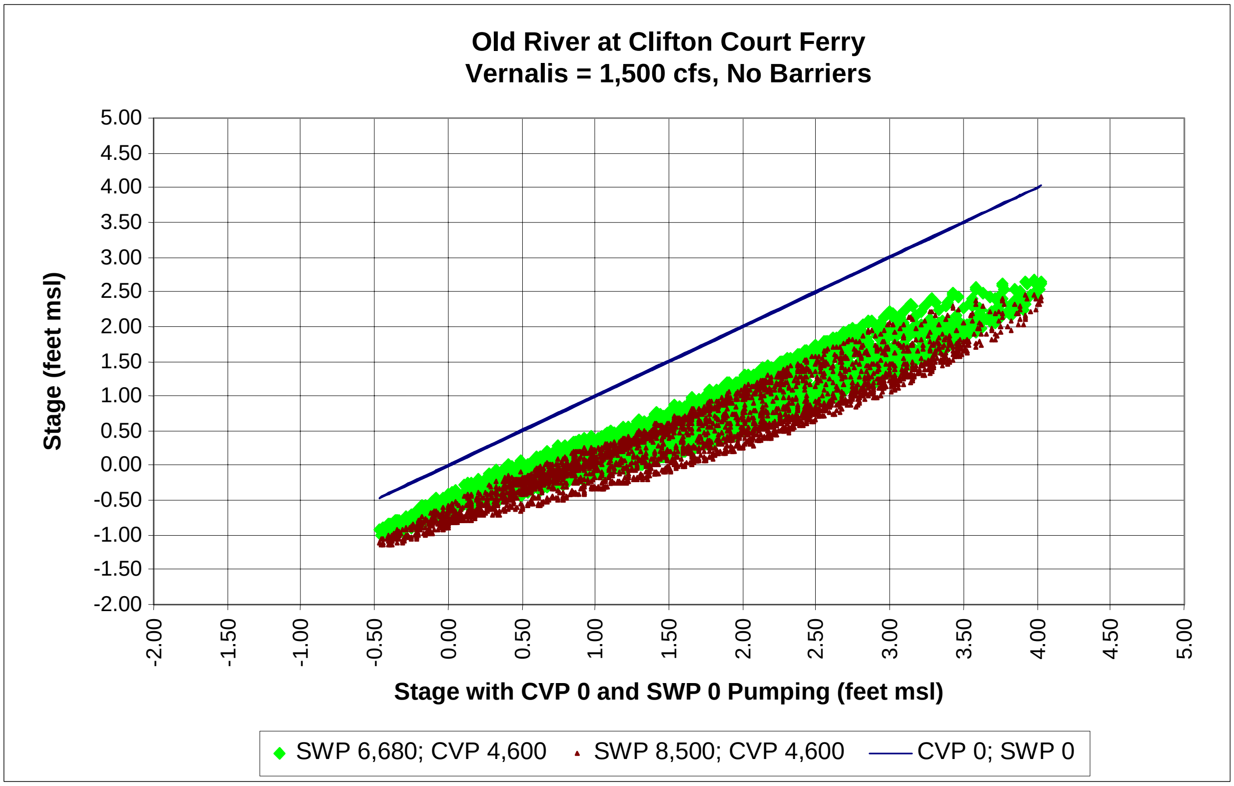


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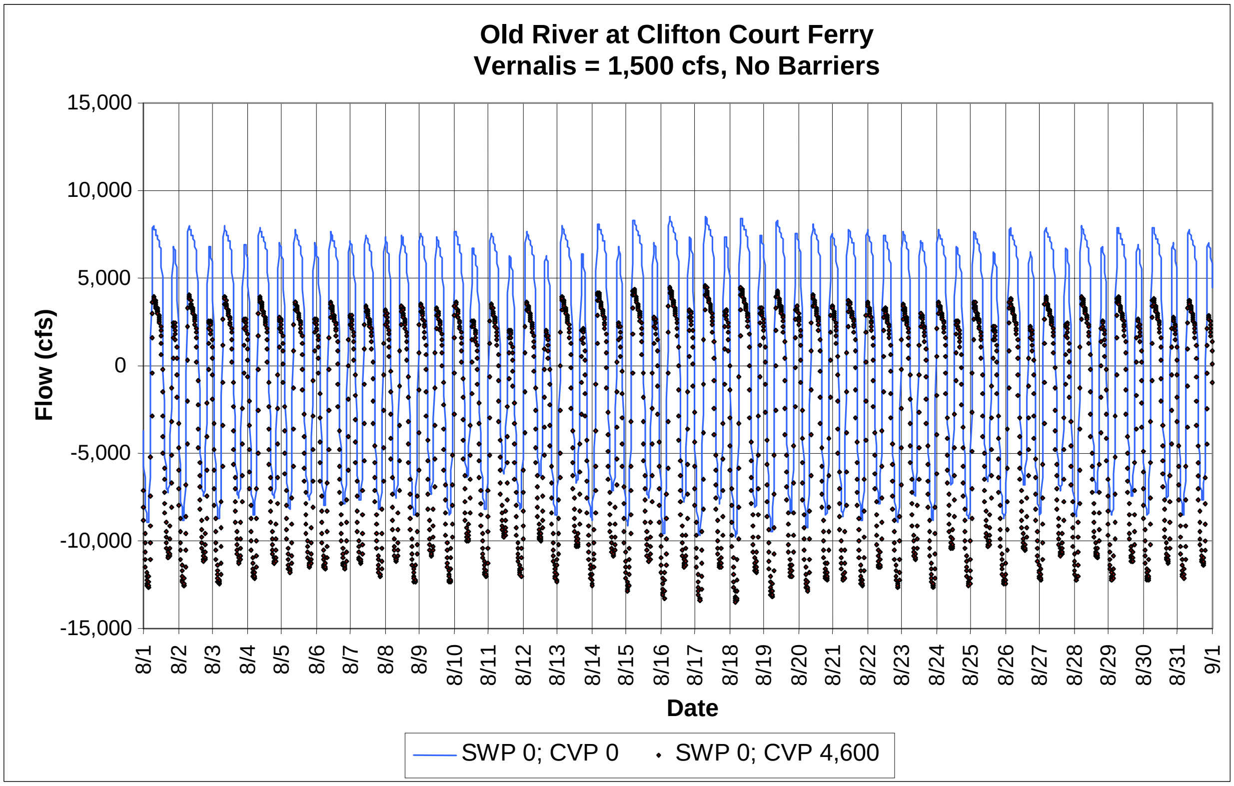
Figure D-92

**Simulated Water Surface Elevation (Stage) in
Old River at Clifton Court Ferry with CVP and SWP Pumping**



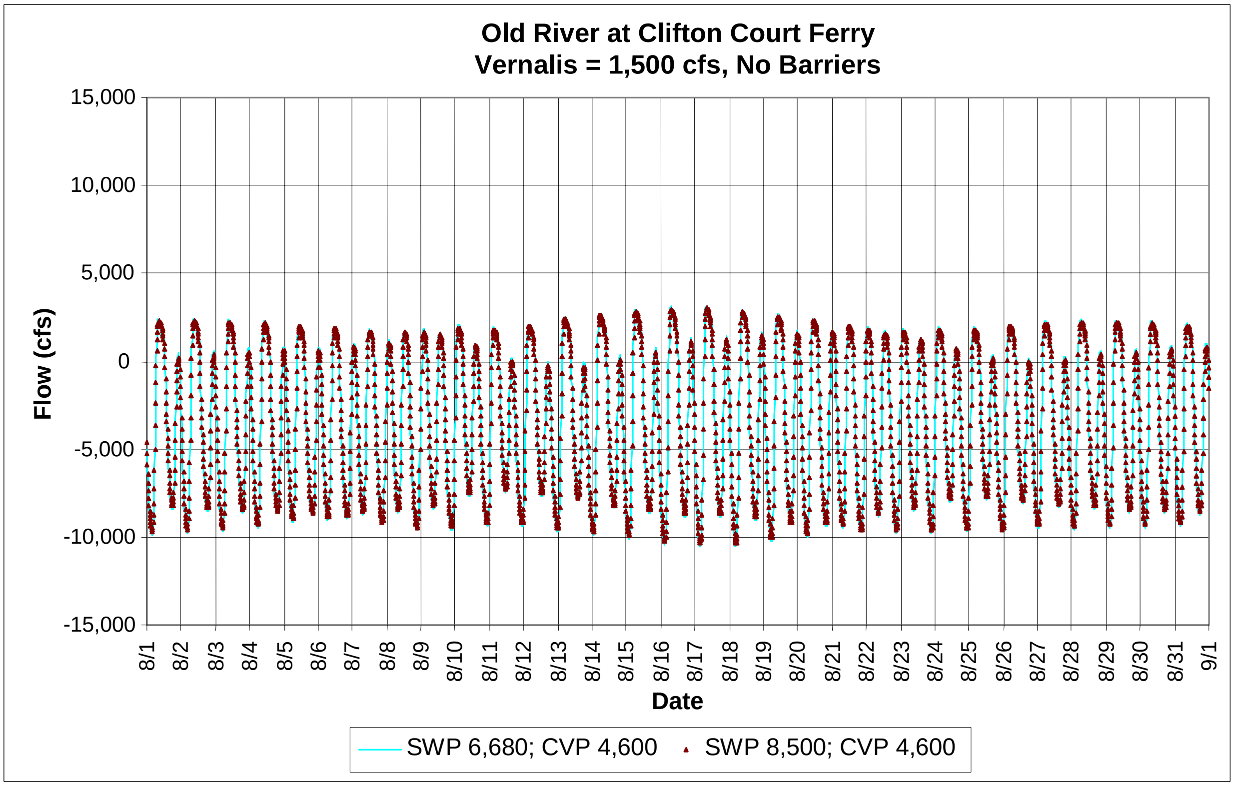


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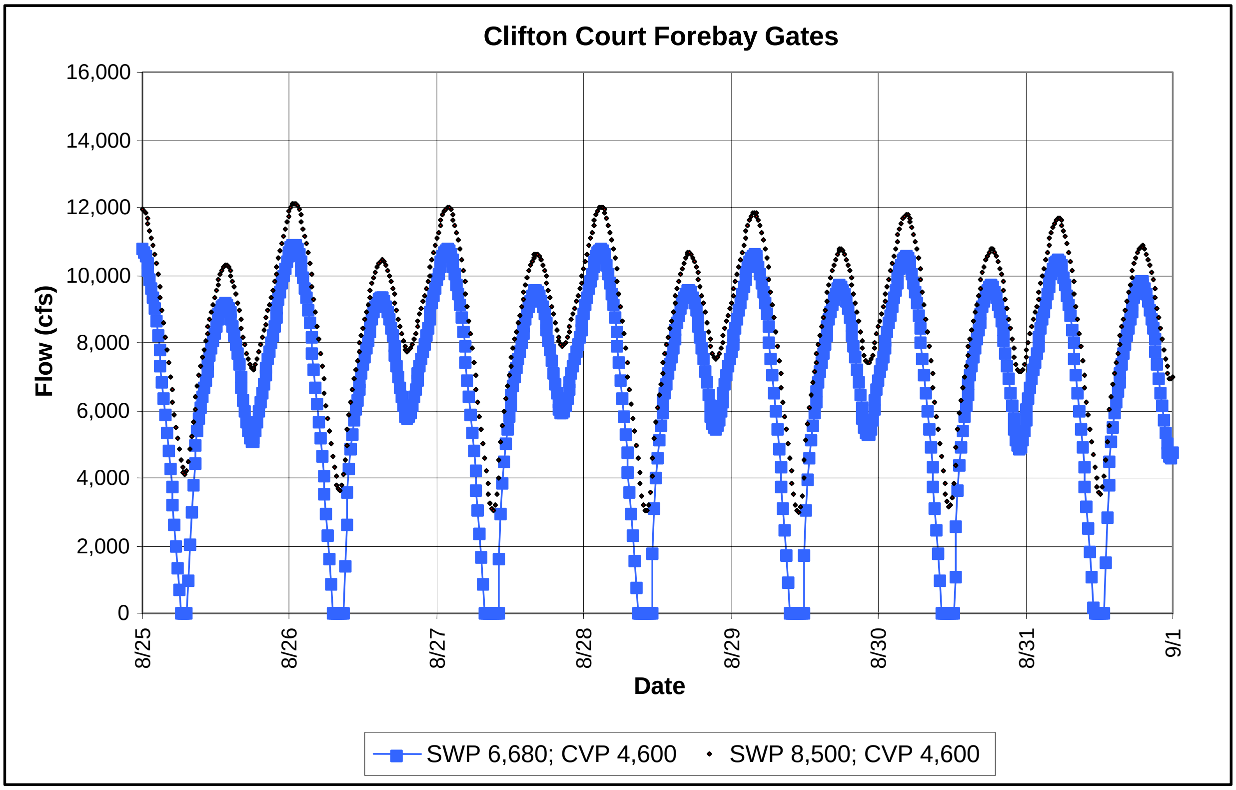
Figure D-93

Simulated Flow in Old River at Clifton Court Ferry with CVP and SWP Pumping



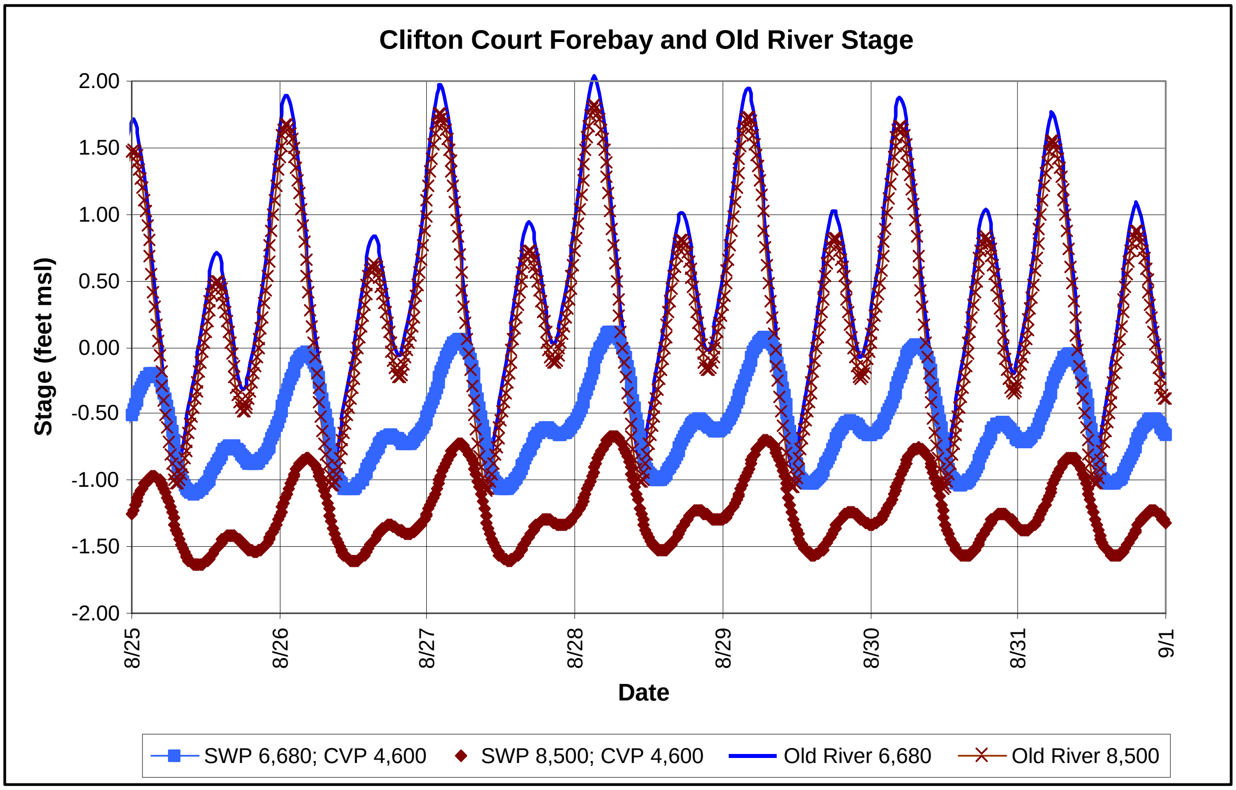


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Figure D-94

Simulated Flow and Stage at Clifton Court Forebay

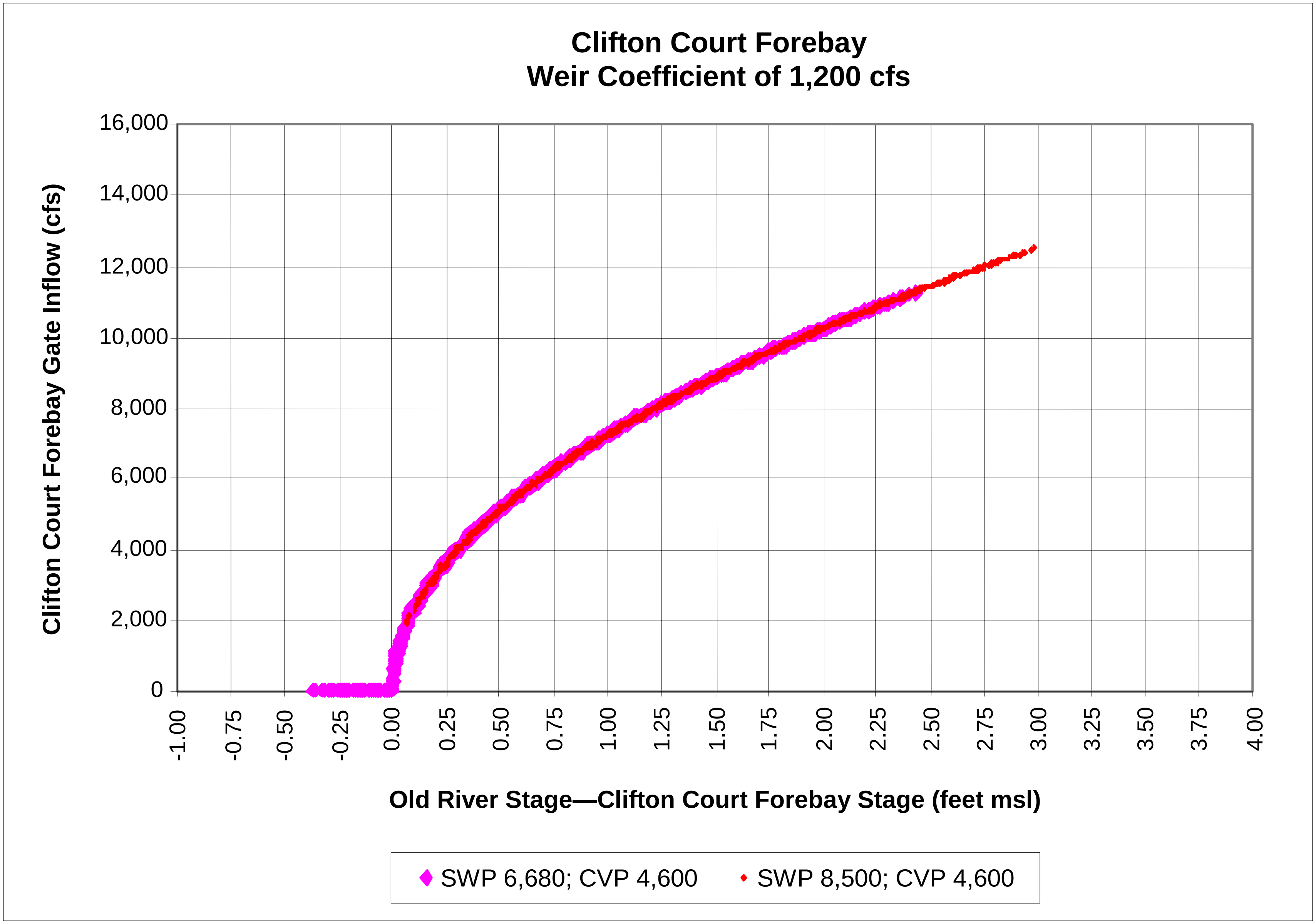

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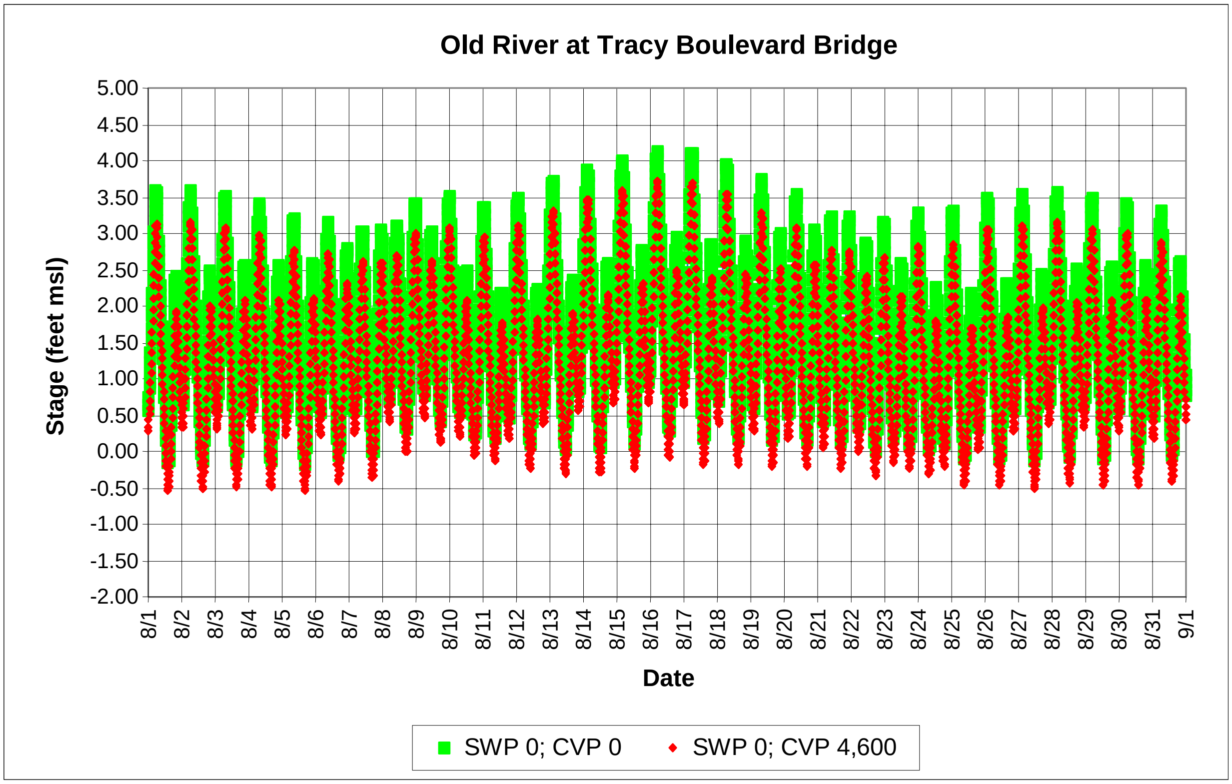
Figure D-95

Simulated Clifton Court Forebay Weir Coefficient



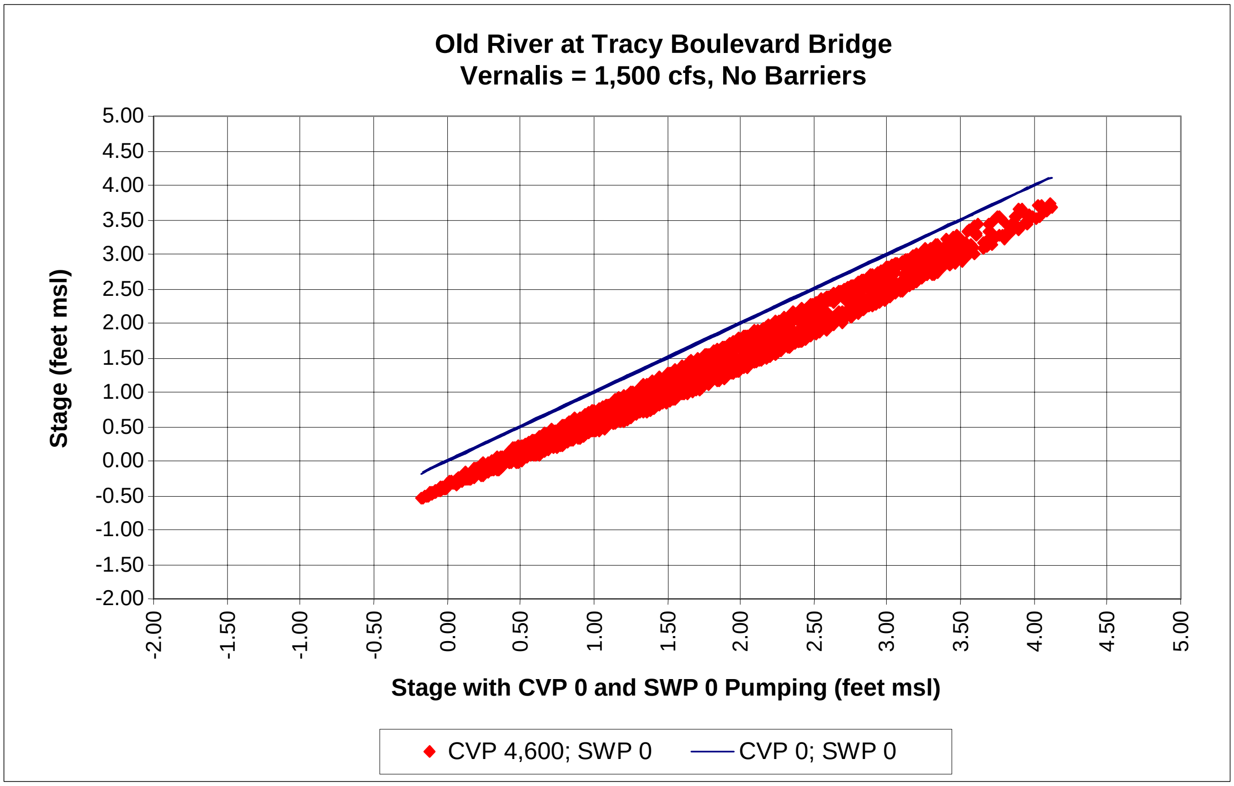


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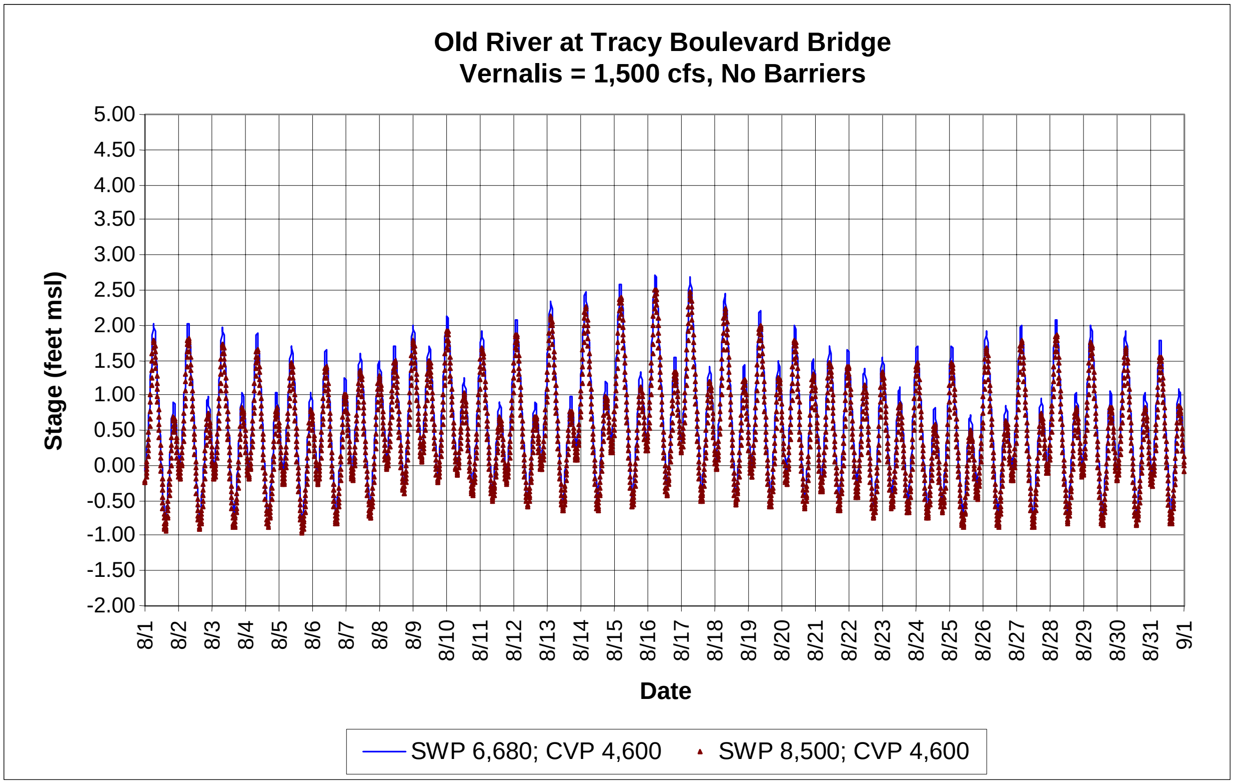
Figure D-96

Simulated Water-Surface Elevation (Stage) in Old River at Tracy Boulevard Bridge with CVP Pumping Only



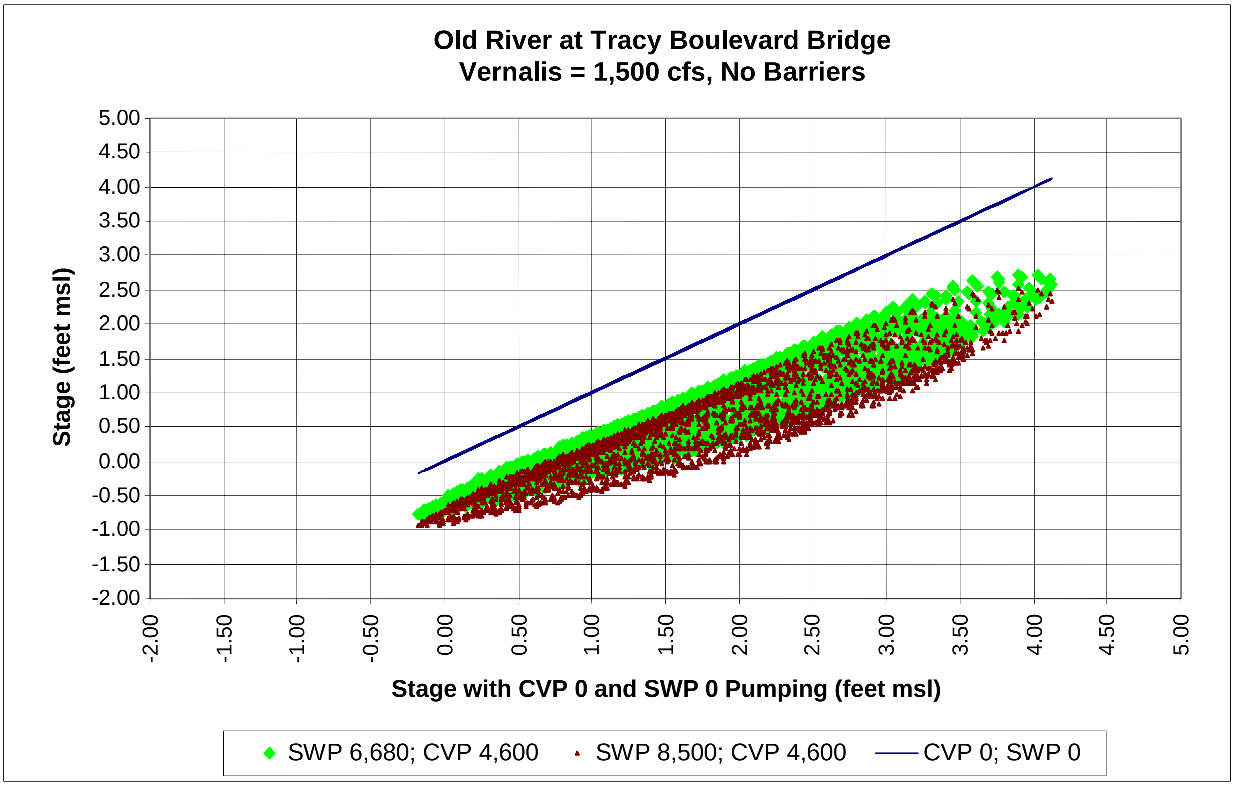


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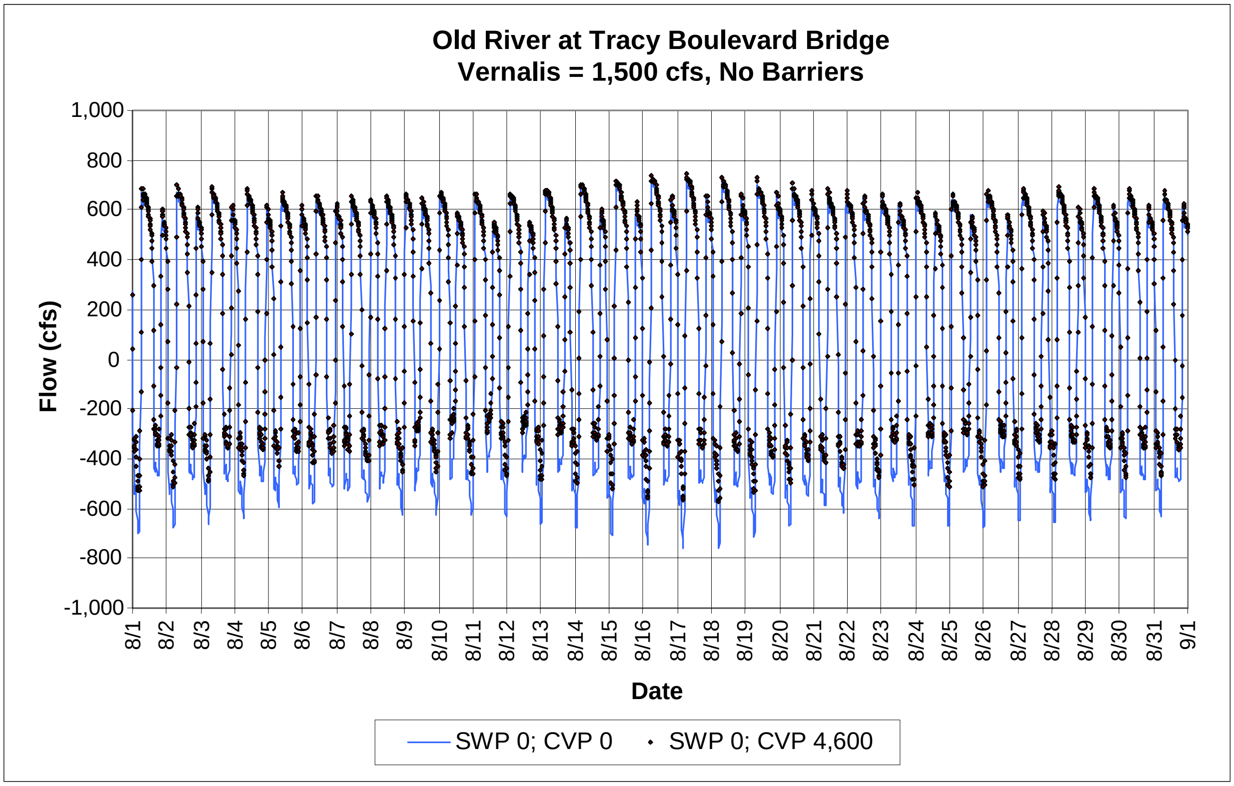
Figure D-97

Simulated Water Surface Elevation (Stage) in Old River at Tracy Boulevard Bridge with CVP and SWP Pumping



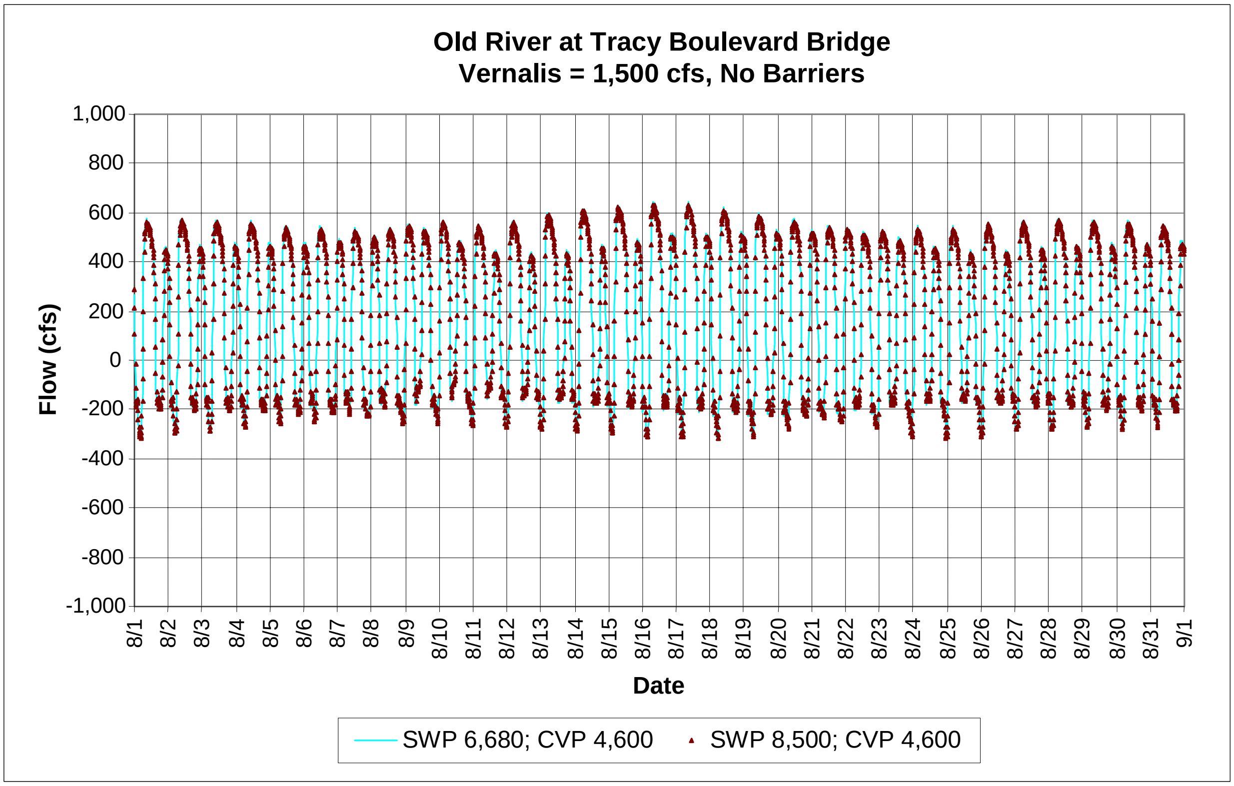
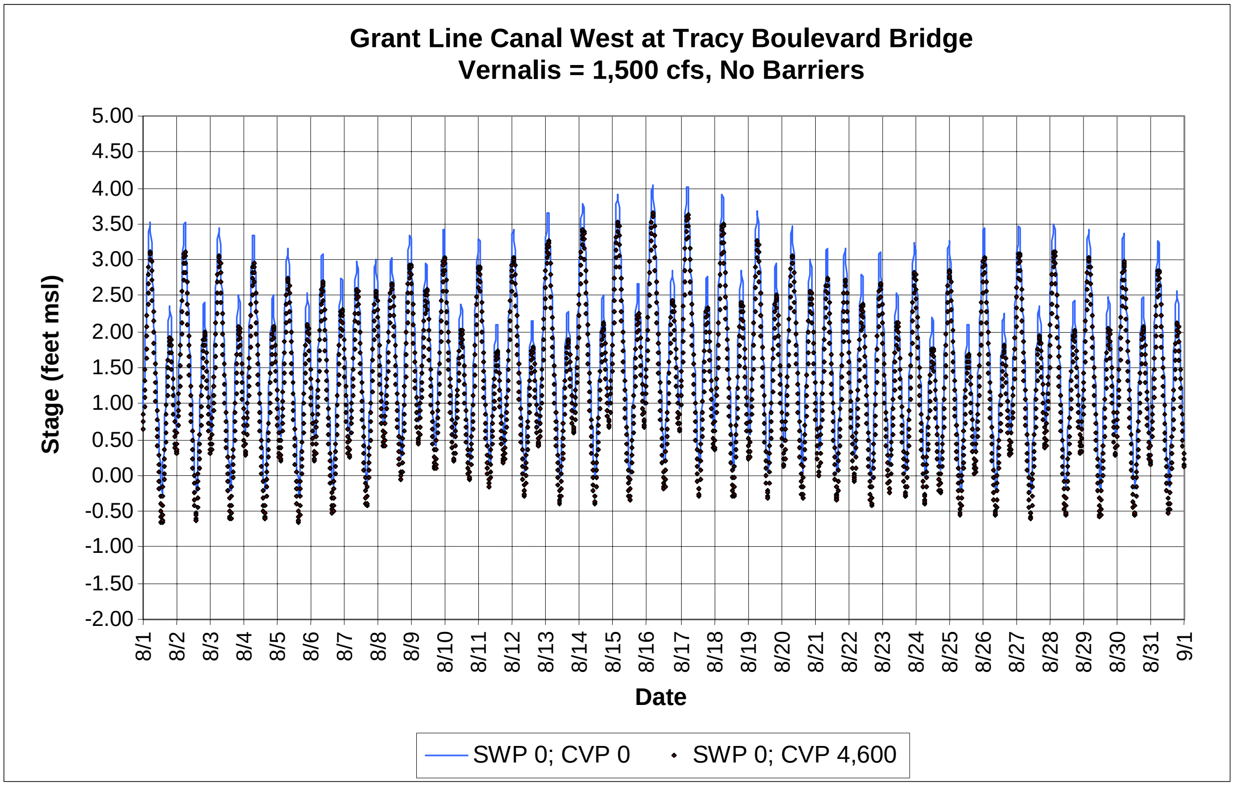


Figure D-98

Simulated Flow in Old River at Tracy Boulevard Bridge with CVP and SWP Pumping



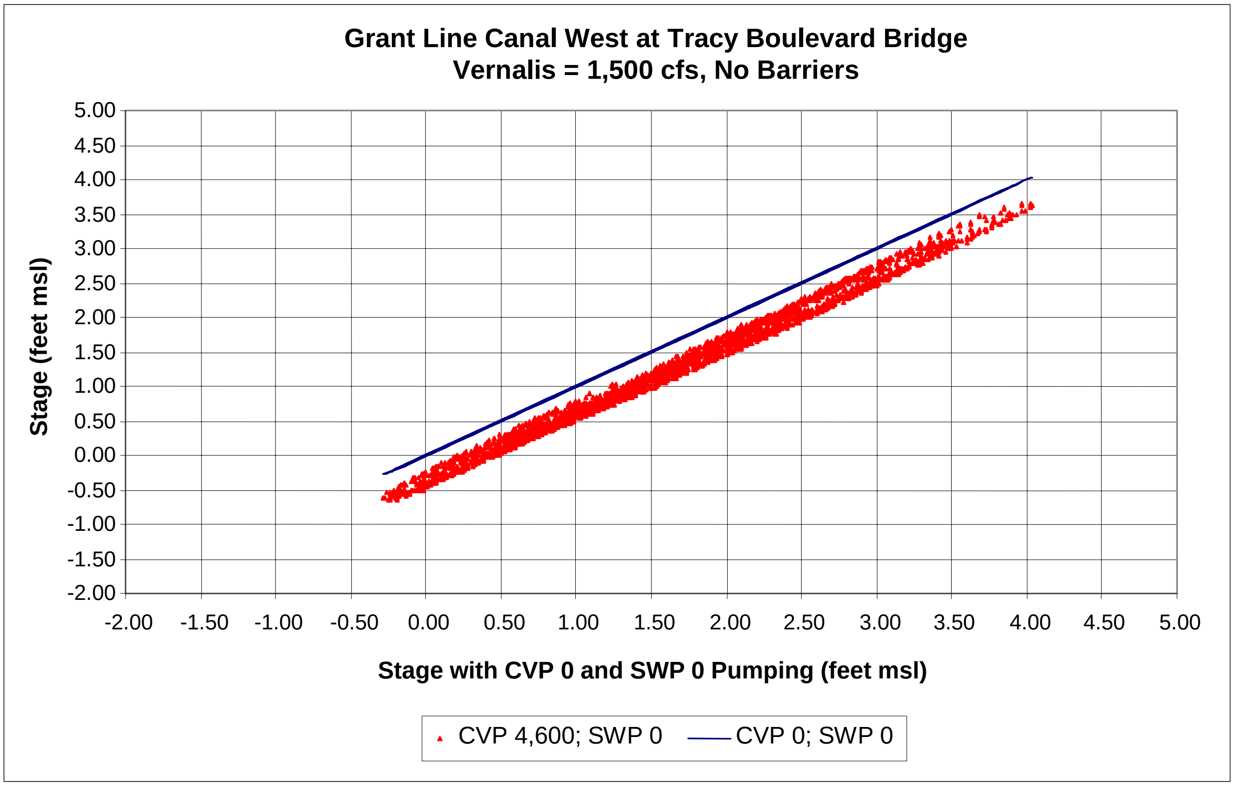


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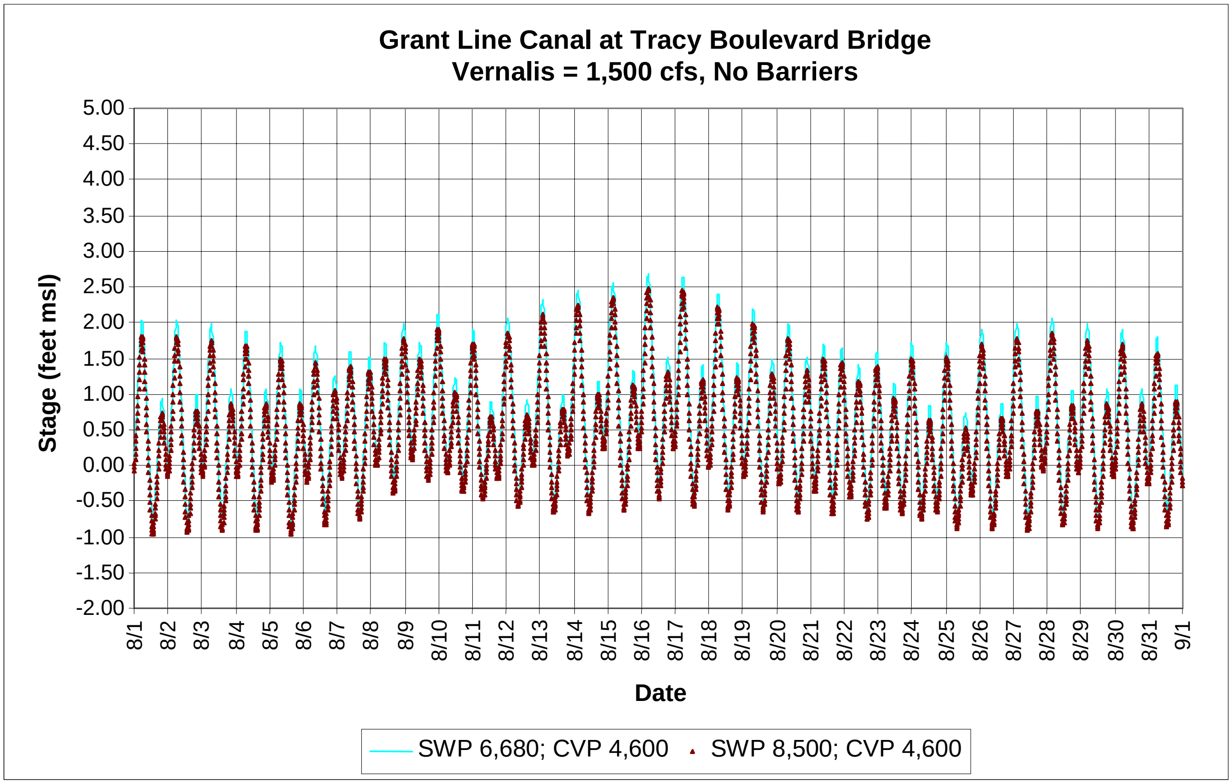
Figure D-99

Simulated Water Surface Elevation (Stage) in Grant Line Canal at Tracy Boulevard Bridge with CVP Pumping



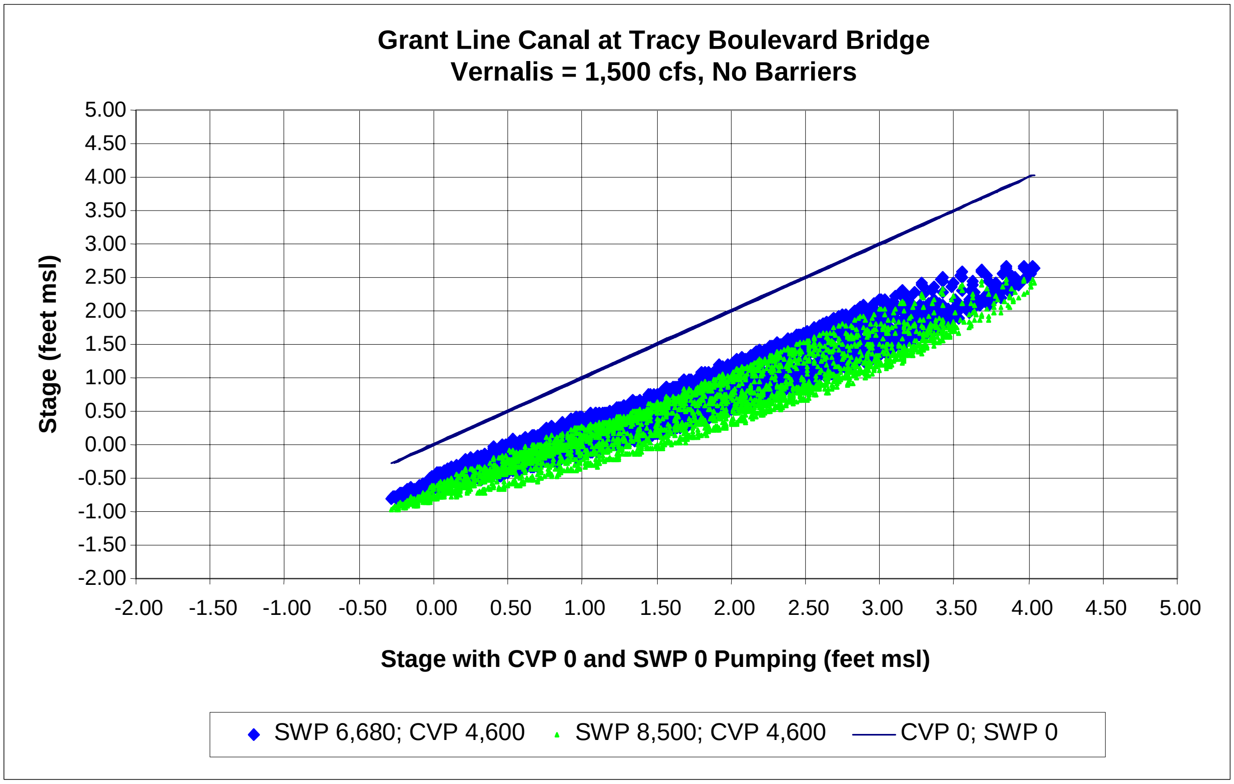


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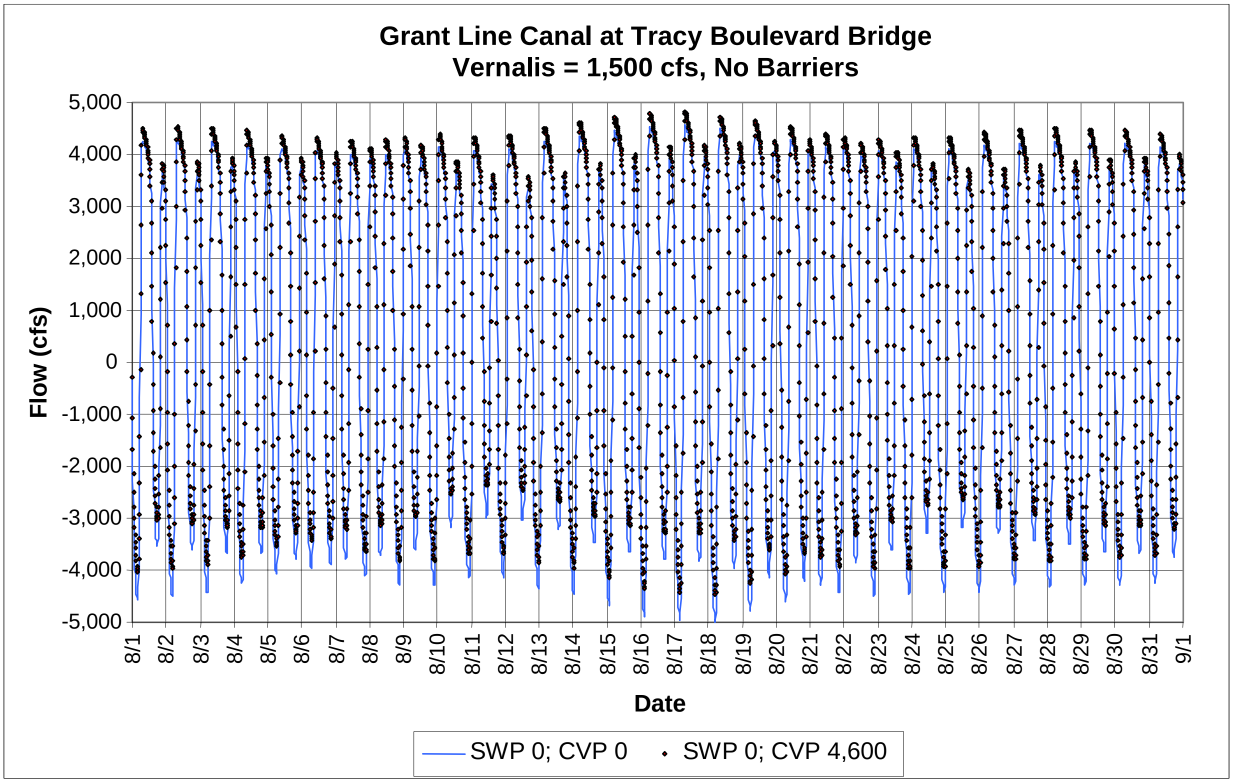
Figure D-100

Simulated Water Surface Elevation (Stage) in Grant Line Canal at Tracy Boulevard Bridge with CVP and SWP Pumping



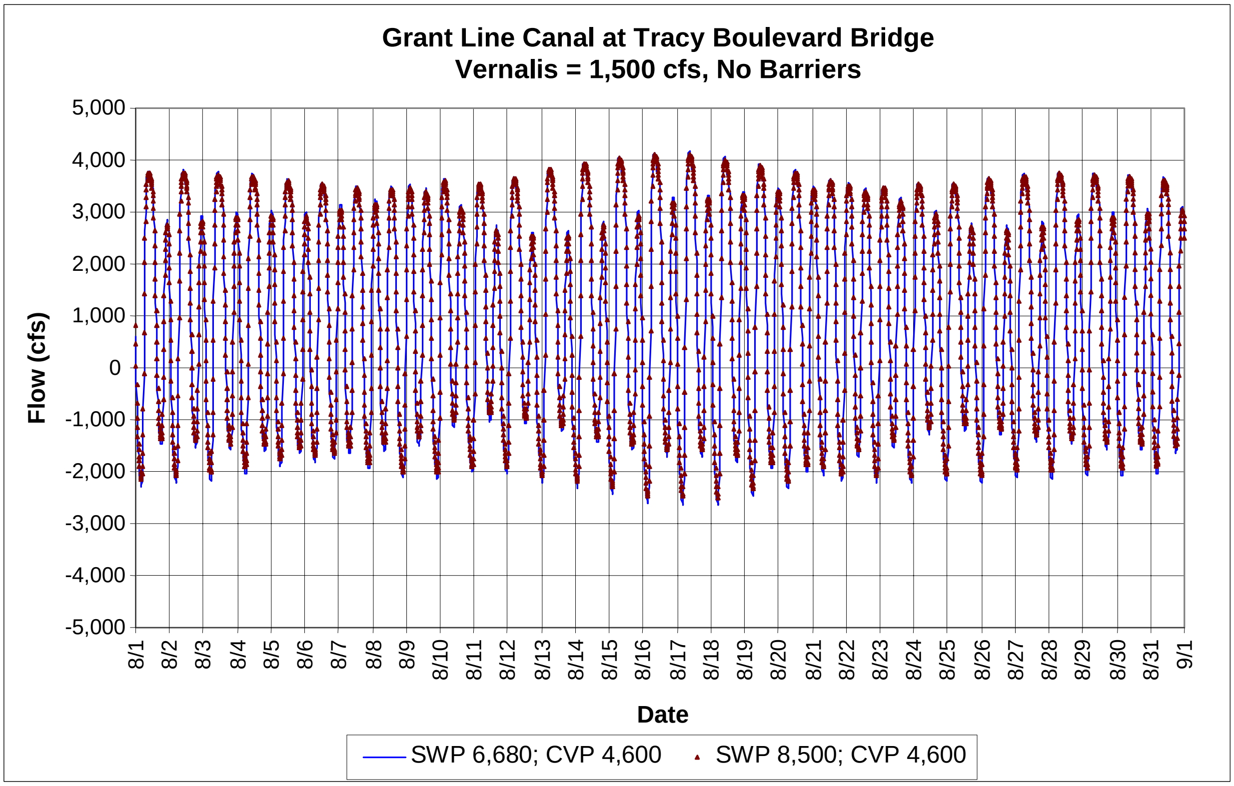


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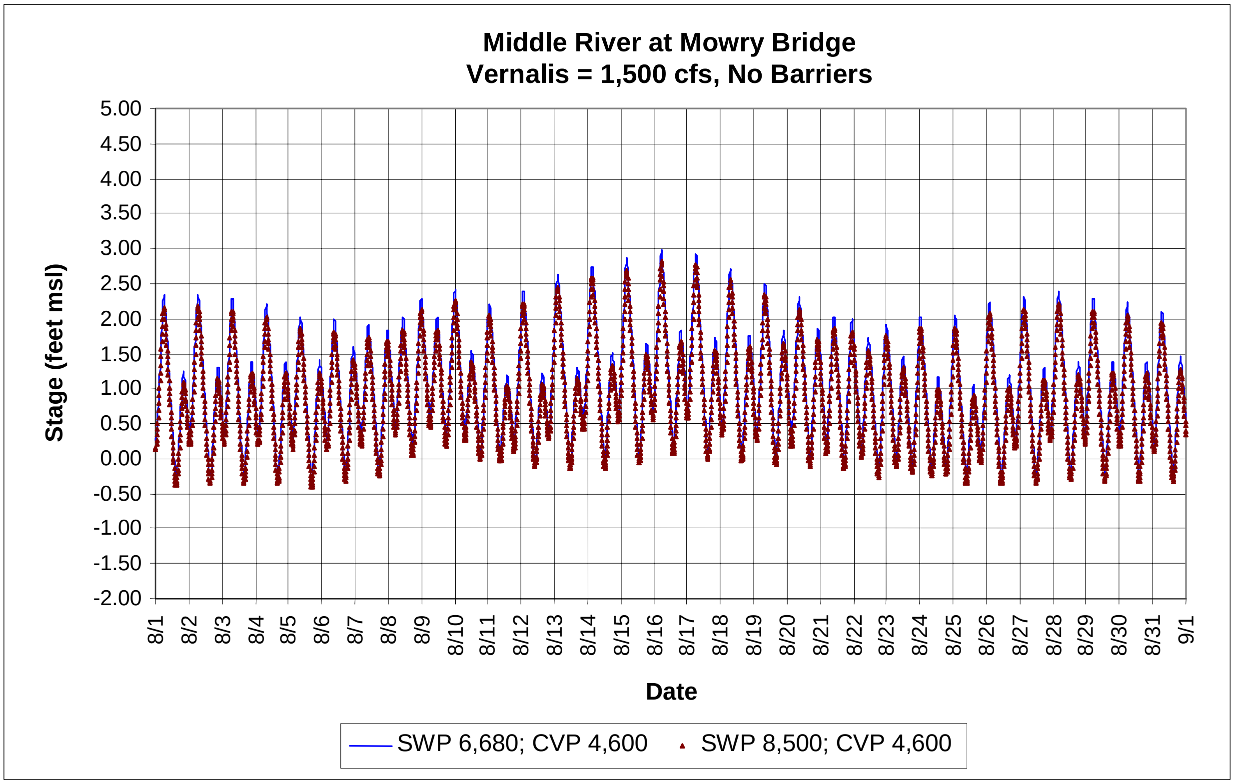
Figure D-101

Simulated Flow in Grant Line Canal at Tracy Boulevard Bridge with CVP and SWP Pumping



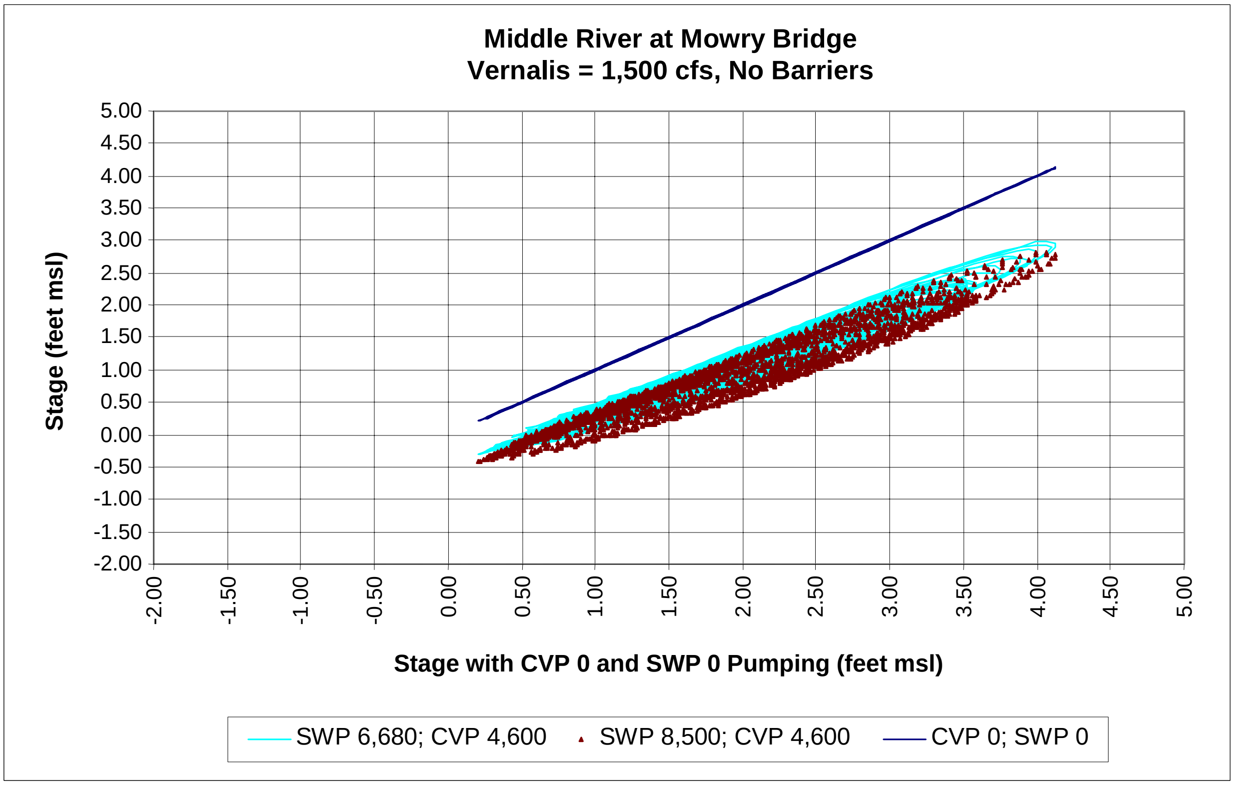


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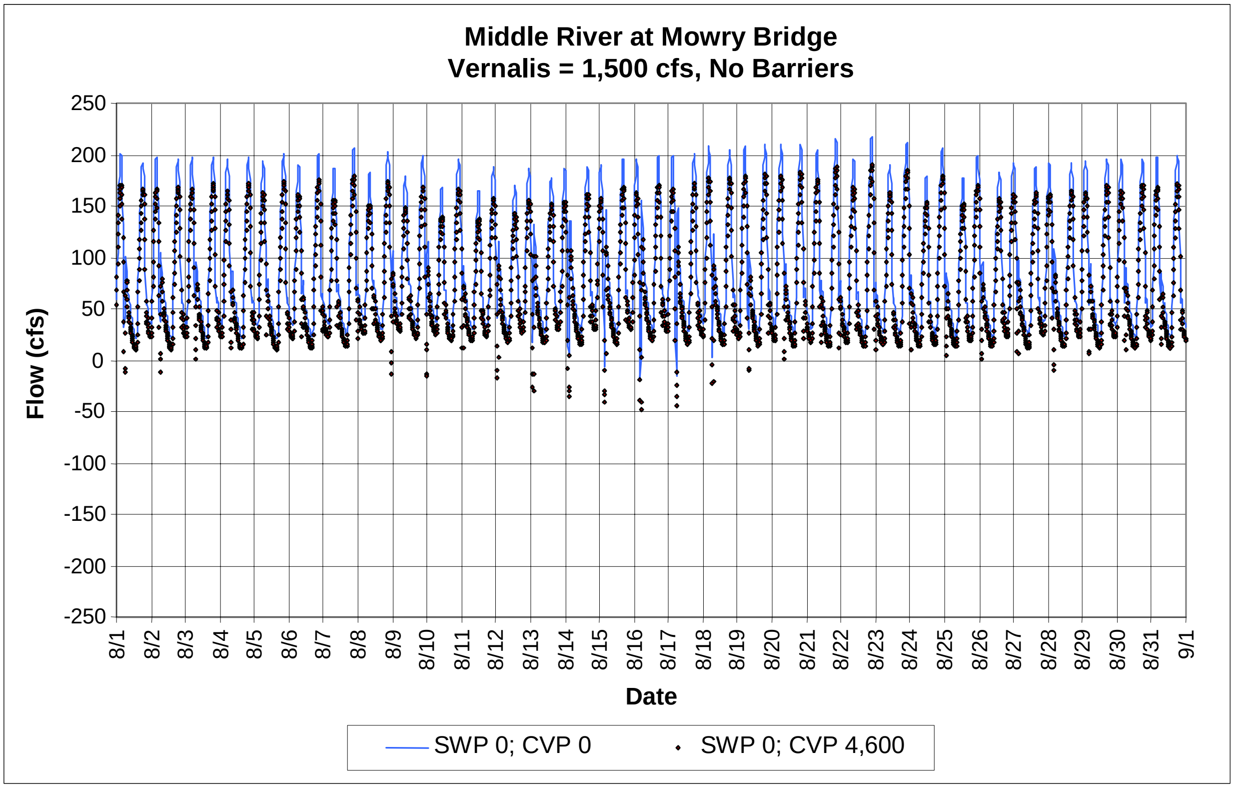
Figure D-102

Simulated Water Surface Elevation (Stage) in Middle River at Mowry Bridge with CVP and SWP Pumping



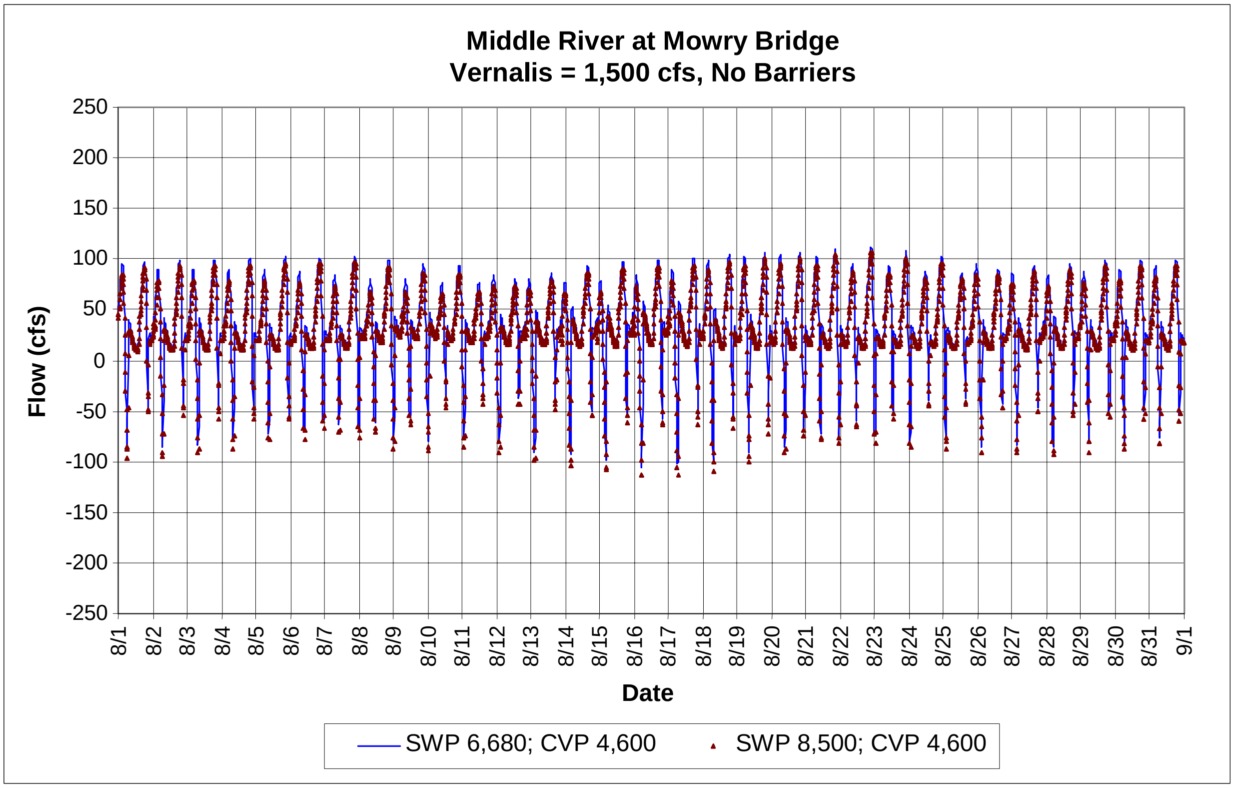


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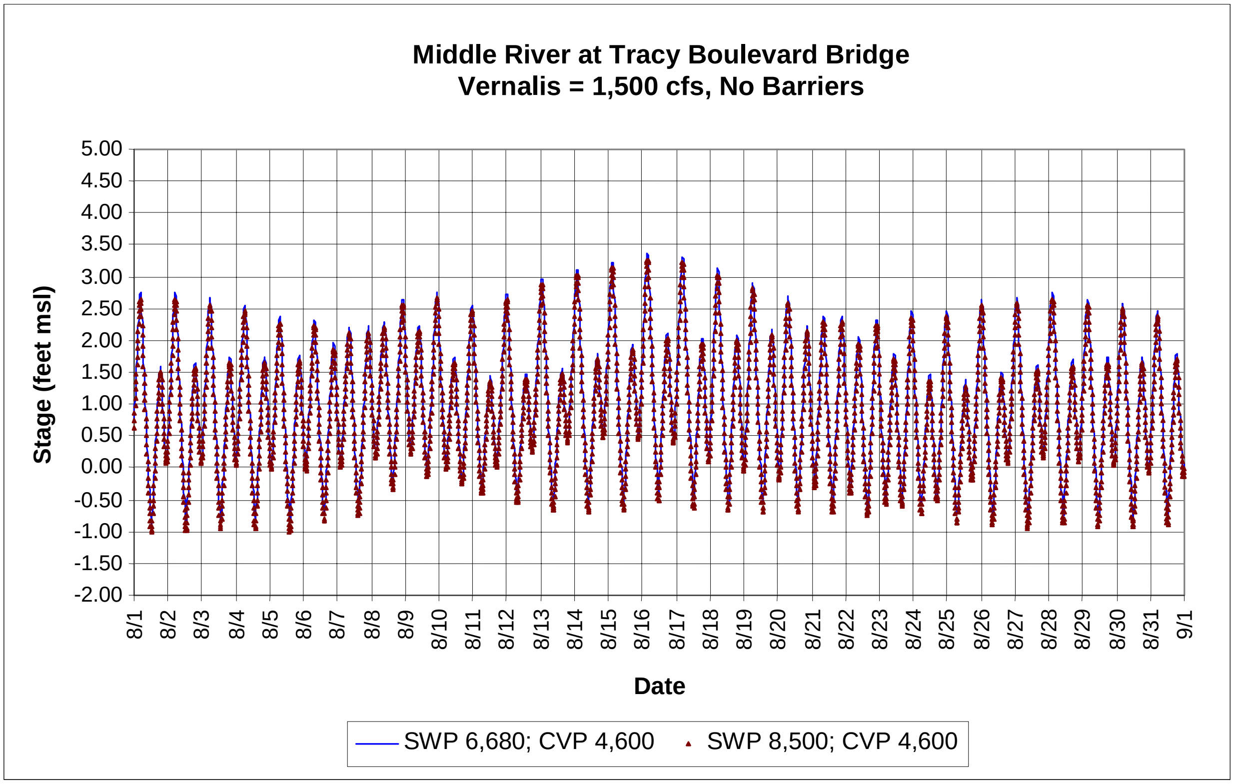
Figure D-103

Simulated Flow in Middle River at Mowry Bridge with CVP and SWP Pumping



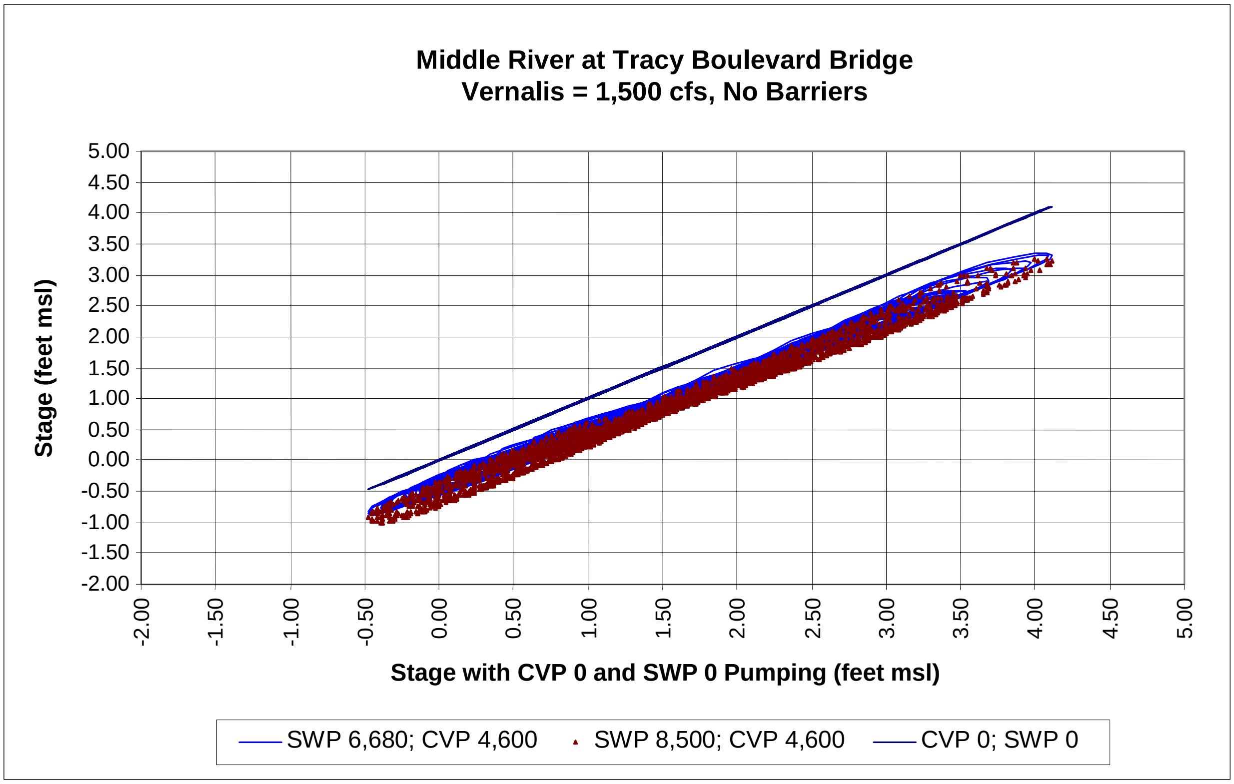


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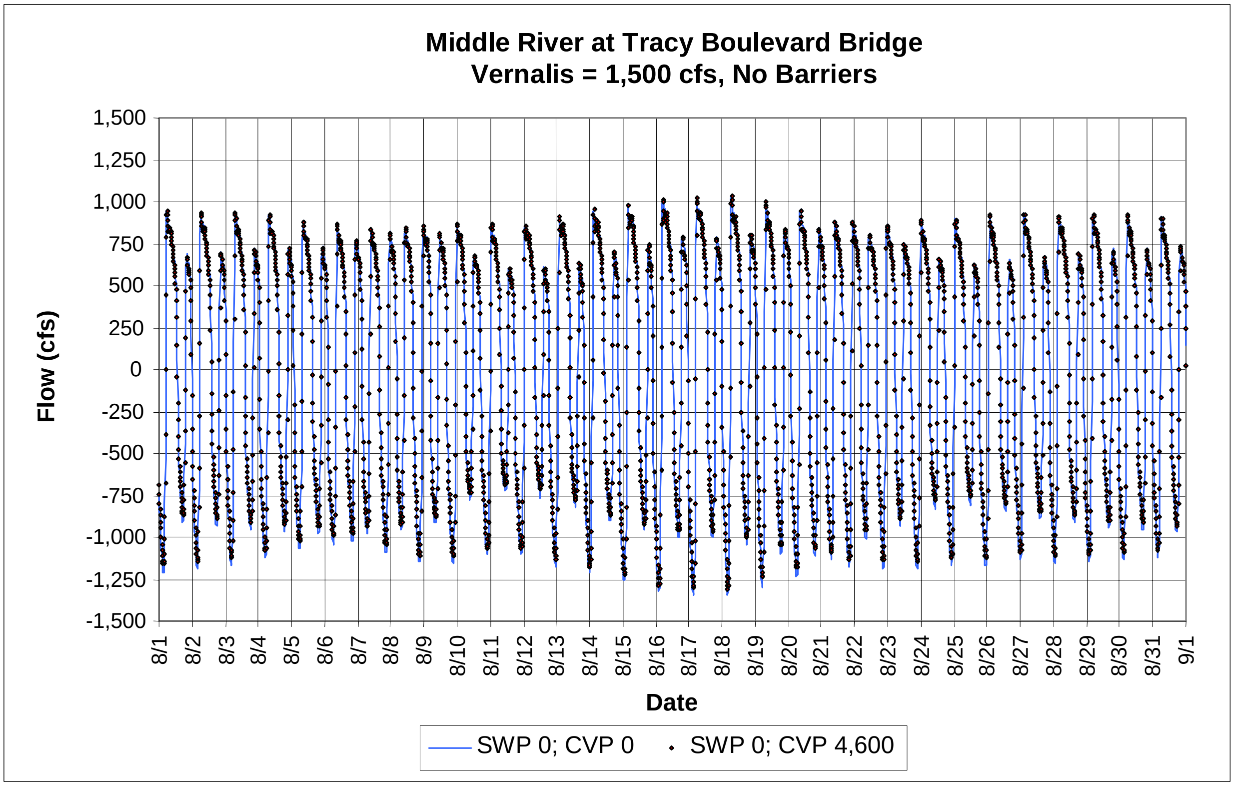
Figure D-104

Simulated Water Surface Elevation (Stage) in Middle River at Tracy Boulevard Bridge with CVP and SWP Pumping



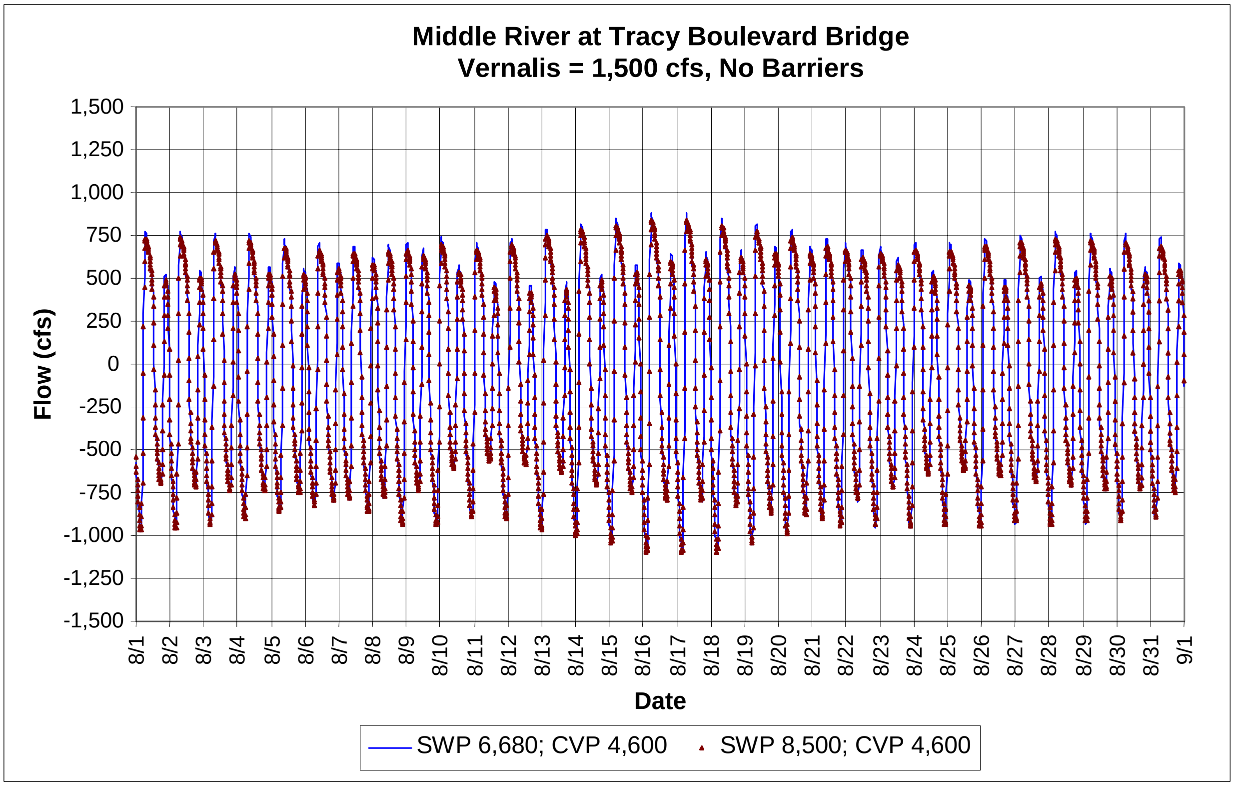


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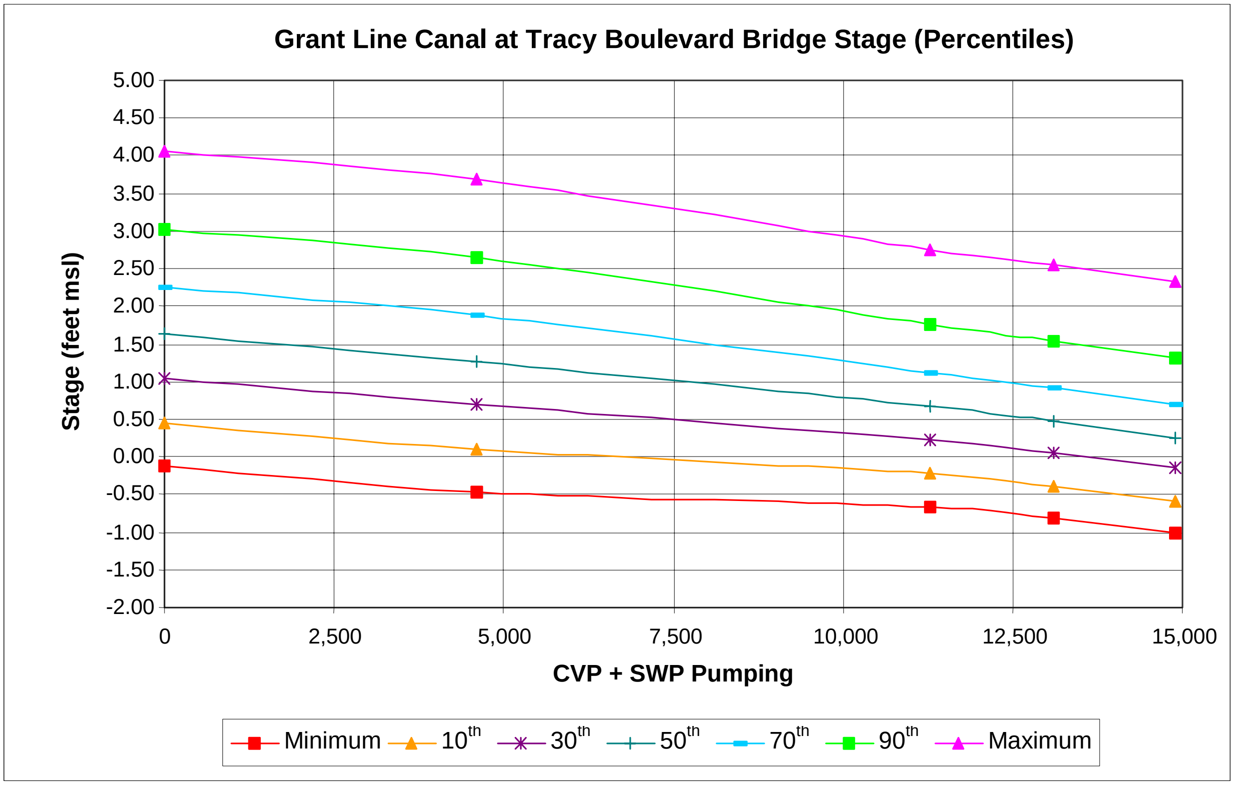
Figure D-105

Simulated Flow in Middle River at Tracy Boulevard Bridge with CVP and SWP Pumping



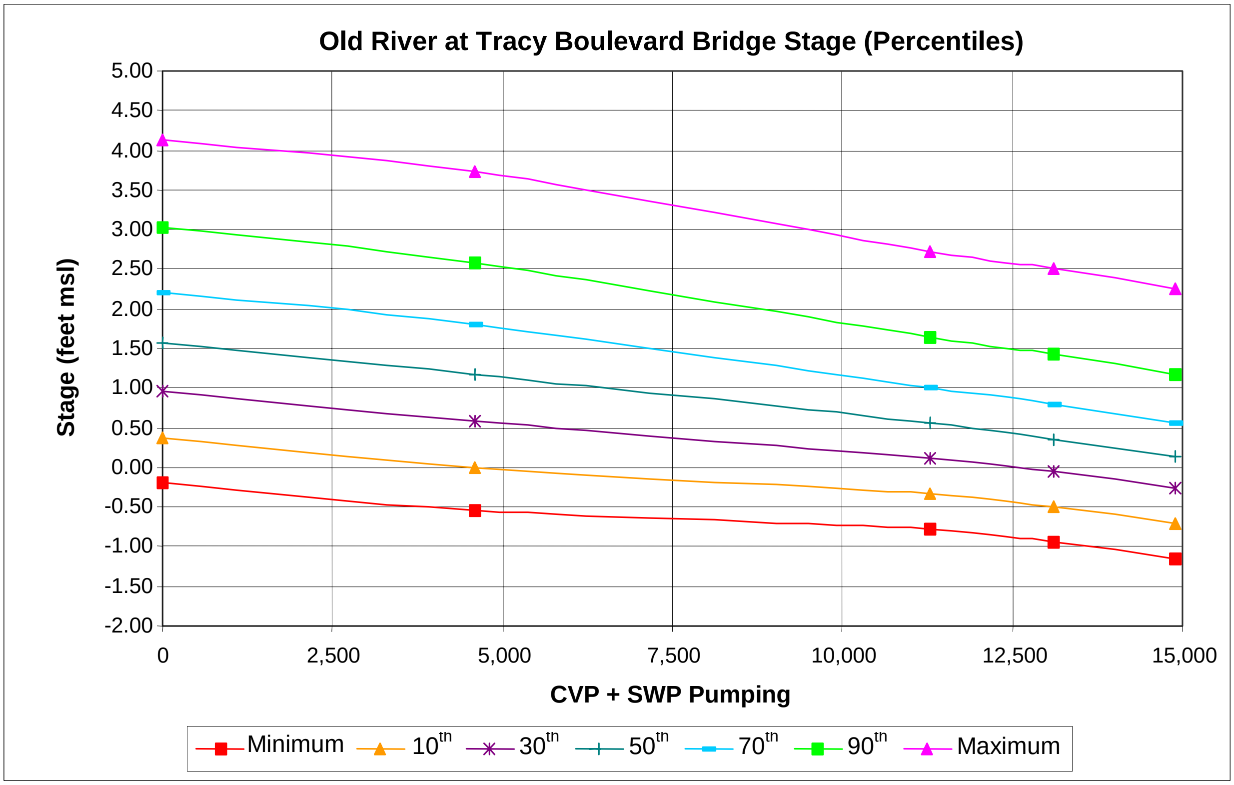


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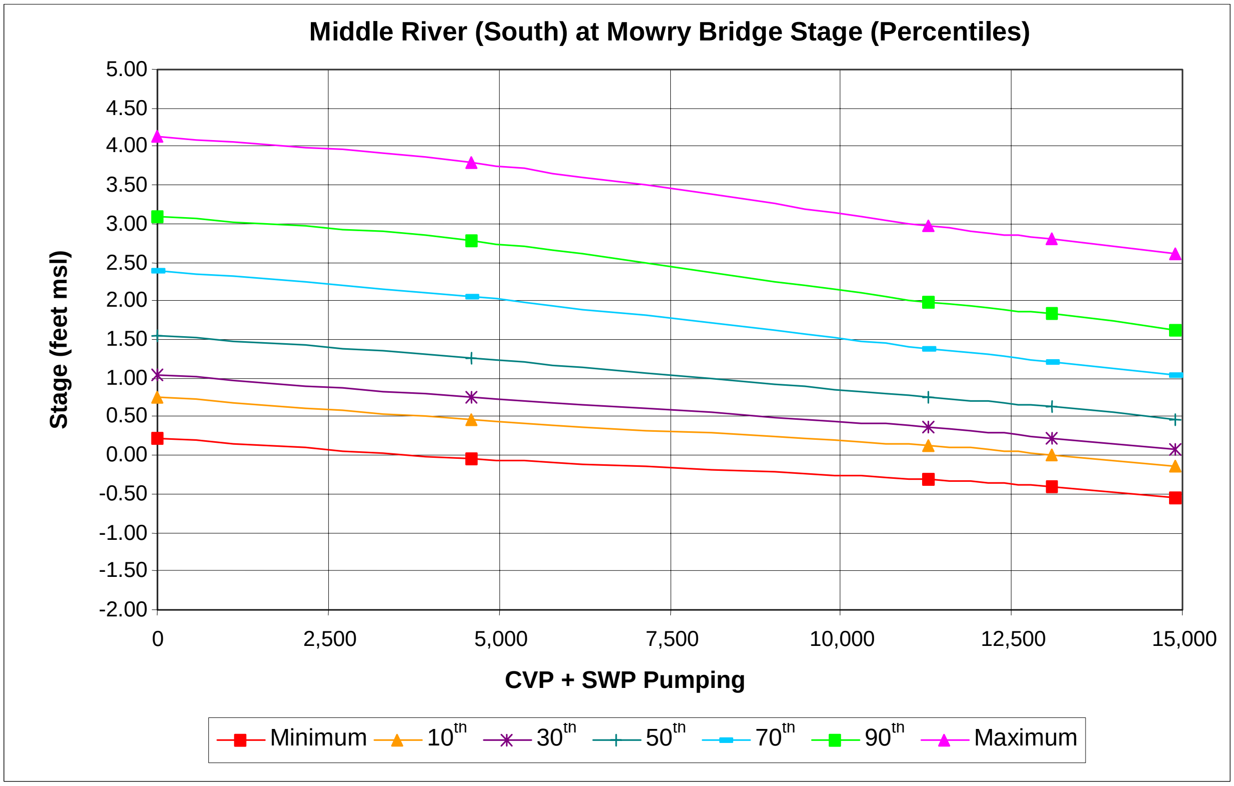
Figure D-106

Simulated Monthly Water-Surface Elevation (Stage) in Grant Line Canal and Old River at Tracy Boulevard Bridge for Combined CVP and SWP Pumping



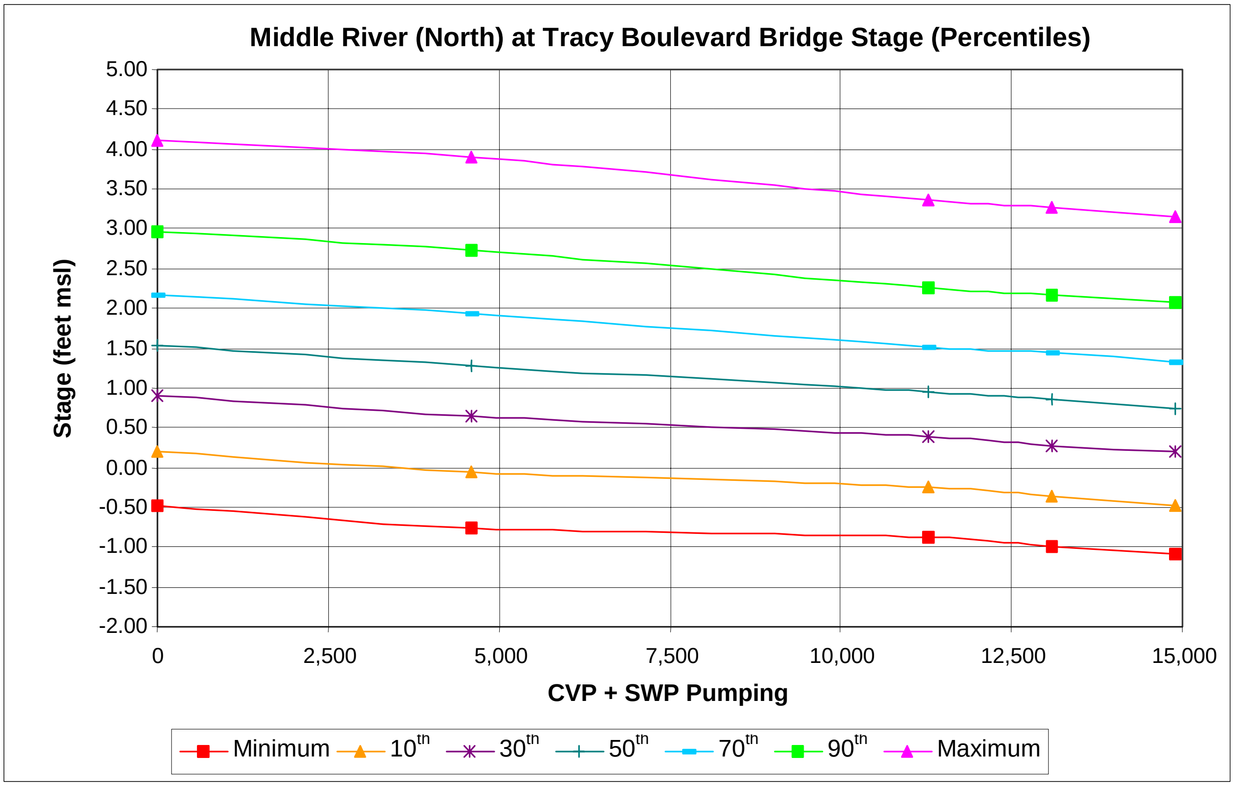


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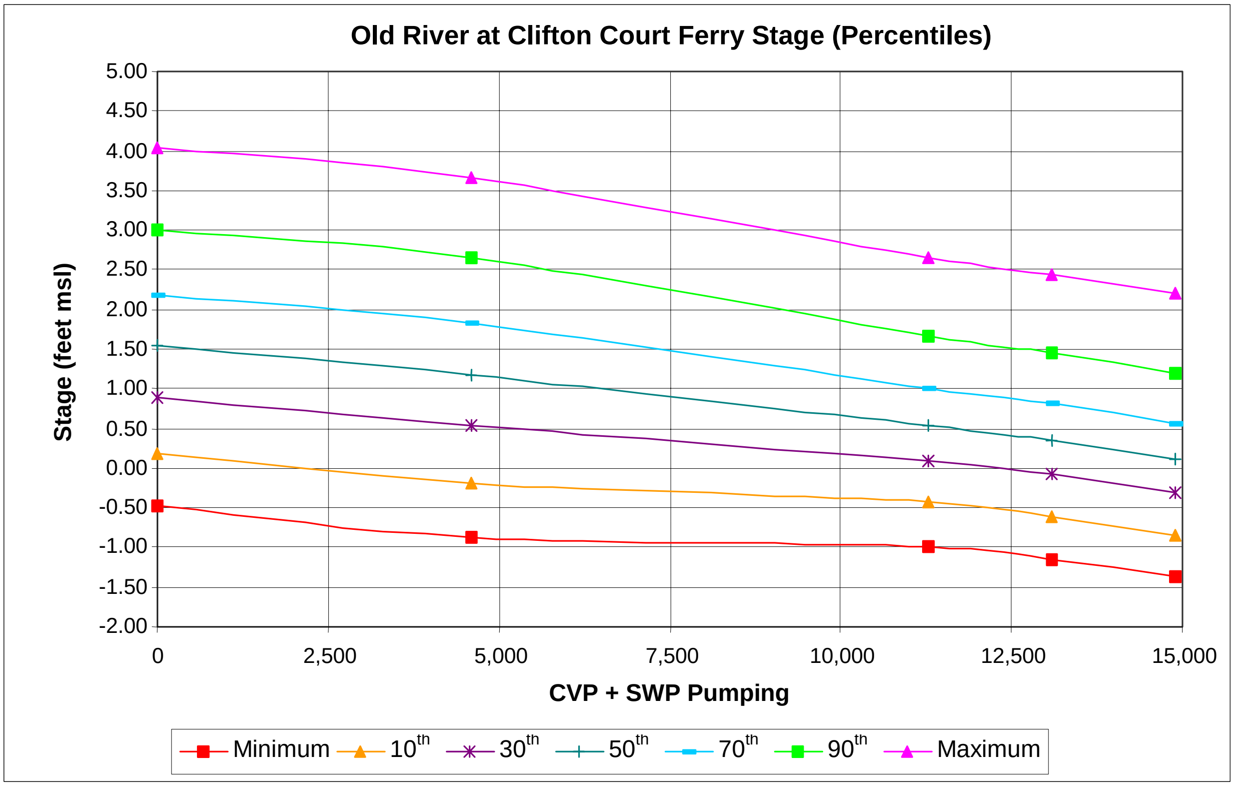
Figure D-107

Simulated Monthly Water-Surface Elevation (Stage) in Middle River at Mowry and Tracy Boulevard Bridges for Combined CVP and SWP Pumping



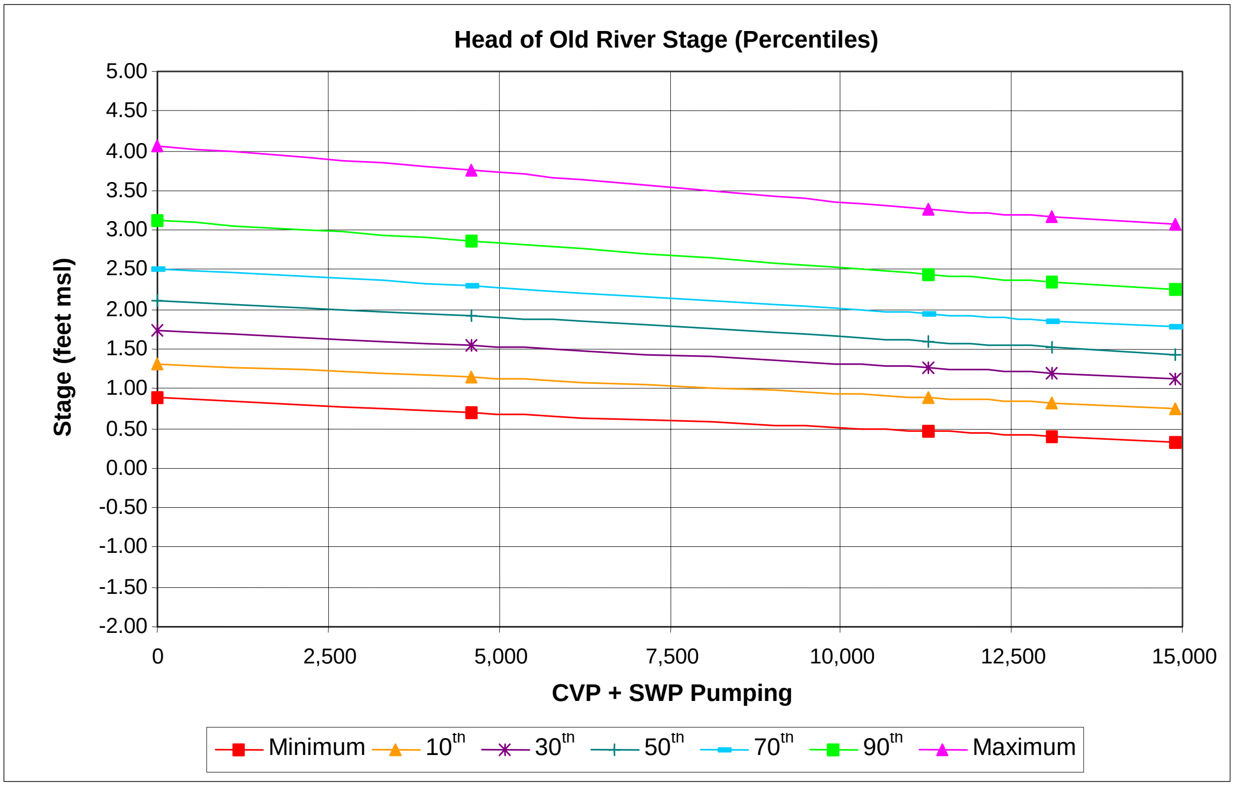


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Figure D-108

Simulated Monthly Water-Surface Elevation (Stage) in Old River at Clifton Court Ferry and at Head of Old River for Combined CVP and SWP Pumping

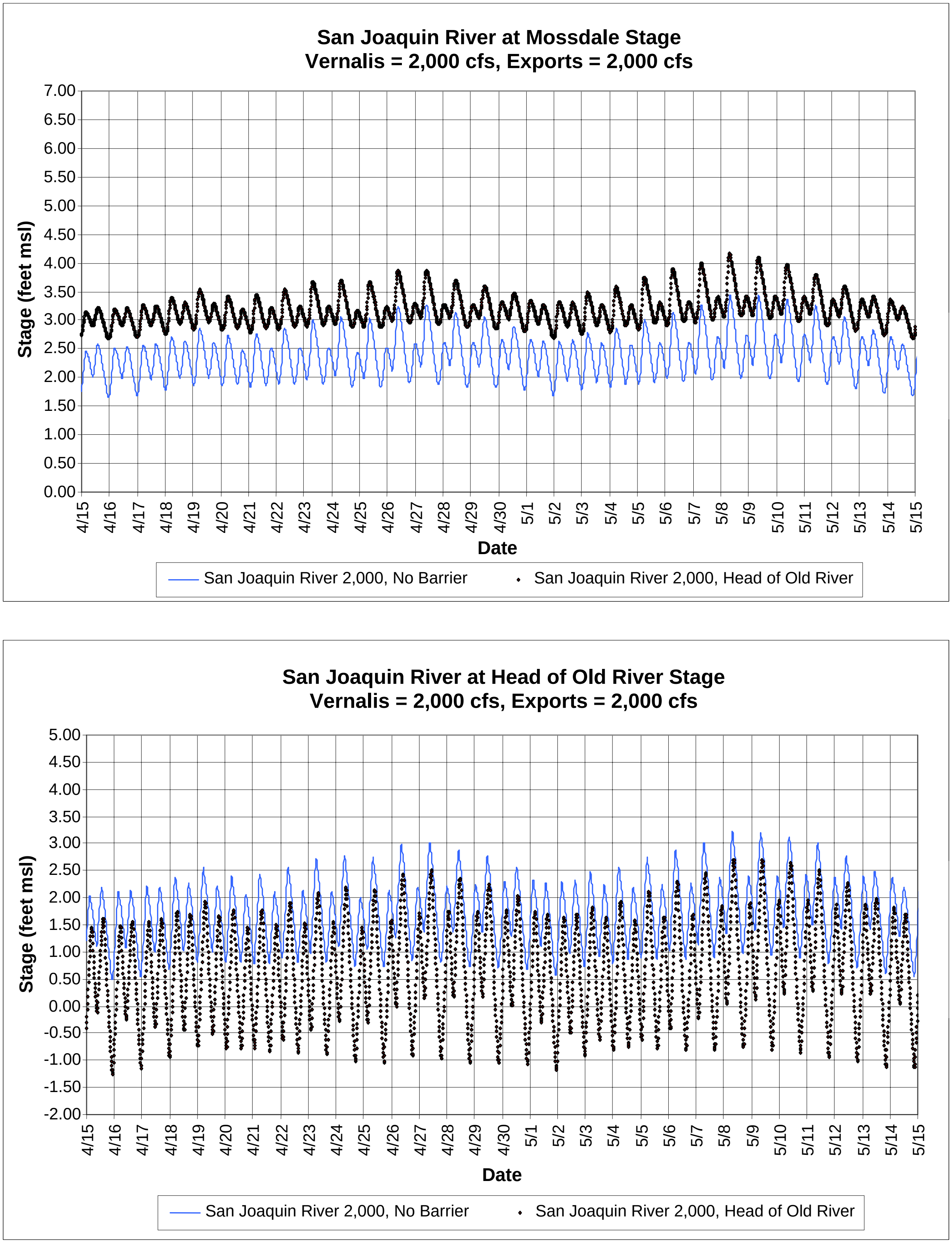

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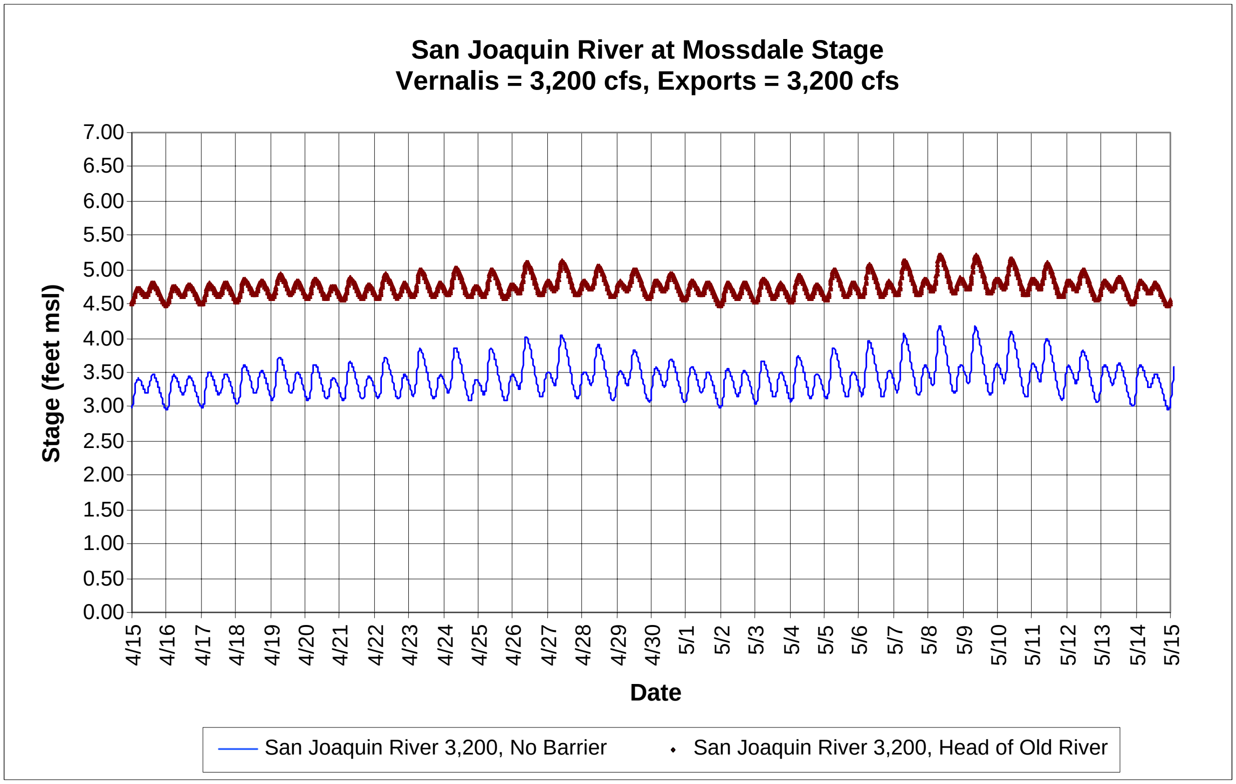
Figure D-109

Simulated Water-Surface Elevation (Stage) in the San Joaquin River at Mossdale and at Head of Old River with VAMP Flows at 2,000 cubic feet per second (cfs)



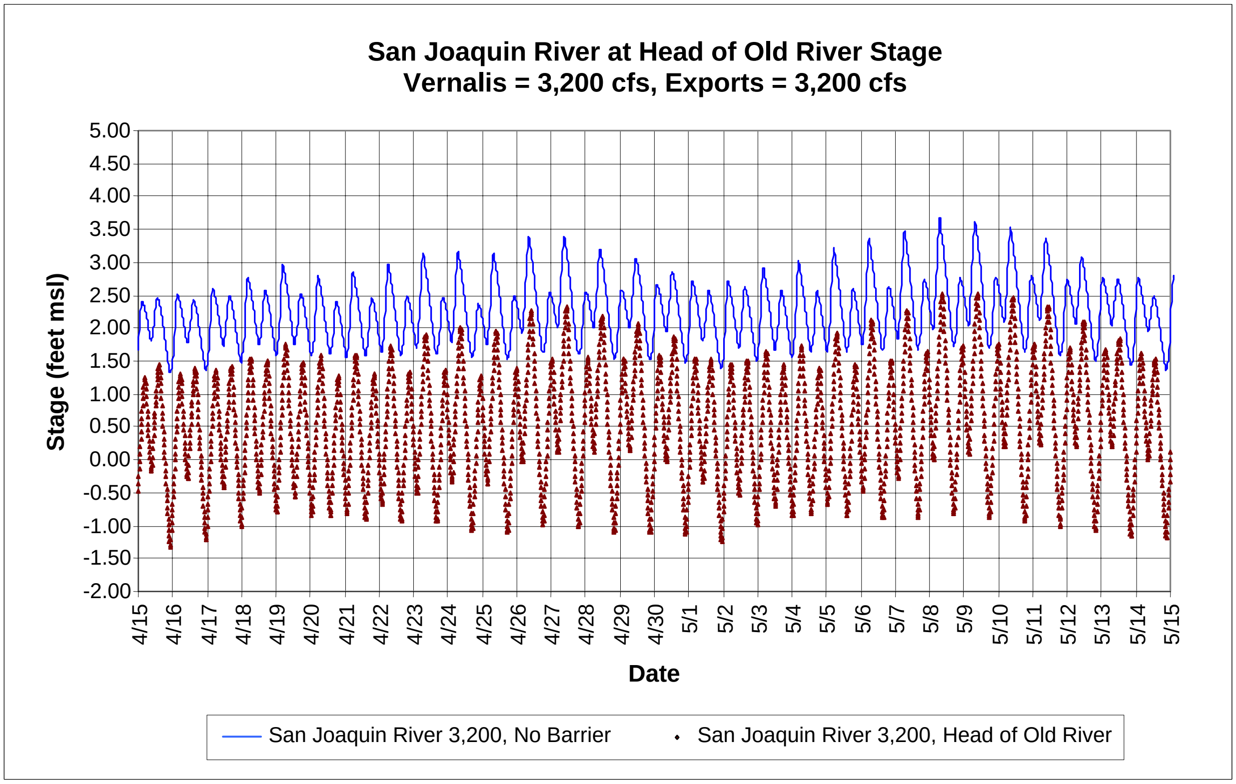


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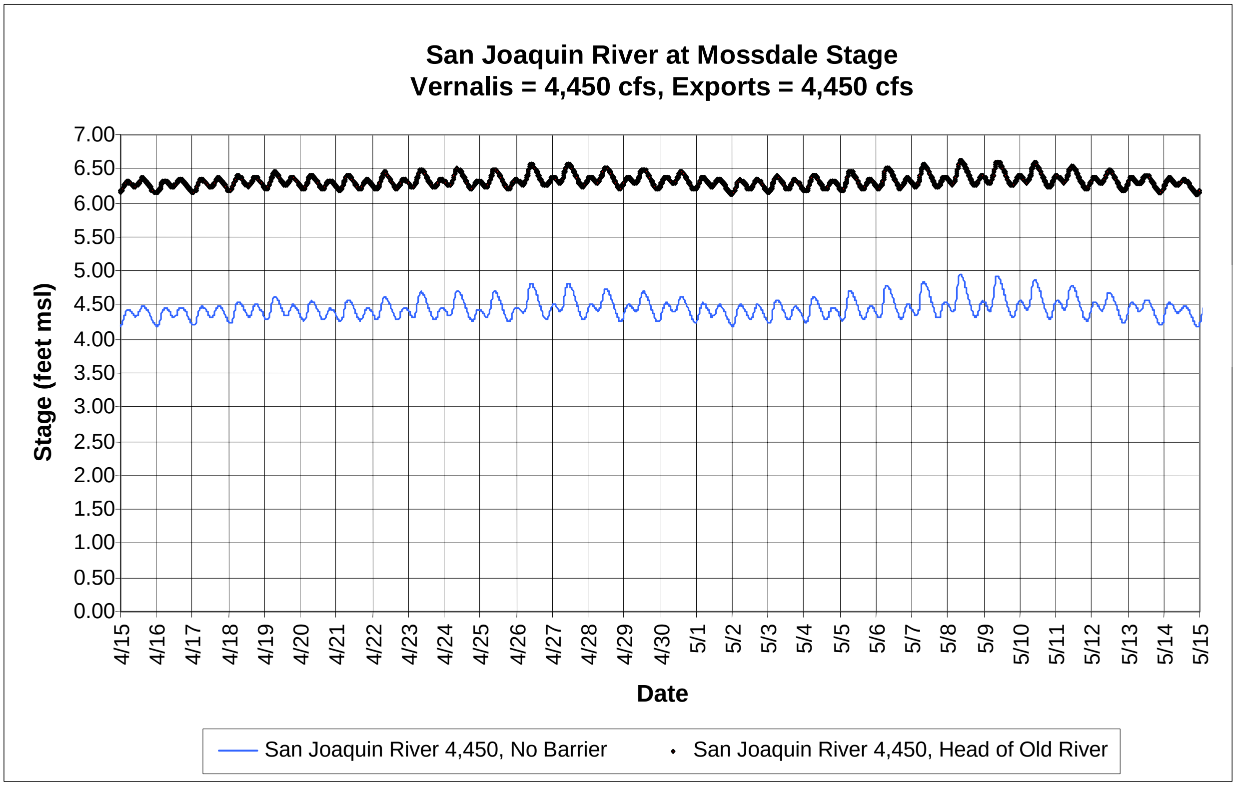
Figure D-110

Simulated Water-Surface Elevation (Stage) in the San Joaquin River at Mossdale and at Head of Old River with VAMP Flows at 3,200 cubic feet per second (cfs)



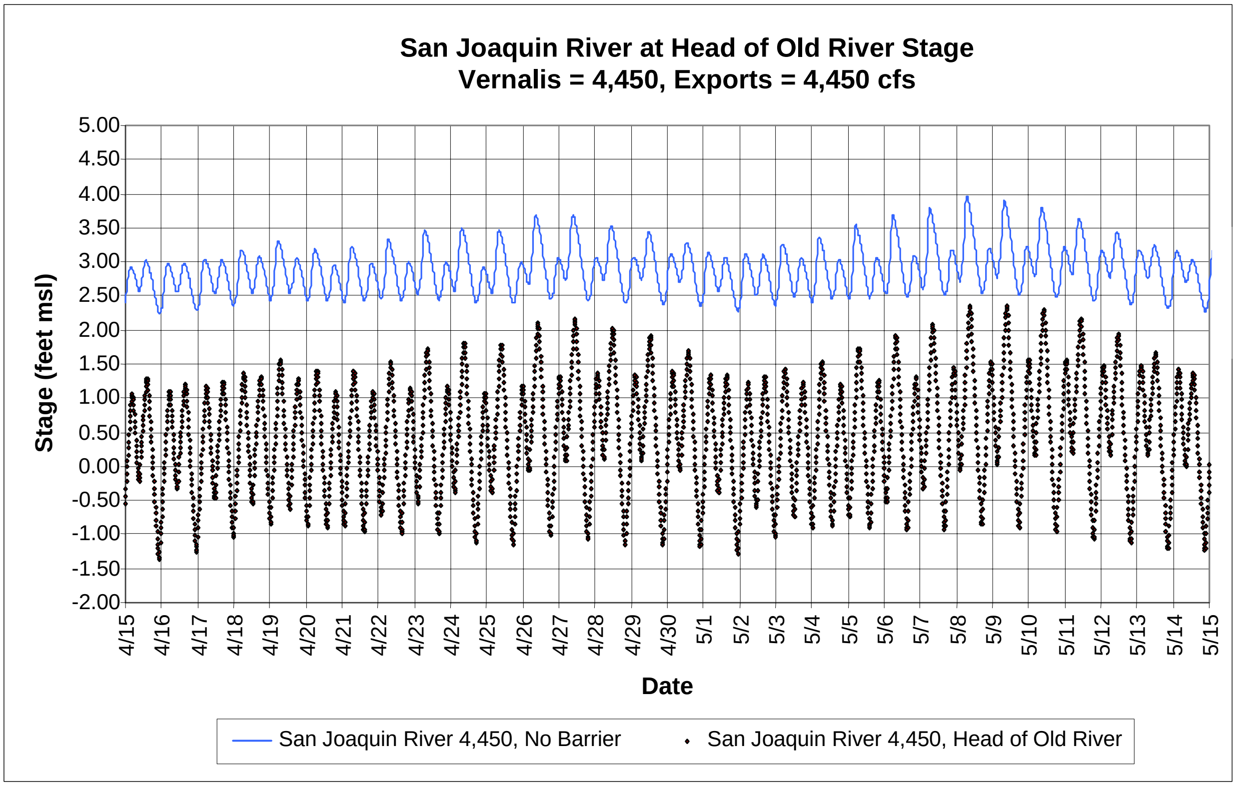


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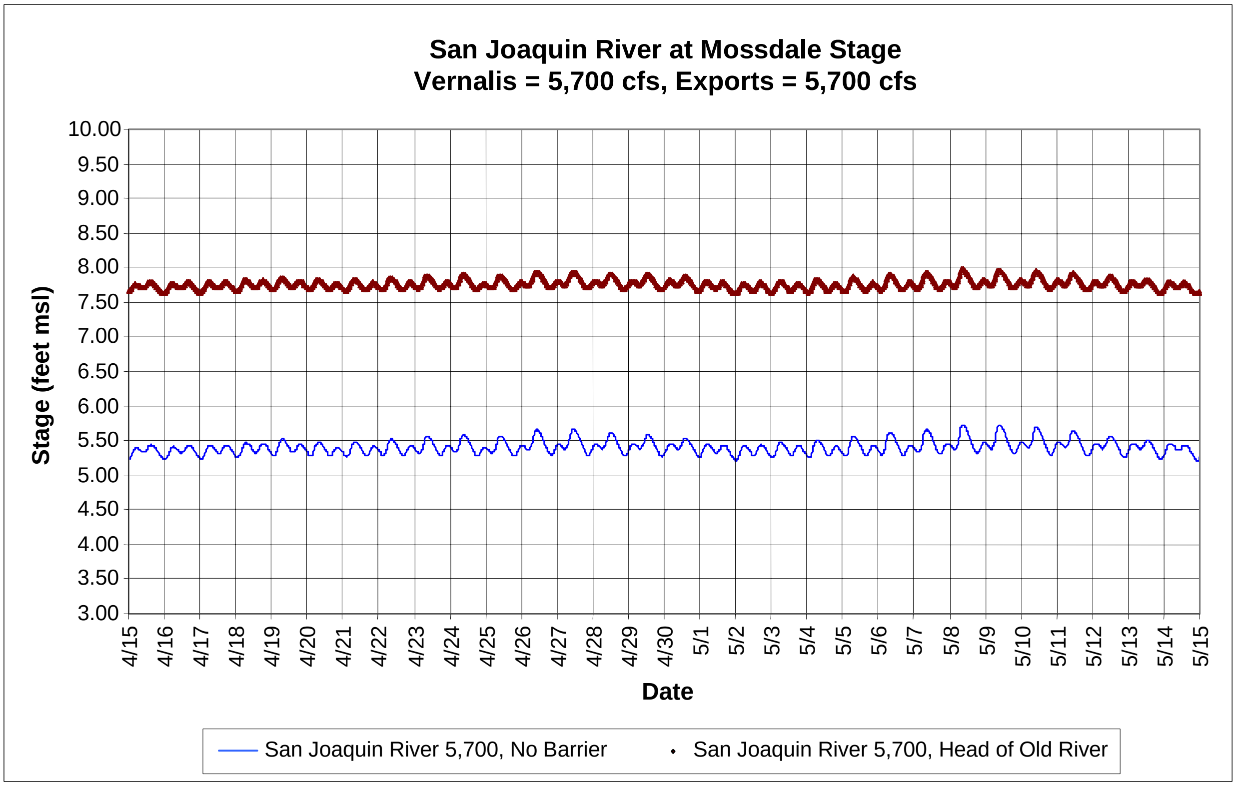
Figure D-111

Simulated Water-Surface Elevation (Stage) in the San Joaquin River at Mossdale and at Head of Old River with VAMP Flows at 4,450 cubic feet per second (cfs)



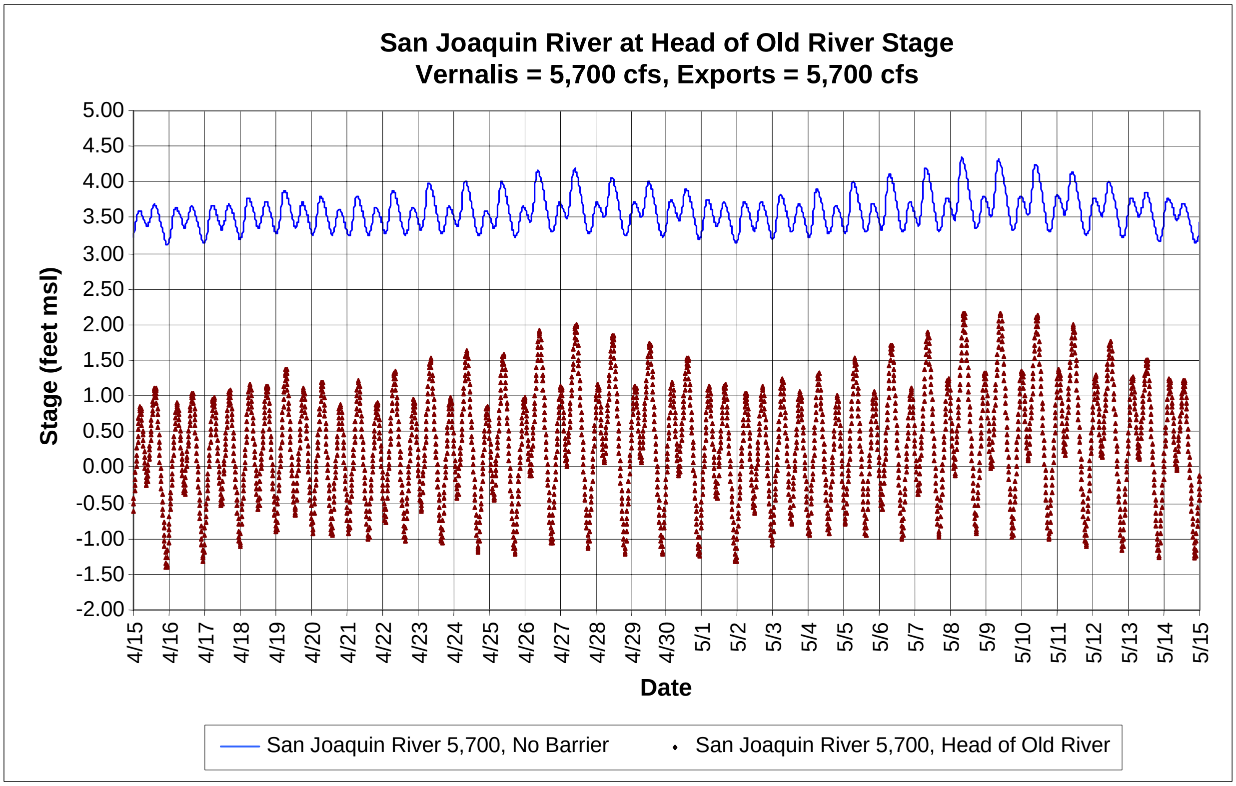


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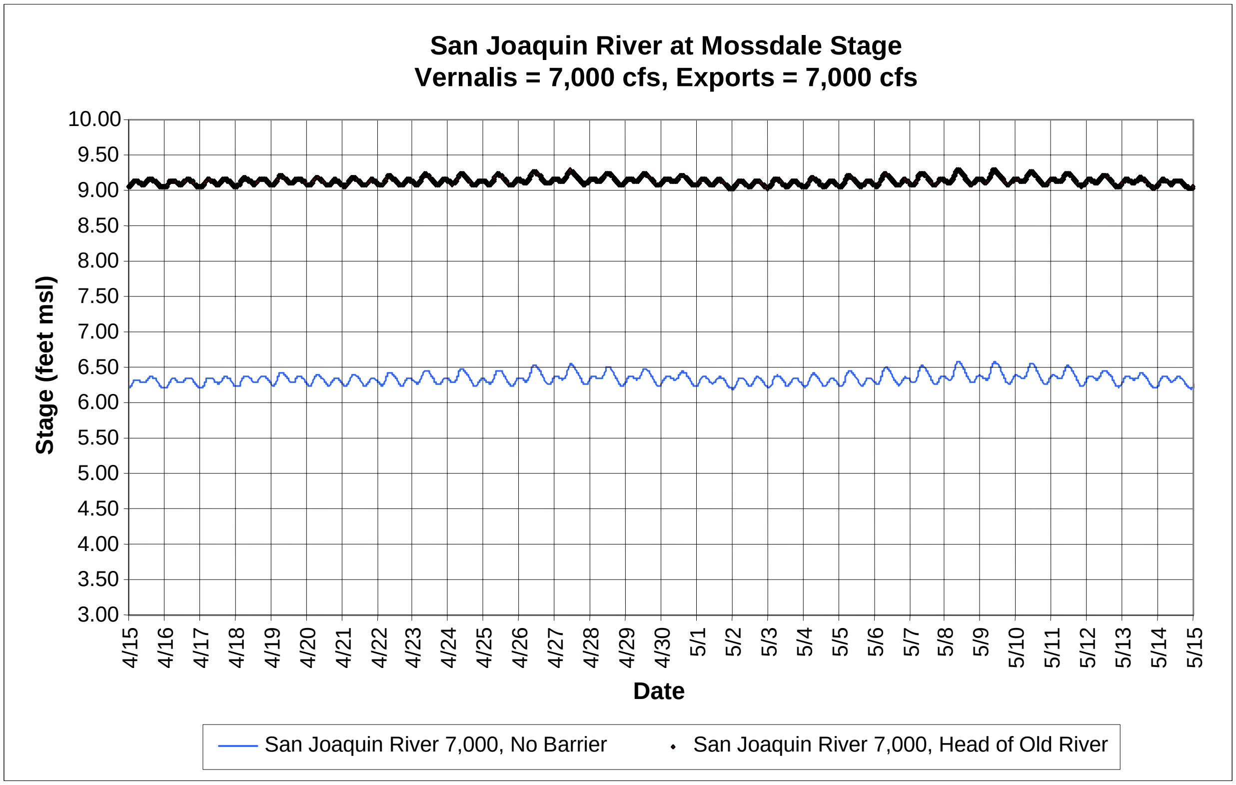
Figure D-112

Simulated Water-Surface Elevation (Stage) in the San Joaquin River at Mossdale and at Head of Old River with VAMP Flows at 5,700 cubic feet per second (cfs)



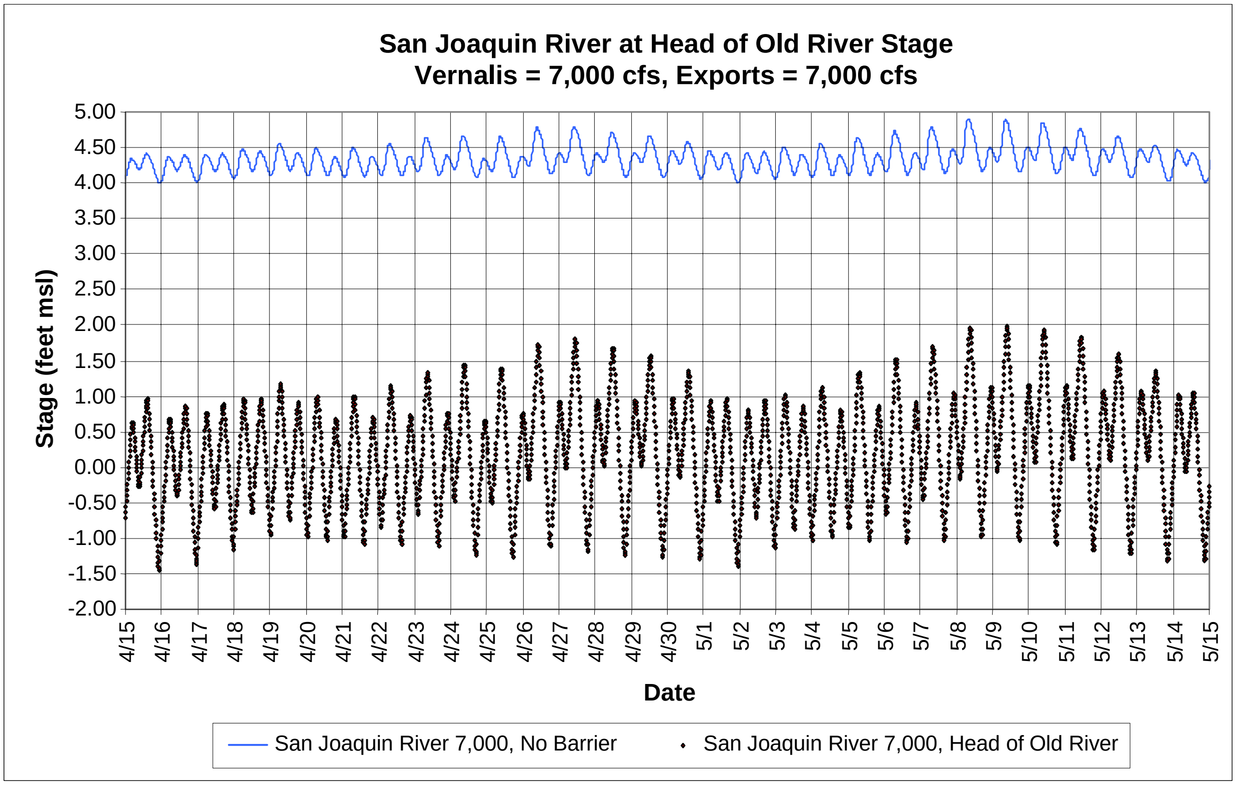


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Figure D-113

Simulated Water-Surface Elevation (Stage) in the San Joaquin River at Mossdale and at Head of Old River with VAMP Flows at 7,000 cubic feet per second (cfs)

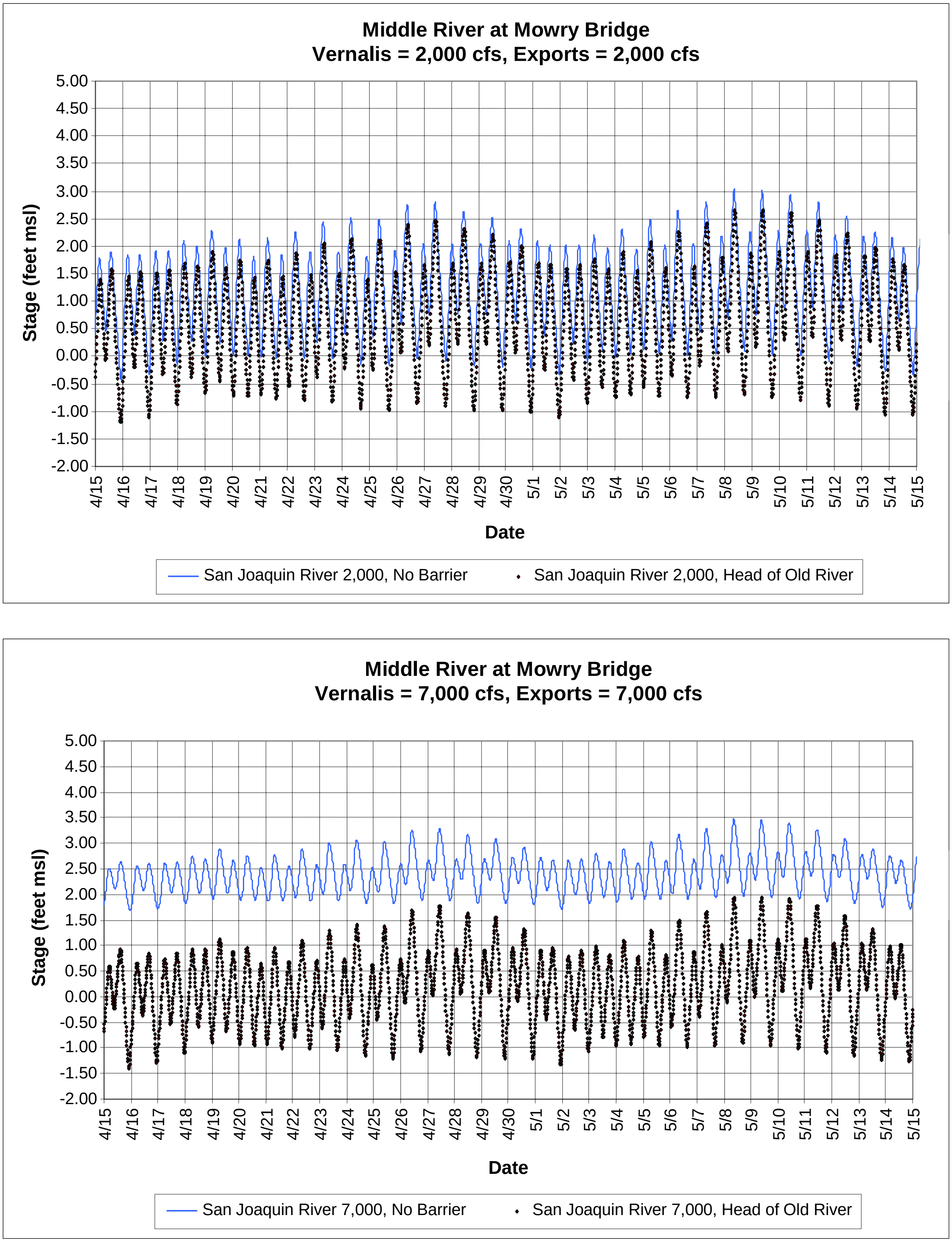

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Figure D-114

**Simulated Water-Surface Elevation (Stage)
in Middle River at Mowry Bridge**

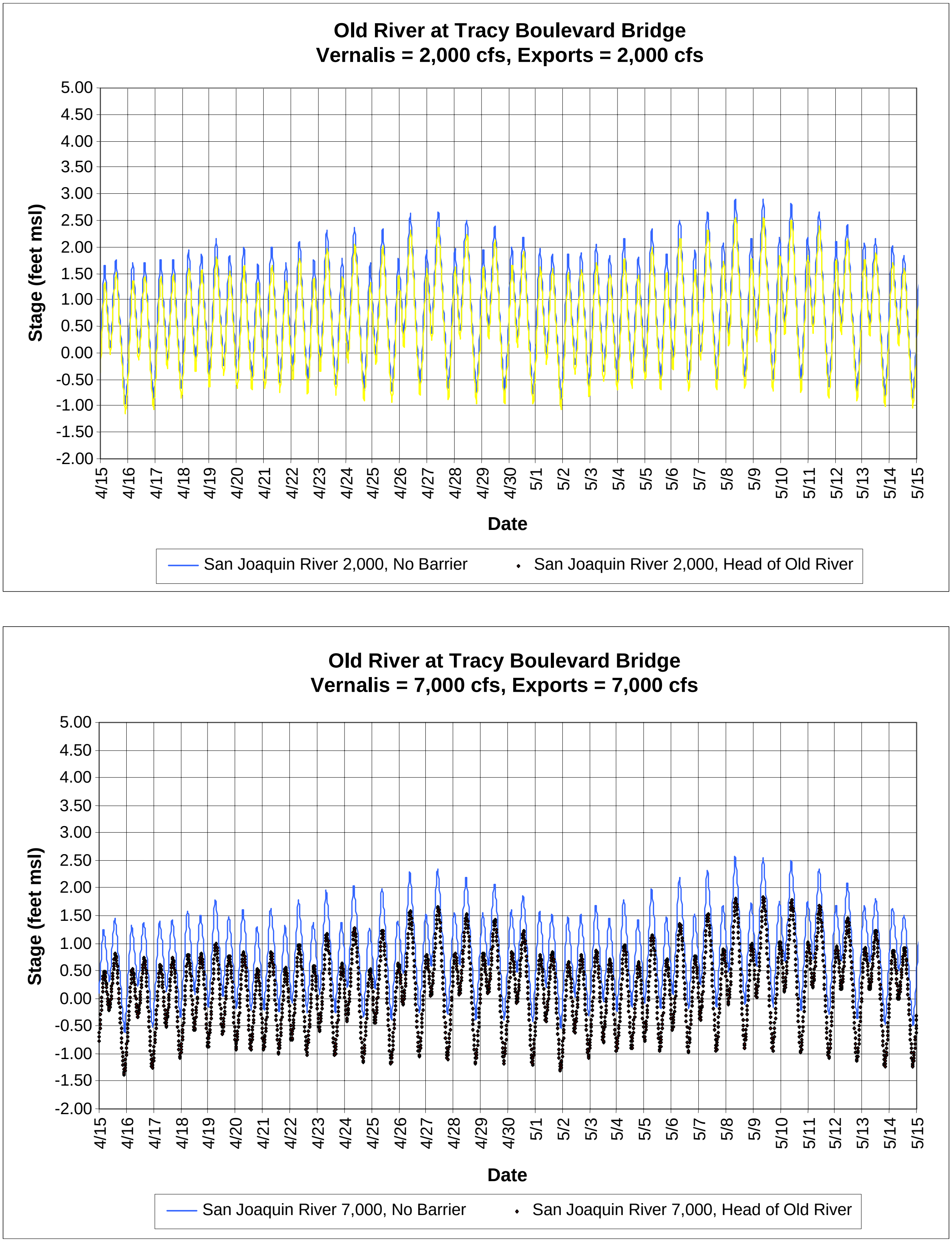

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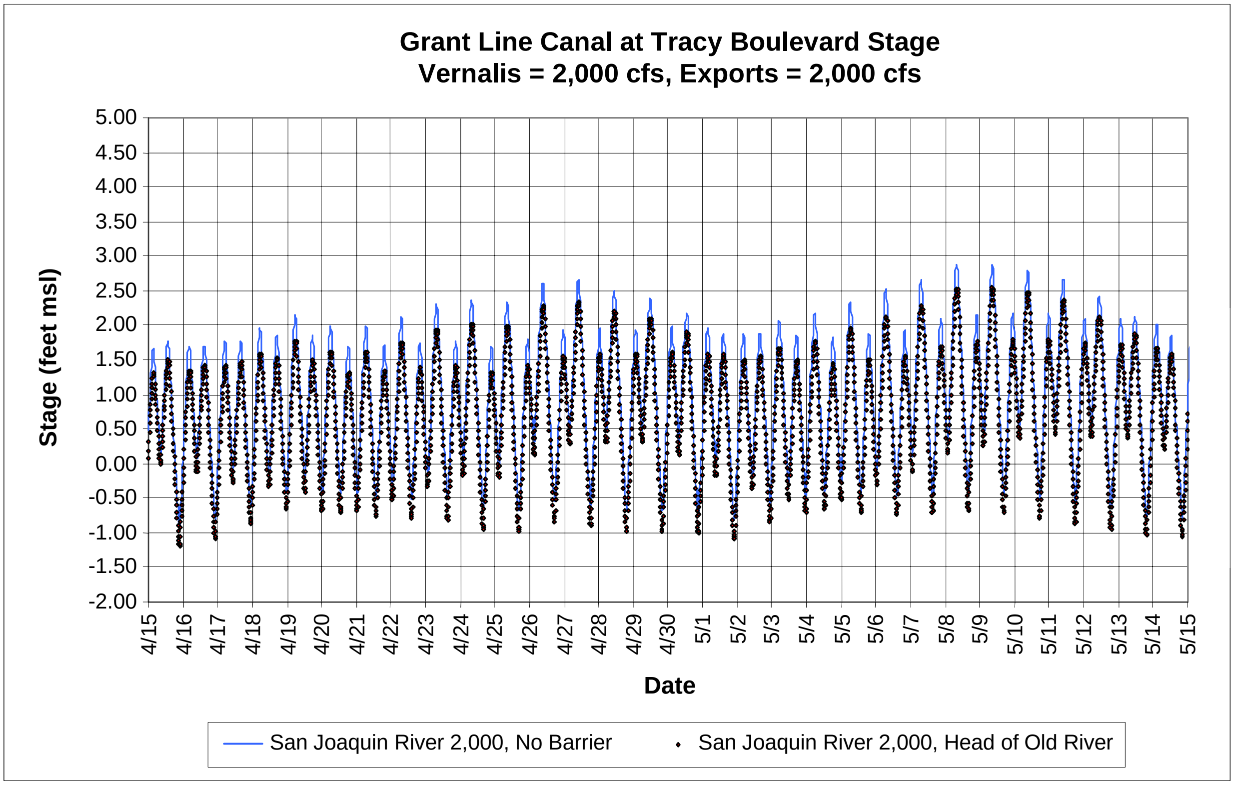
Figure D-115

**Simulated Water-Surface Elevation (Stage)
in Old River at Tracy Boulevard Bridge**



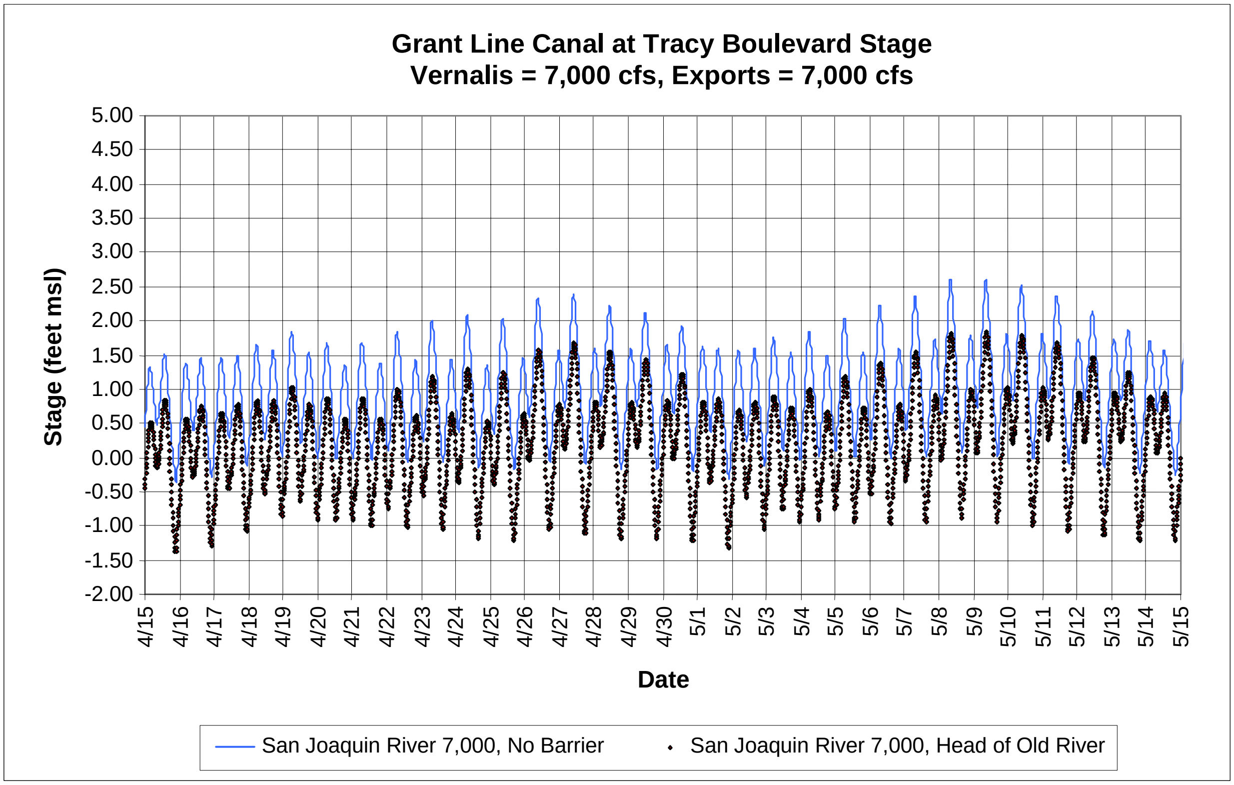
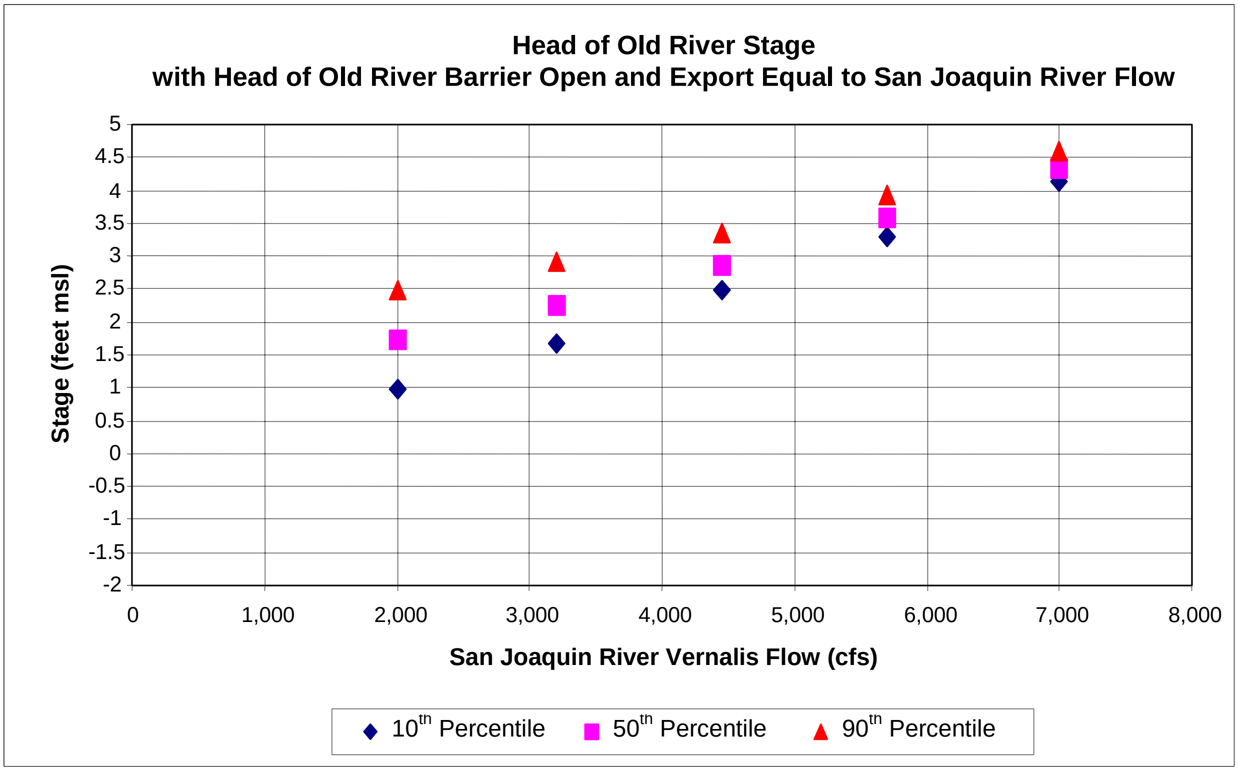


Figure D-116

**Simulated Water-Surface Elevation (Stage)
in Grant Line Canal at Tracy Boulevard Bridge**



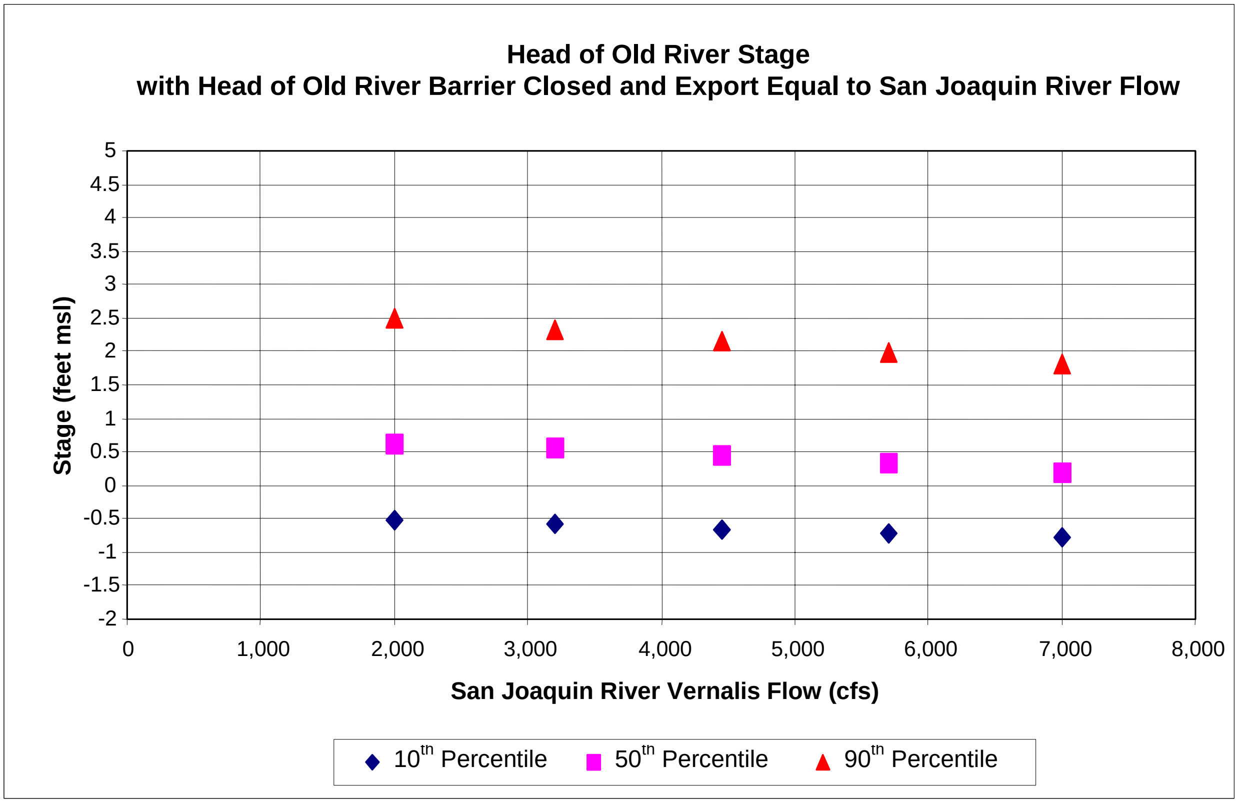


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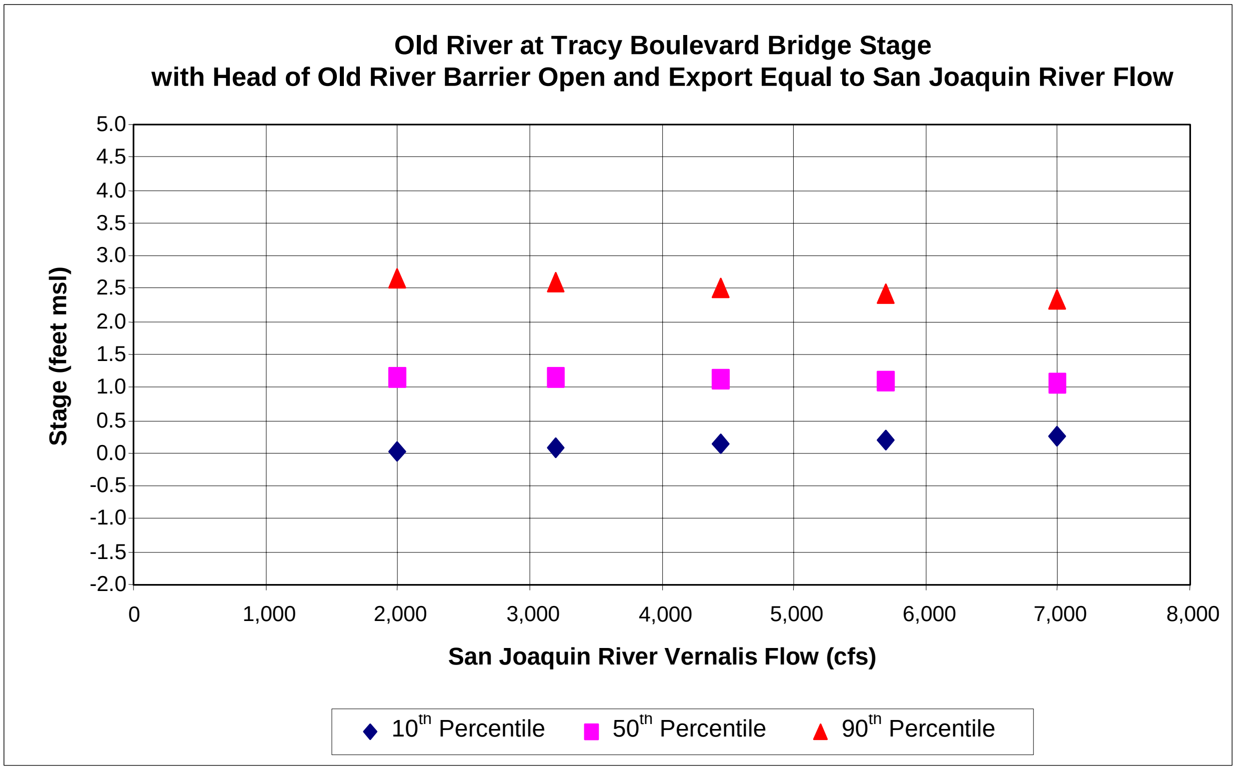
Figure D-117a

**Simulated Water-Surface Elevation (Stage)
at Head of Old River with Various VAMP Flows**



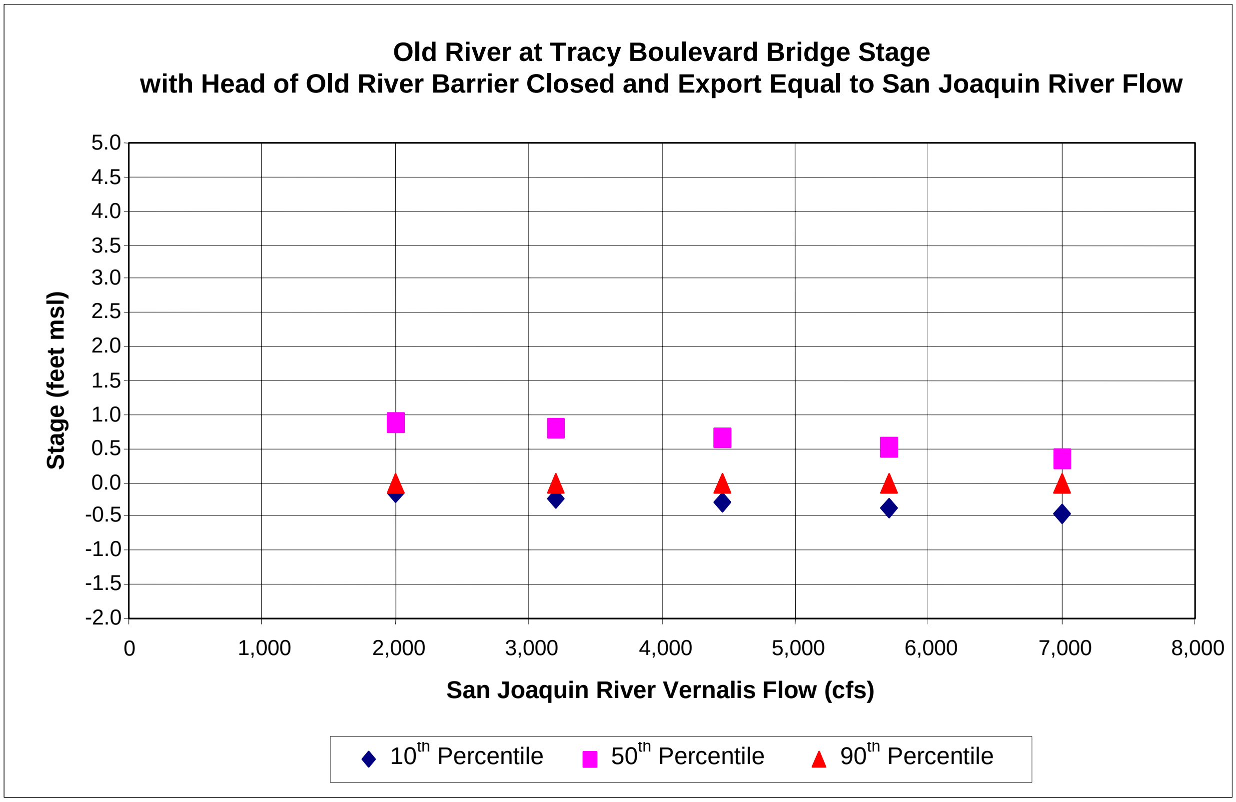


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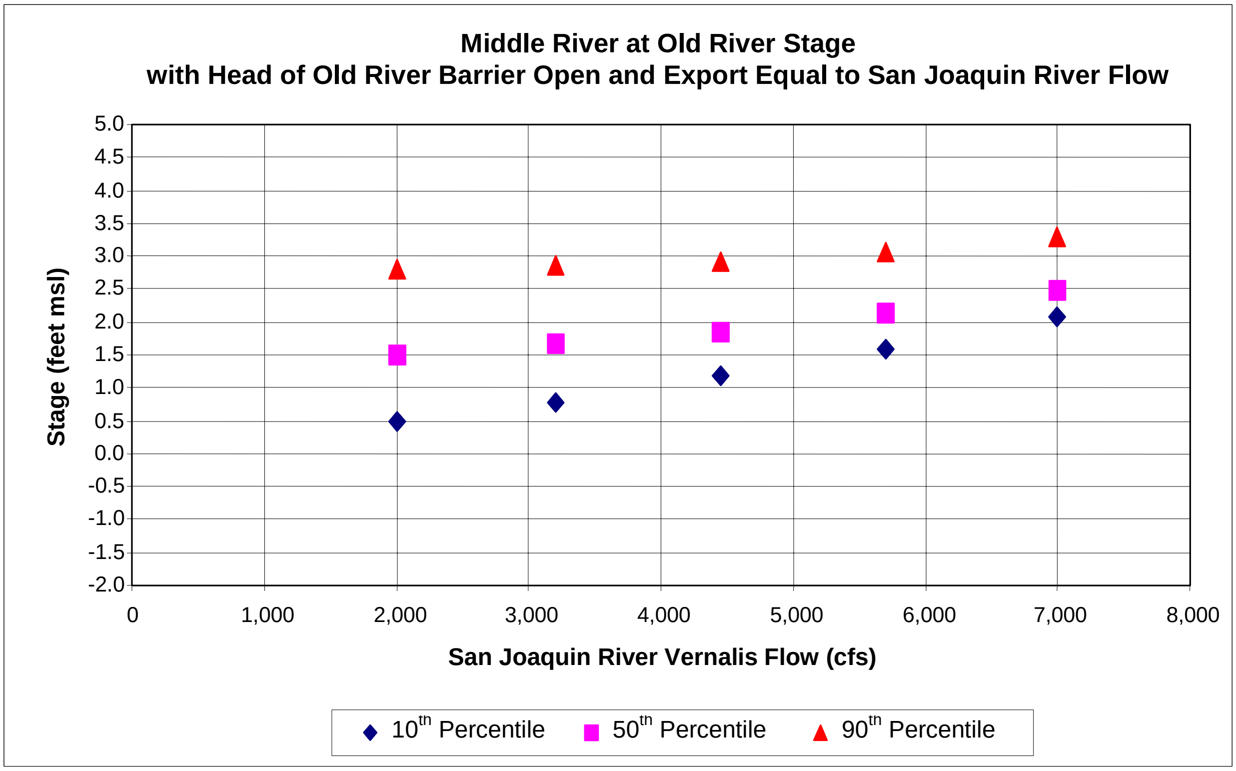
Figure D-117b

Simulated Water-Surface Elevation (Stage) in Old River at Tracy Boulevard Bridge with Various VAMP Flows



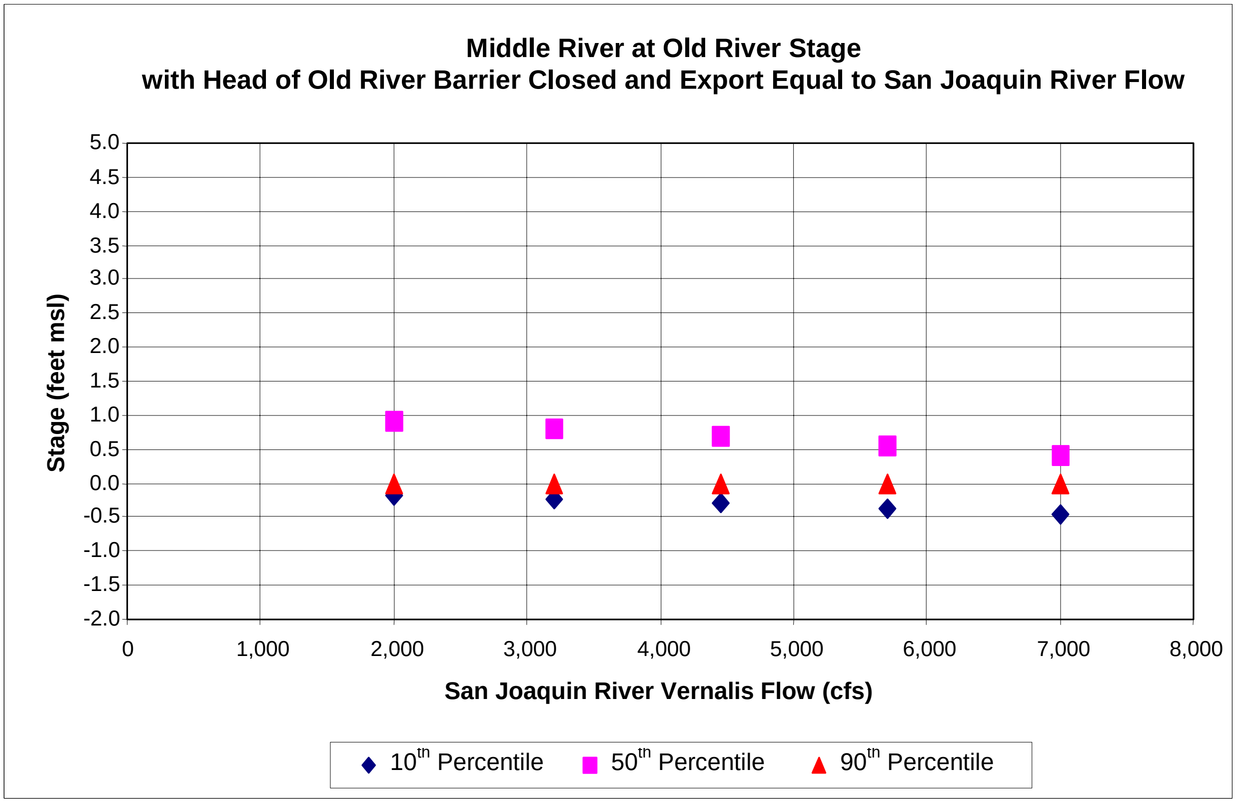


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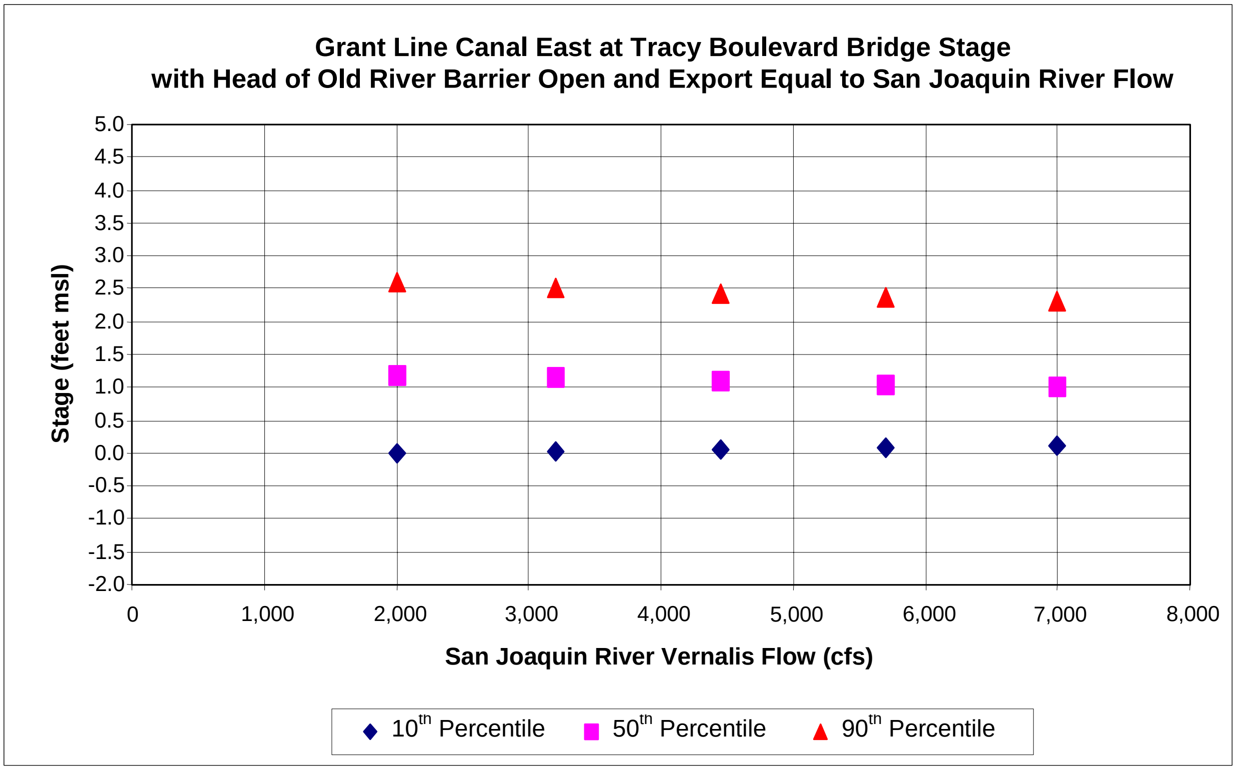
Figure D-117c

Simulated Water-Surface Elevation (Stage) in Middle River at Old River with Various VAMP Flows



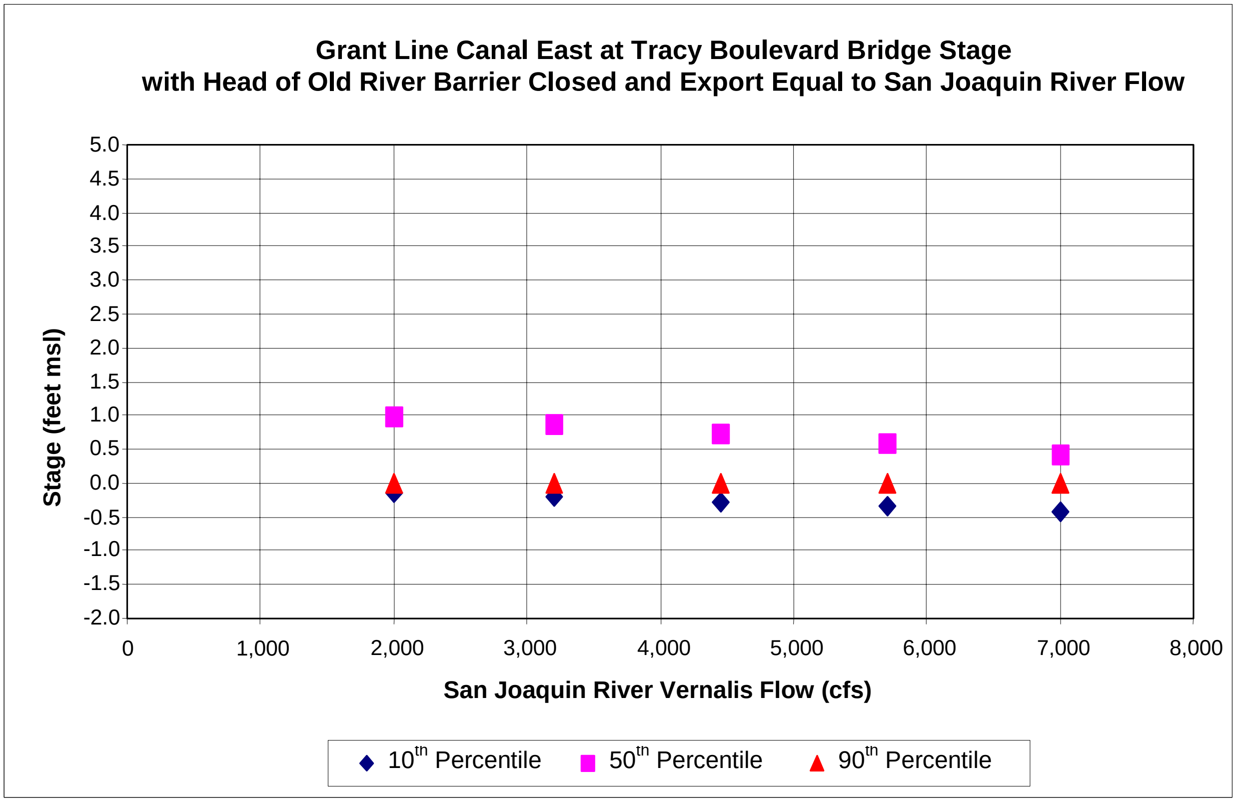


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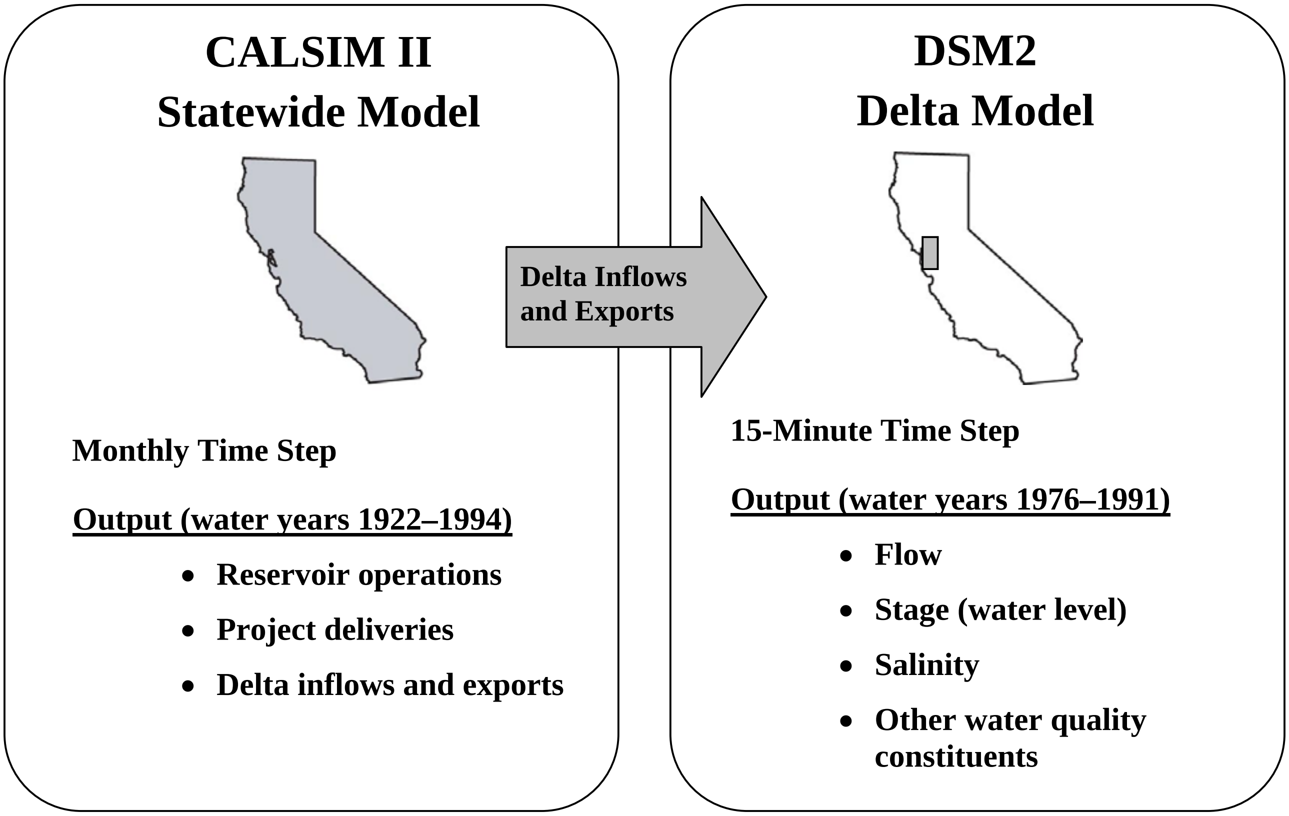
Figure D-117d

Simulated Water-Surface Elevation (Stage) in Grant Line Canal at Tracy Boulevard Bridge with Various VAMP Flows



CALSIM II
Statewide Model

Monthly Time Step

Output (water years 1922–1994)

- **Reservoir operations**
- **Project deliveries**
- **Delta inflows and exports**

Delta Inflows and Exports

DSM2
Delta Model

15-Minute Time Step

Output (water years 1976–1991)

- **Flow**
- **Stage (water level)**
- **Salinity**
- **Other water quality constituents**

Figure D-118

Relationship between CALSIM II and DSM2

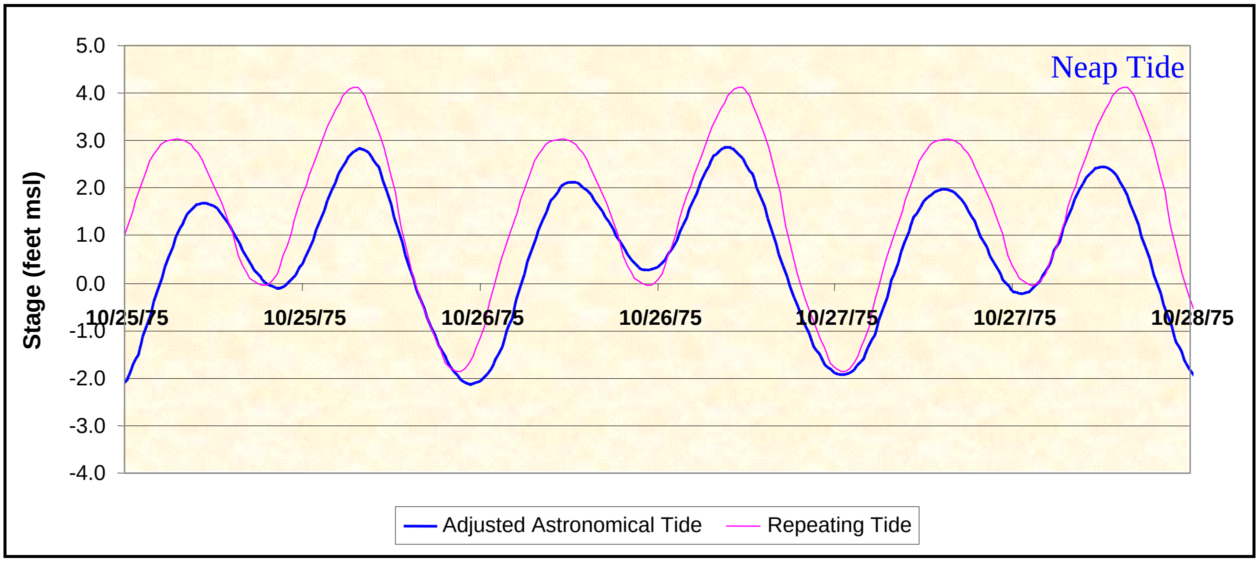


Figure D-119a. Three-Day Sequence of Adjusted Astronomical and 25-Hour-Repeating 19-Year Mean Tides

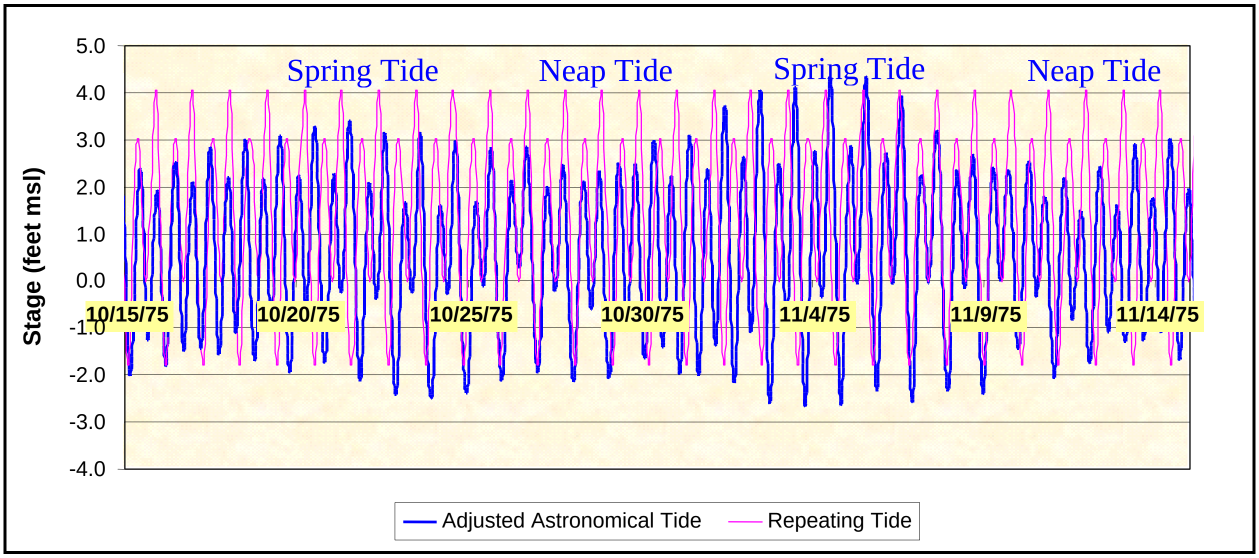


Figure D-119b. Two-Week Sequence of Adjusted Astronomical and 25-Hour-Repeating 19-Year Mean Tides

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Figures D-119a and D-119b

Adjusted Astronomical Tides

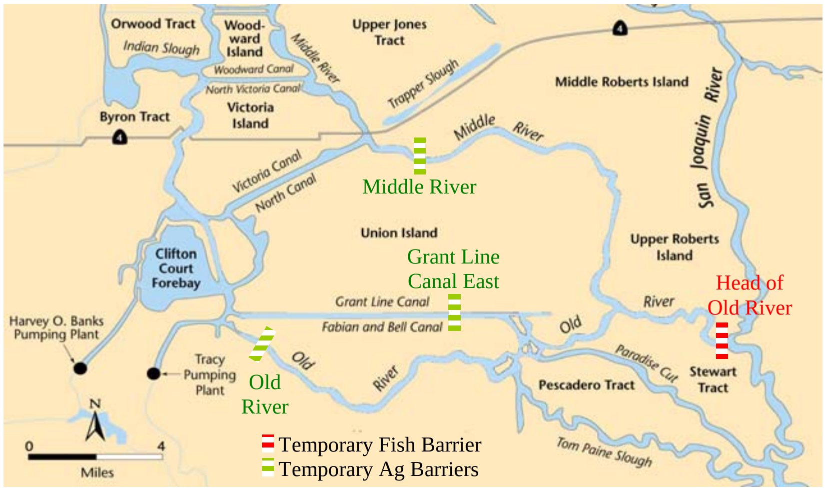

Figure D-120a. Temporary Barriers: One Fish and Two Agricultural Barriers

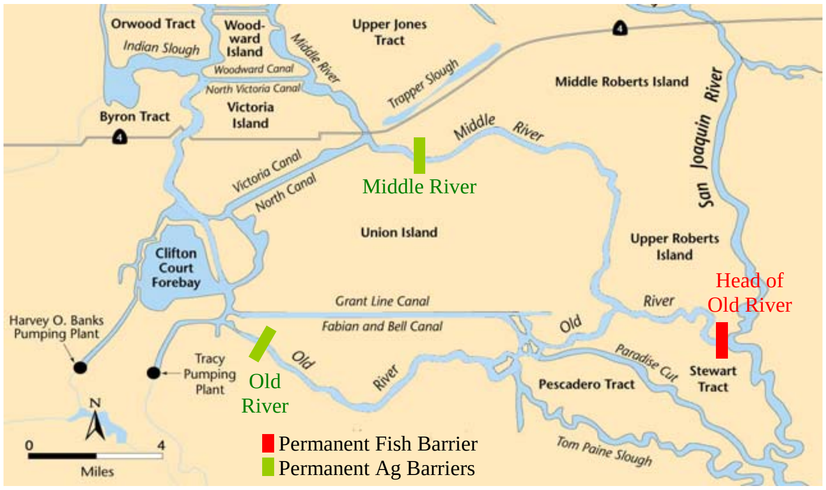

Figure D-210b. Permanent Barriers: One Fish and Two Agricultural Barriers

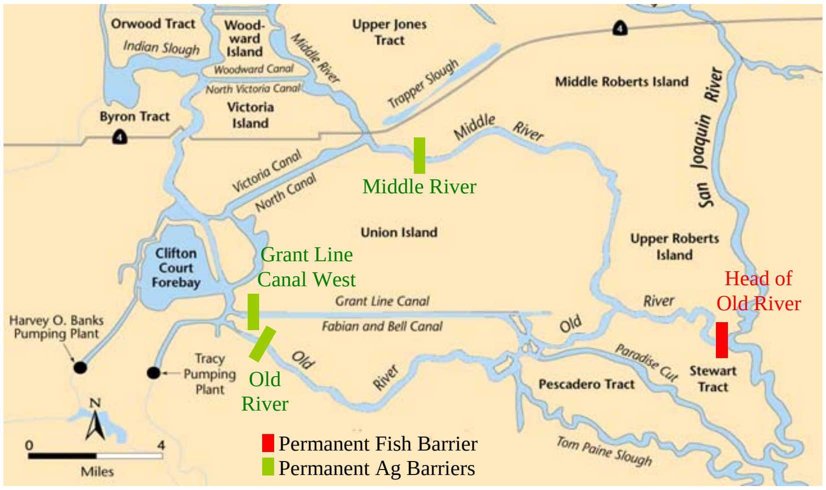

Figure D-120c. Permanent Barriers: One Fish and Three Agricultural Barriers

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Figures D-120a, D-120b, and D-120c

Locations of Temporary and Permanent Barriers

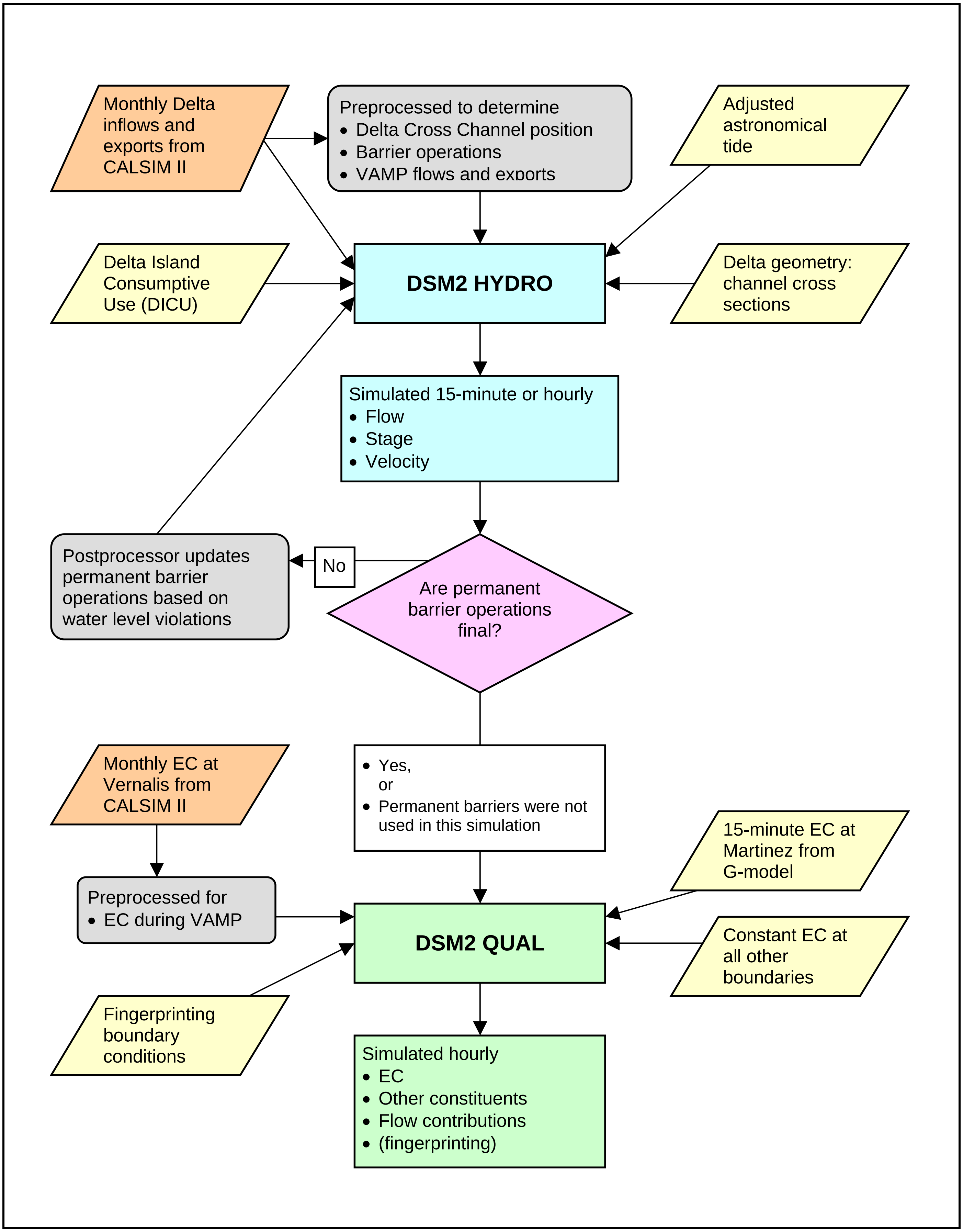

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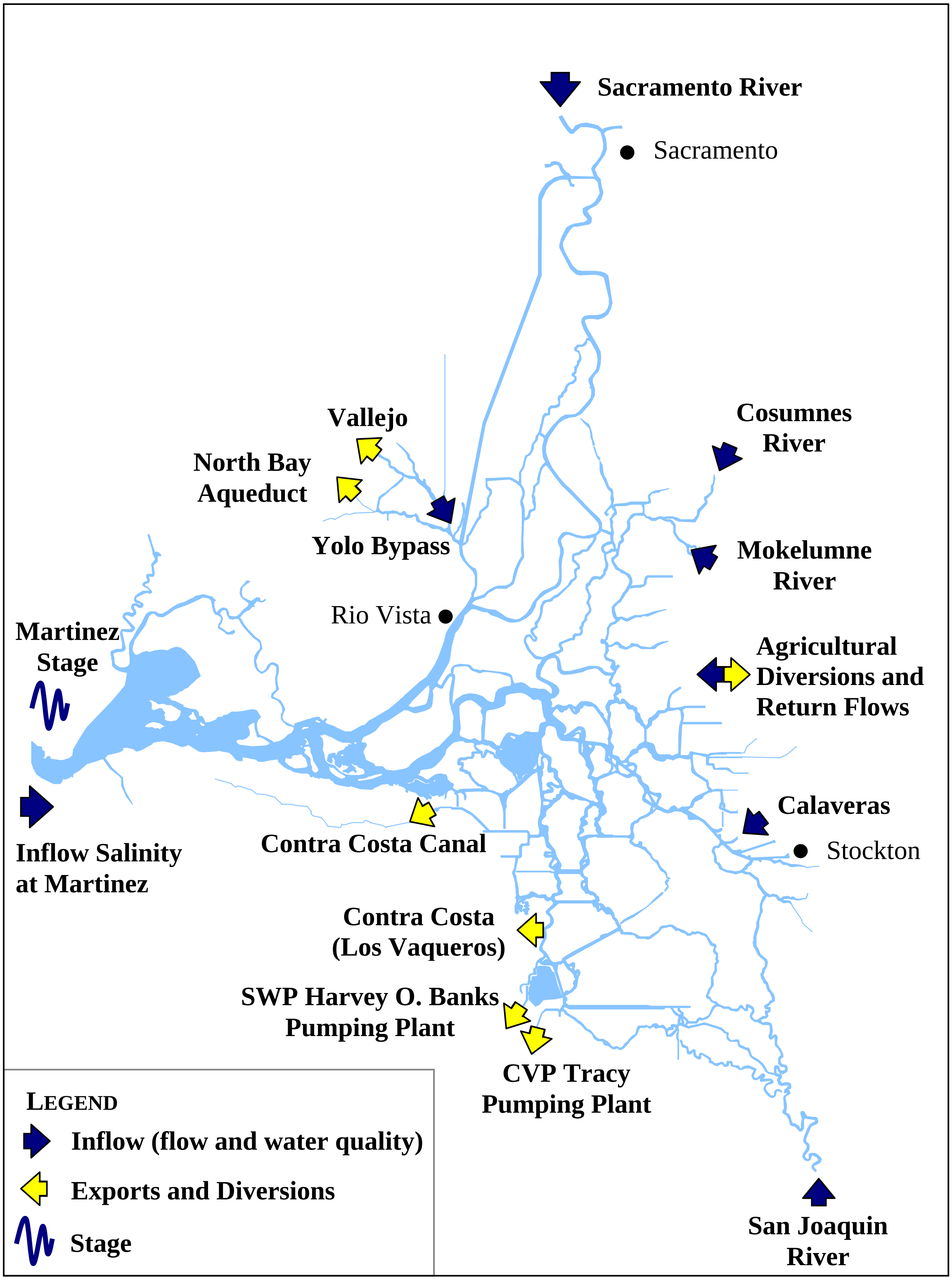
Figure D-121

Flow Chart of DSM2 Modeling Process



Project Number

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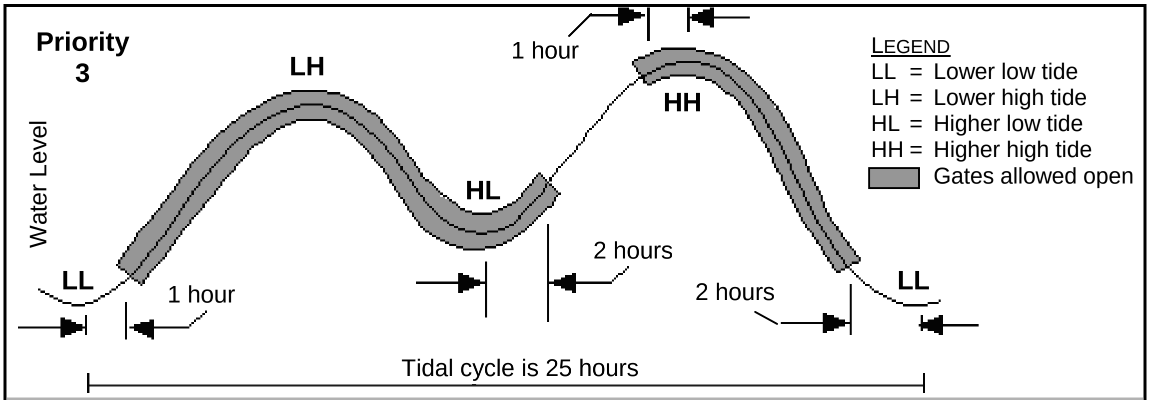
Figure D-122

DSM2 Hydrodynamic and Water Quality Boundary Conditions



Priority 4

Gates are open at all times. Flow enters Clifton Court Forebay any time differences in water levels inside the forebay and outside the intake channel dictate.

Figure D-123. Clifton Court Forebay Gate Operating Priorities in DSM2

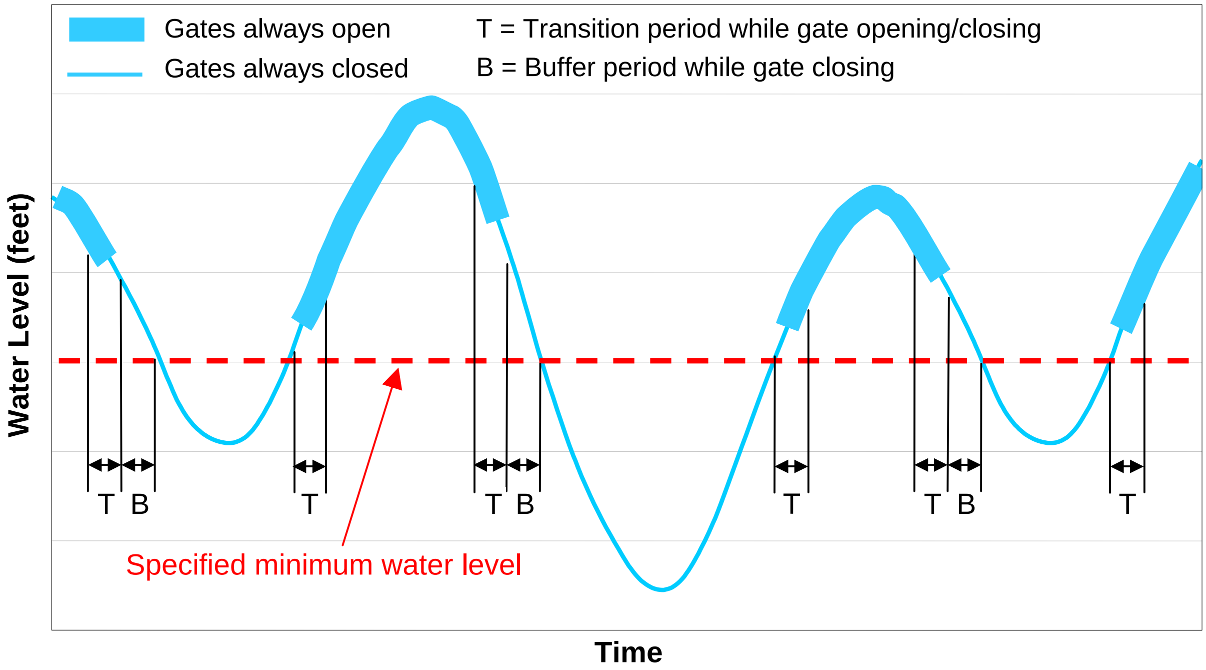


Figure D-124. Conceptualization of Permanent Barrier Operations

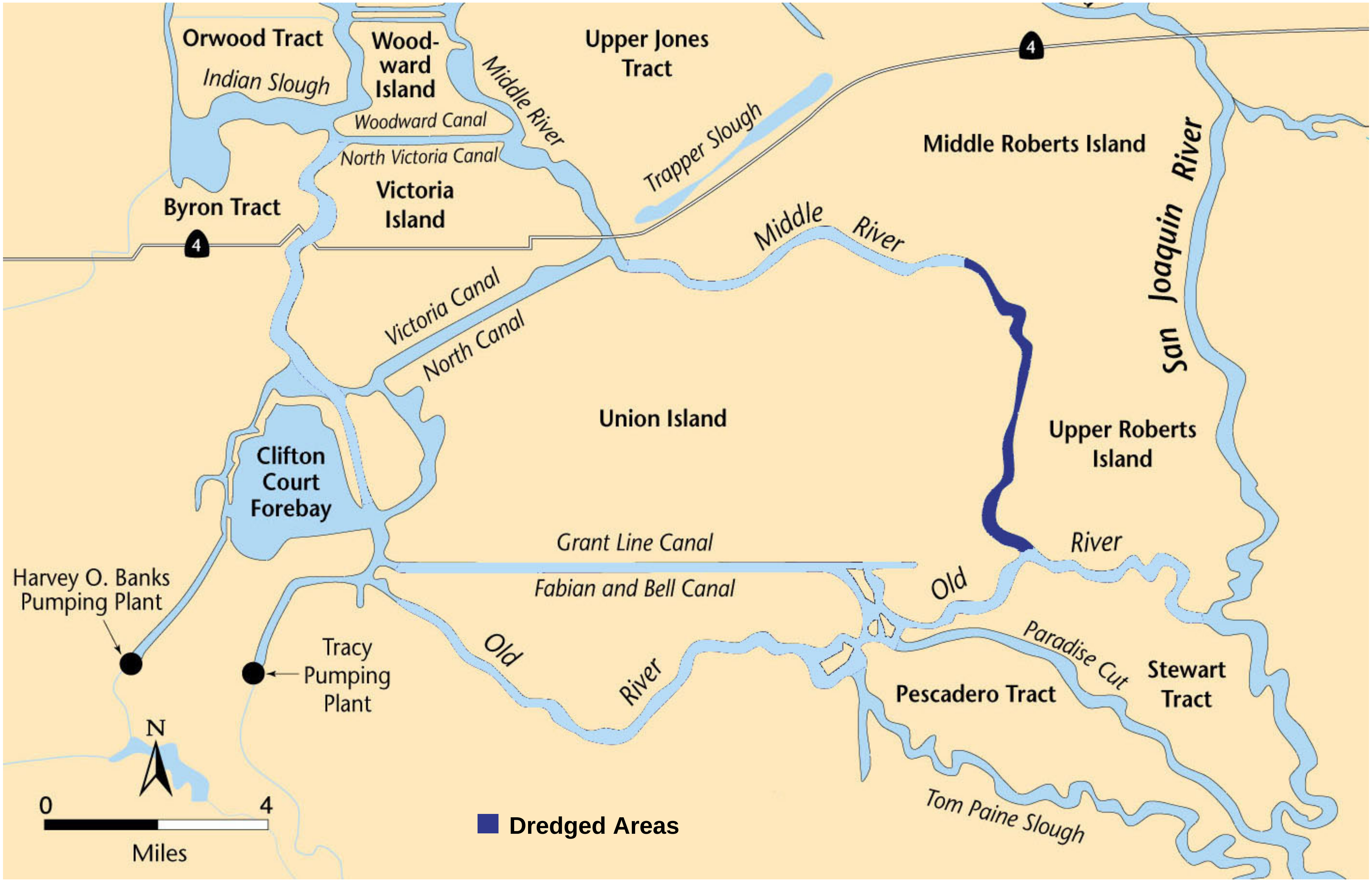


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Figure D-125

Location of Dredging in DSM2 16-Year Planning Simulations for SDIP

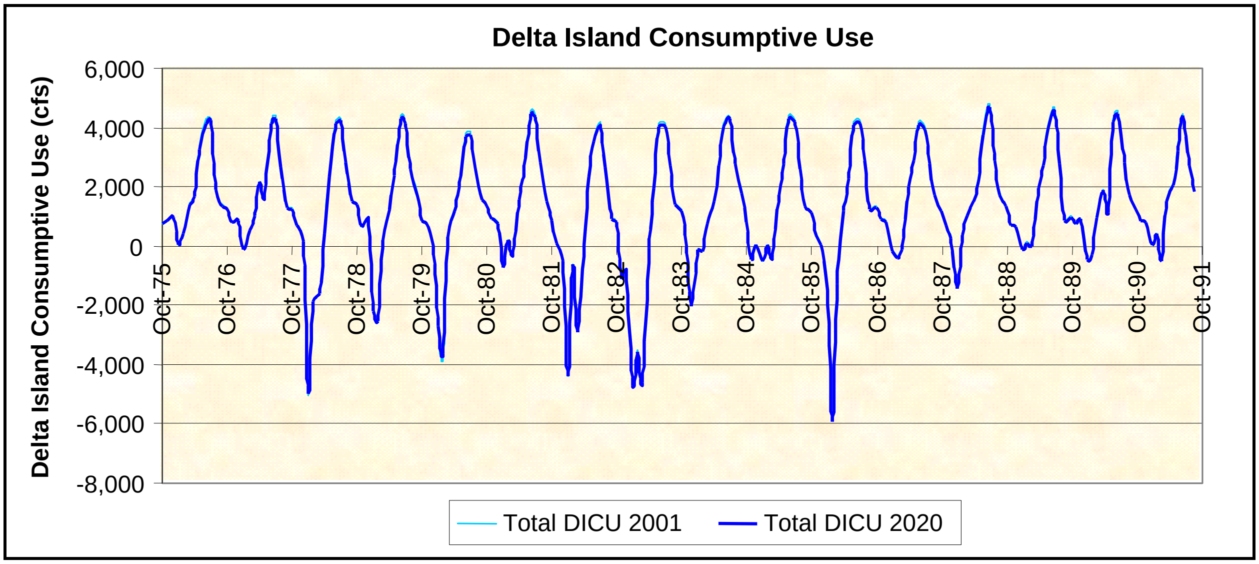


Figure D-126. Delta Island Consumptive Use for the DSM2 16-Year Planning Studies

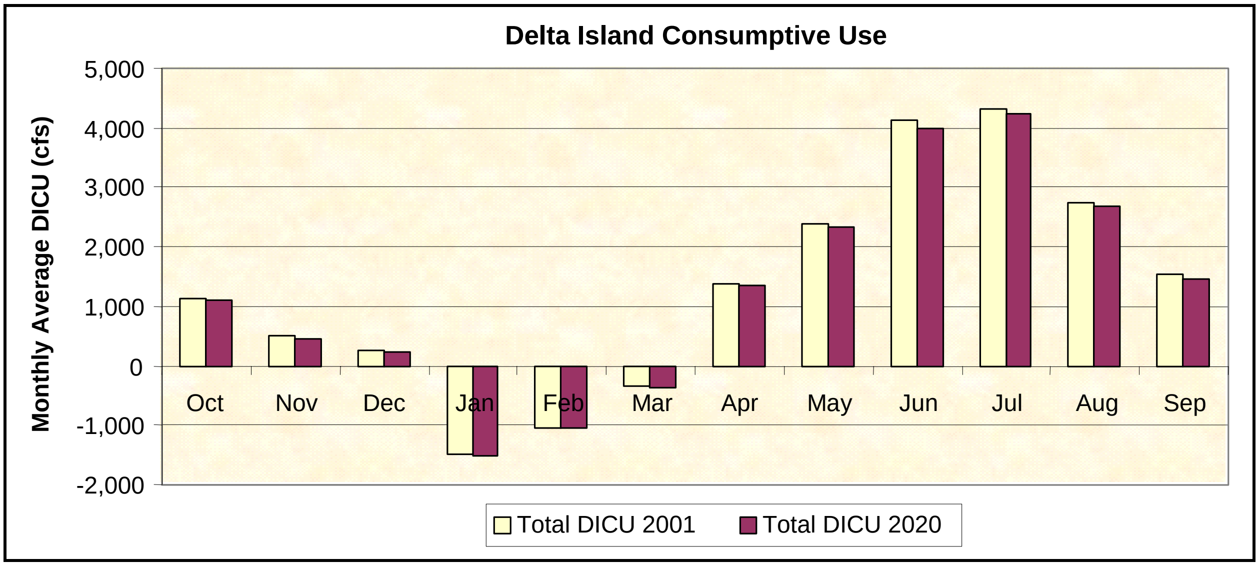


Figure D-127. Monthly Average Delta Island Consumptive Use for the DSM2 16-Year Planning Studies

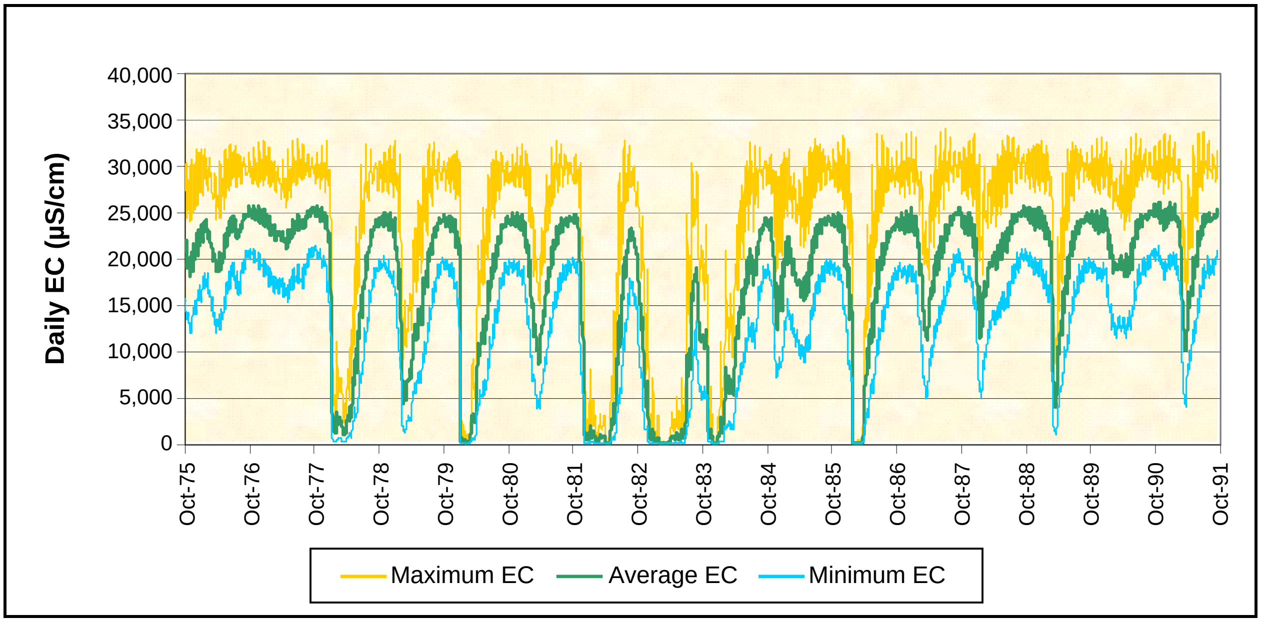


Figure D-128. Martinez Electrical Conductivity (EC) from G-model for 2020 Baseline Conditions with Temporary Barriers

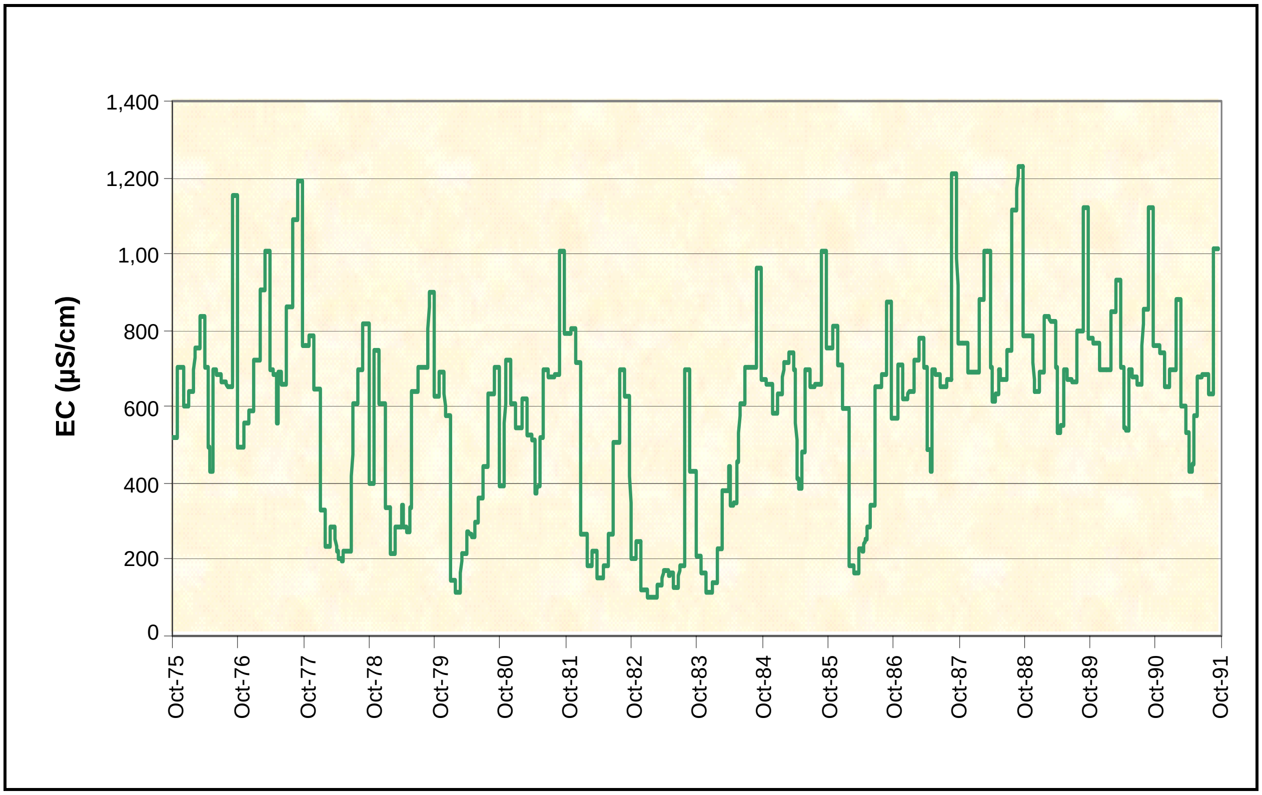


Figure D-129. Vernalis Electrical Conductivity (EC) from CALSIM II for 2020 Baseline Conditions with Temporary Barriers

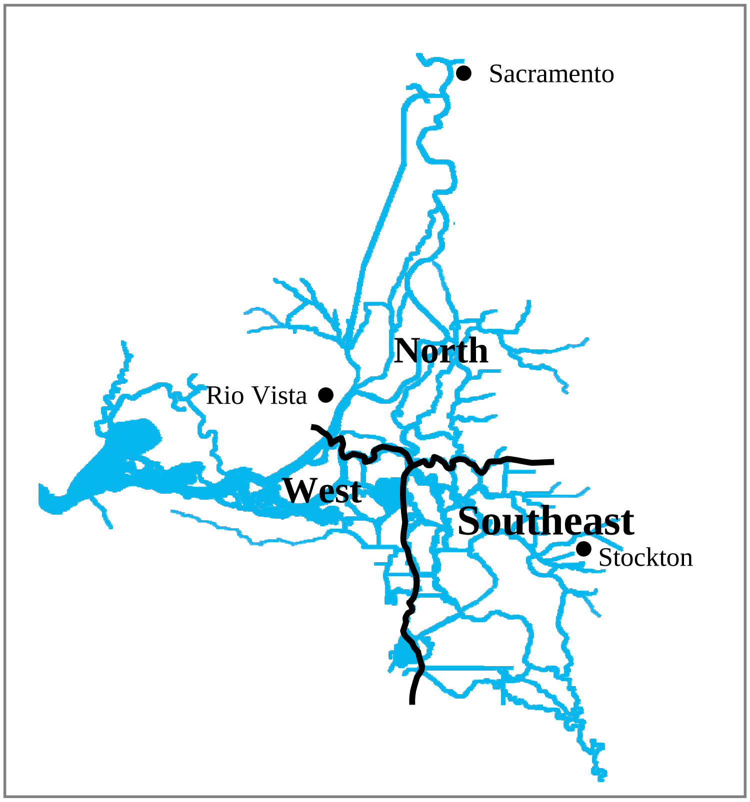


Figure D-130. Delta Regions for Drainage and Return Flow Electrical Conductivity

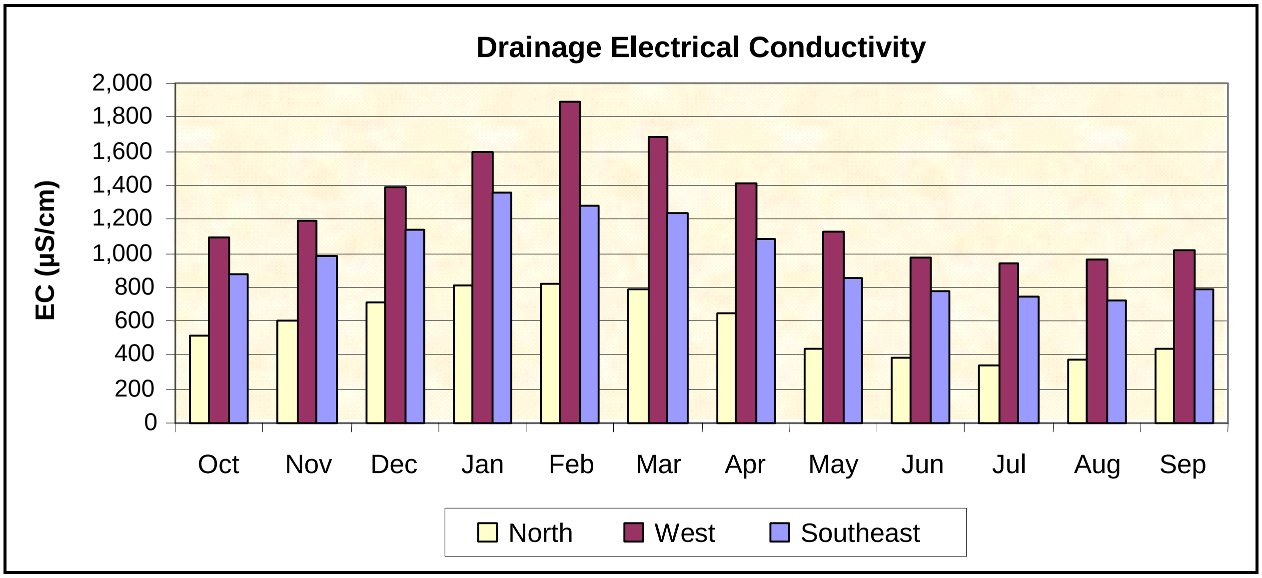
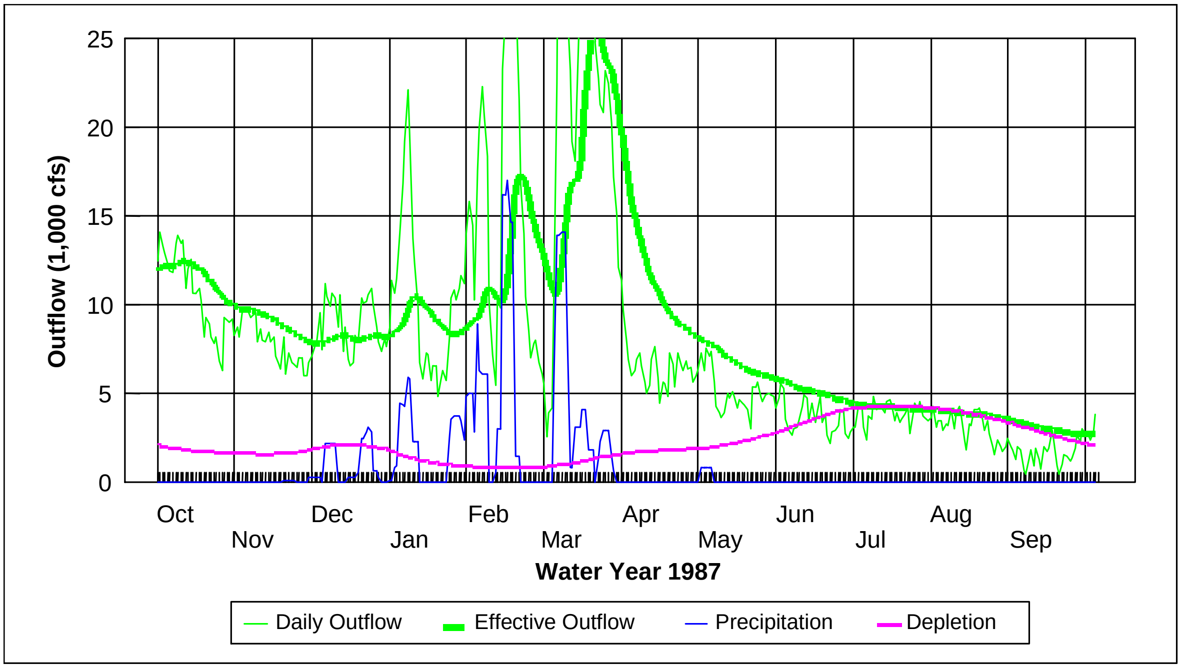
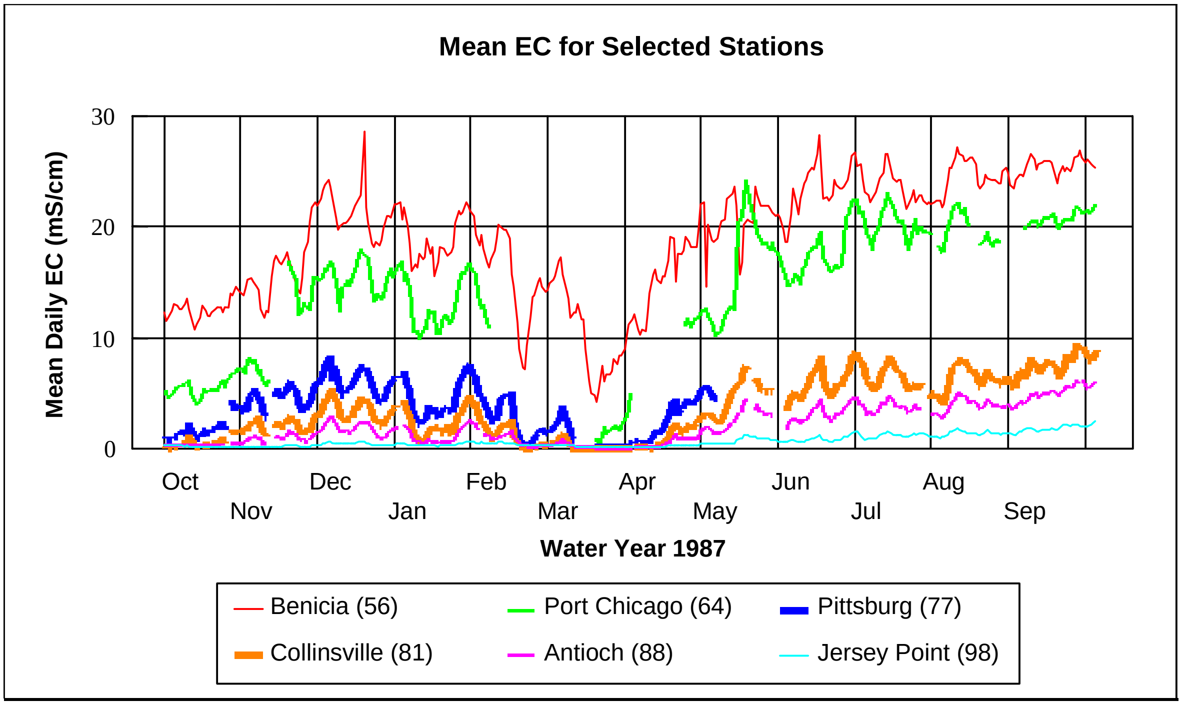


Figure D-131. Drainage and Return Flow Electrical Conductivity by Region for DSM2 Simulations





Note: The measured response of electrical conductivity appears to follow the effective outflow, which is a lagged moving average of the daily outflow estimates.

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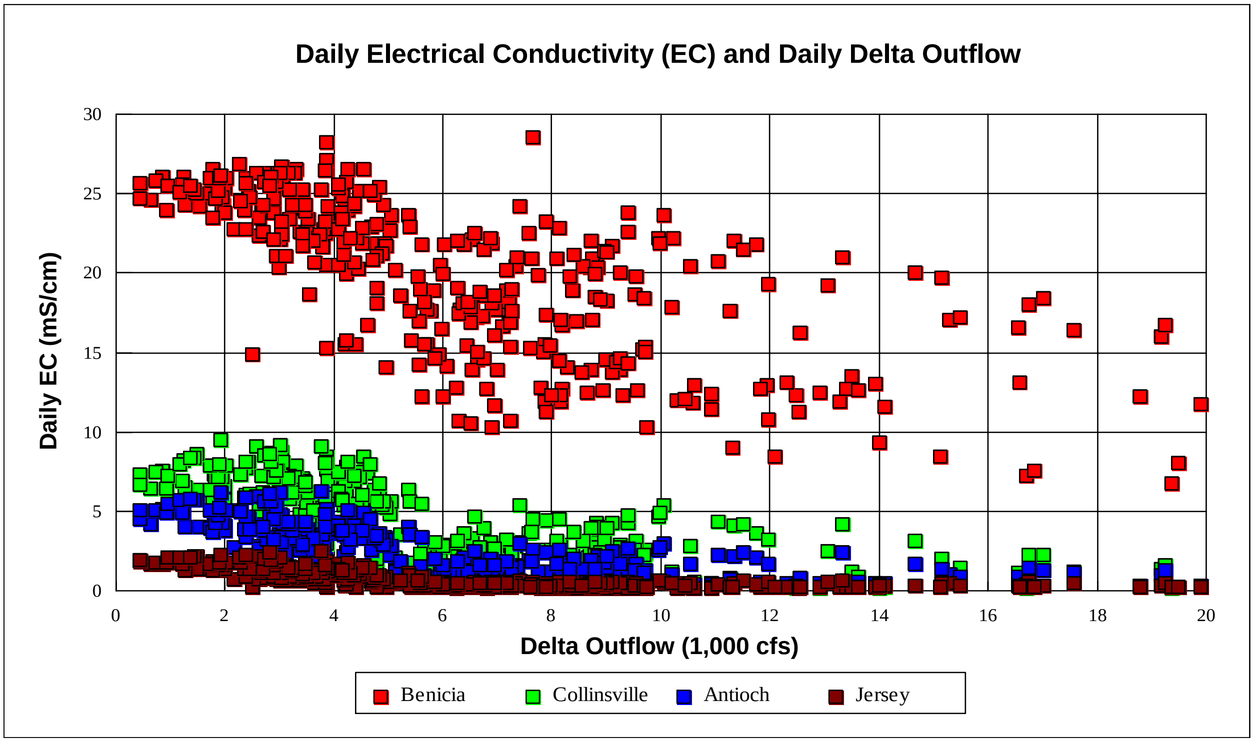
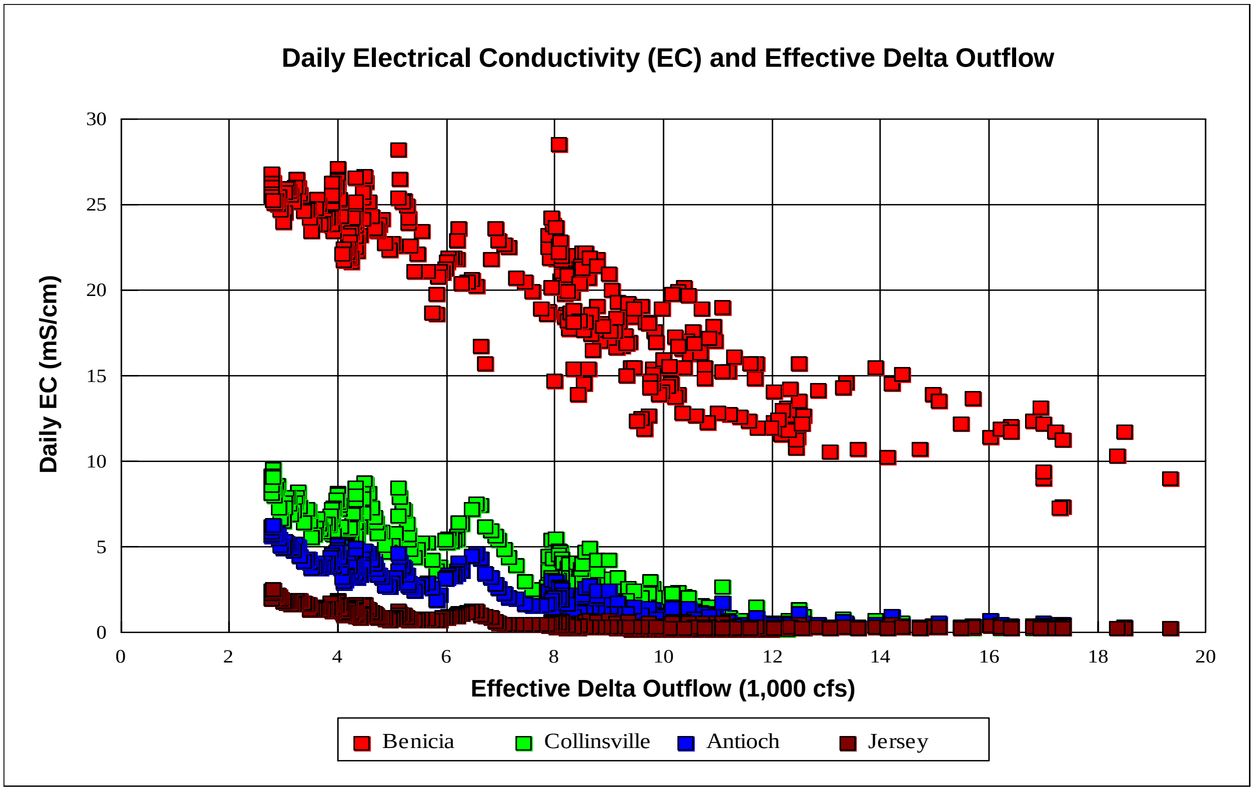
Figure D-132

Estimates of Effective Delta Outflow for Water Year 1987 with Corresponding Electrical Conductivity Measurements during 1987


Daily Electrical Conductivity (EC) and Daily Delta Outflow


Daily Electrical Conductivity (EC) and Effective Delta Outflow

Note: Electrical conductivity at each station is reduced at higher effective outflow. A negative exponential relationship was proposed by Contra Costa Water District staff as the expected relationship for salinity intrusion.

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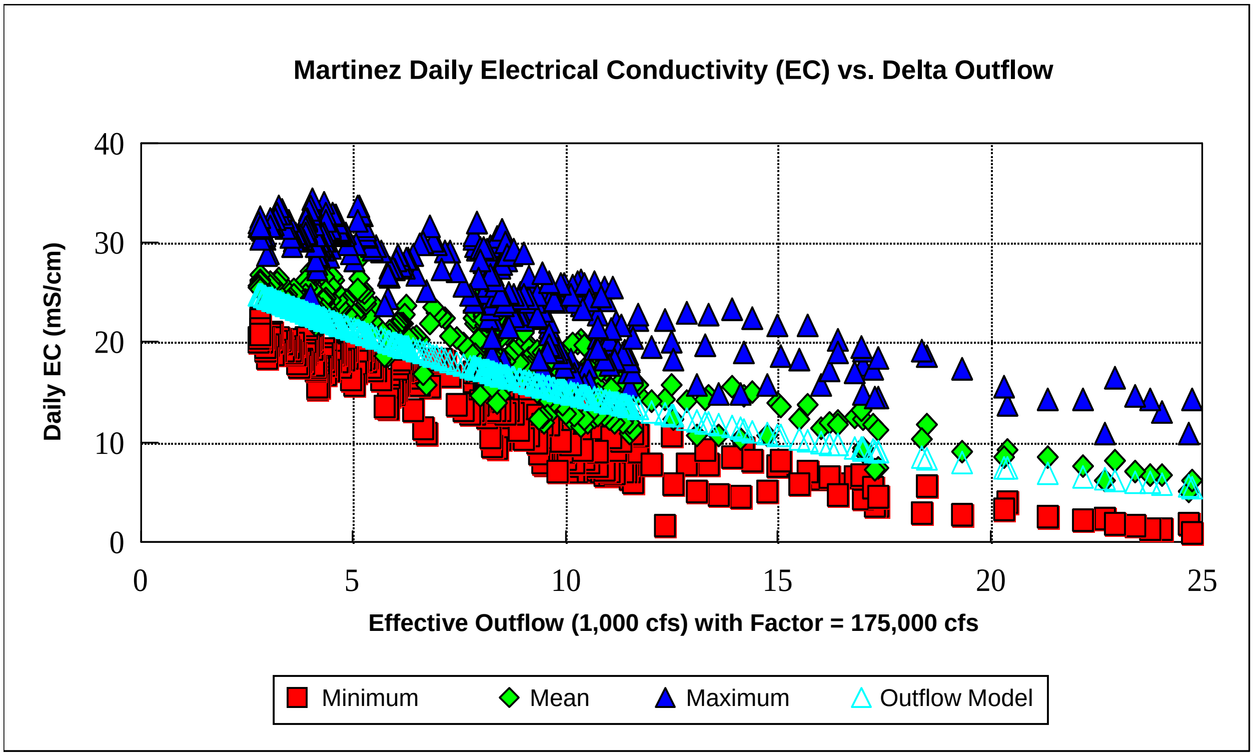
Figure D-133

Measured Daily Electrical Conductivity from Western Delta Stations vs. Daily Delta Outflow and Effective Delta Outflow for Water Year 1987



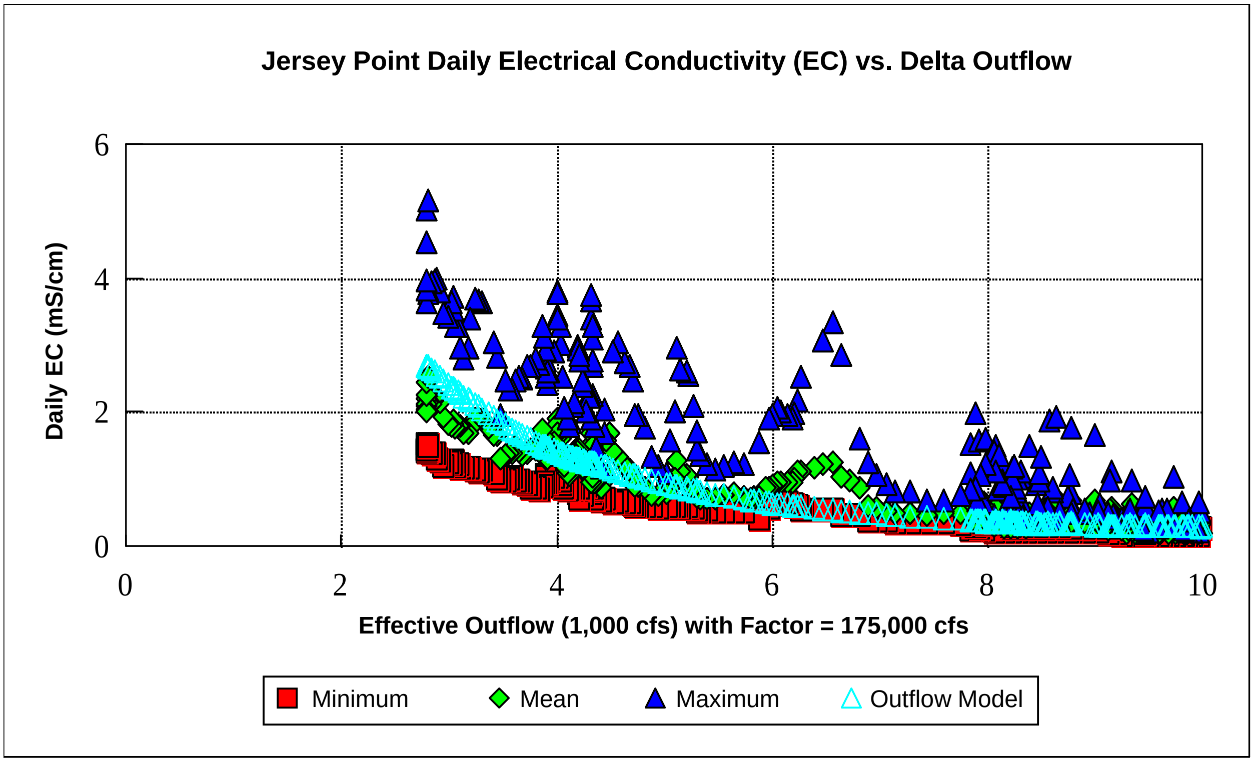
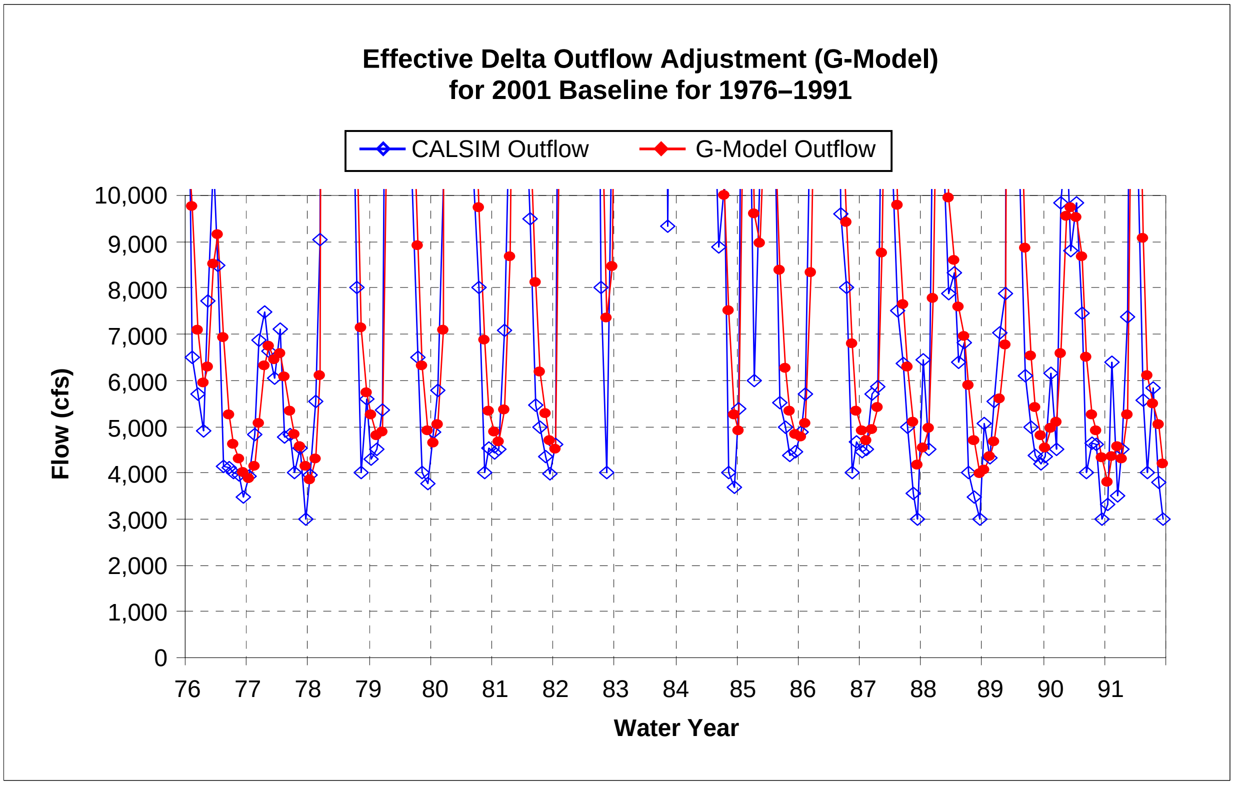


Figure D-134

Relationship (Negative Exponential) between Effective Delta Outflow (cfs) and Electrical Conductivity (mS/cm) at Martinez and Jersey Point for Water Year 1987



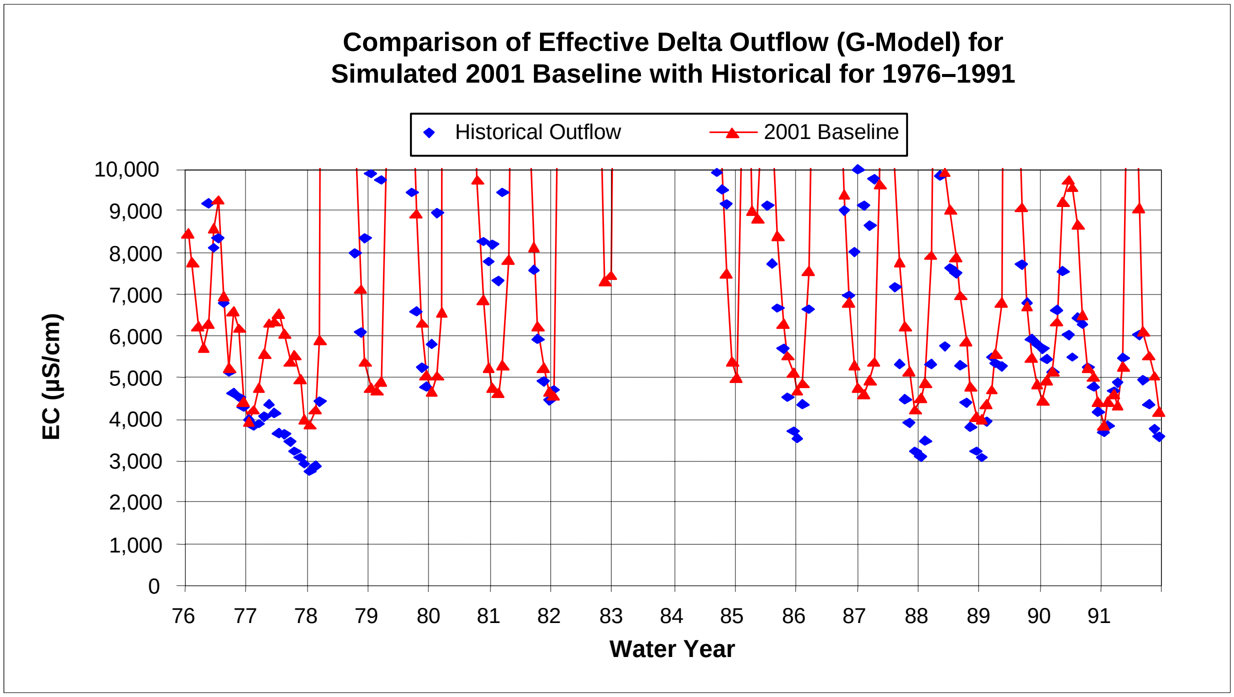


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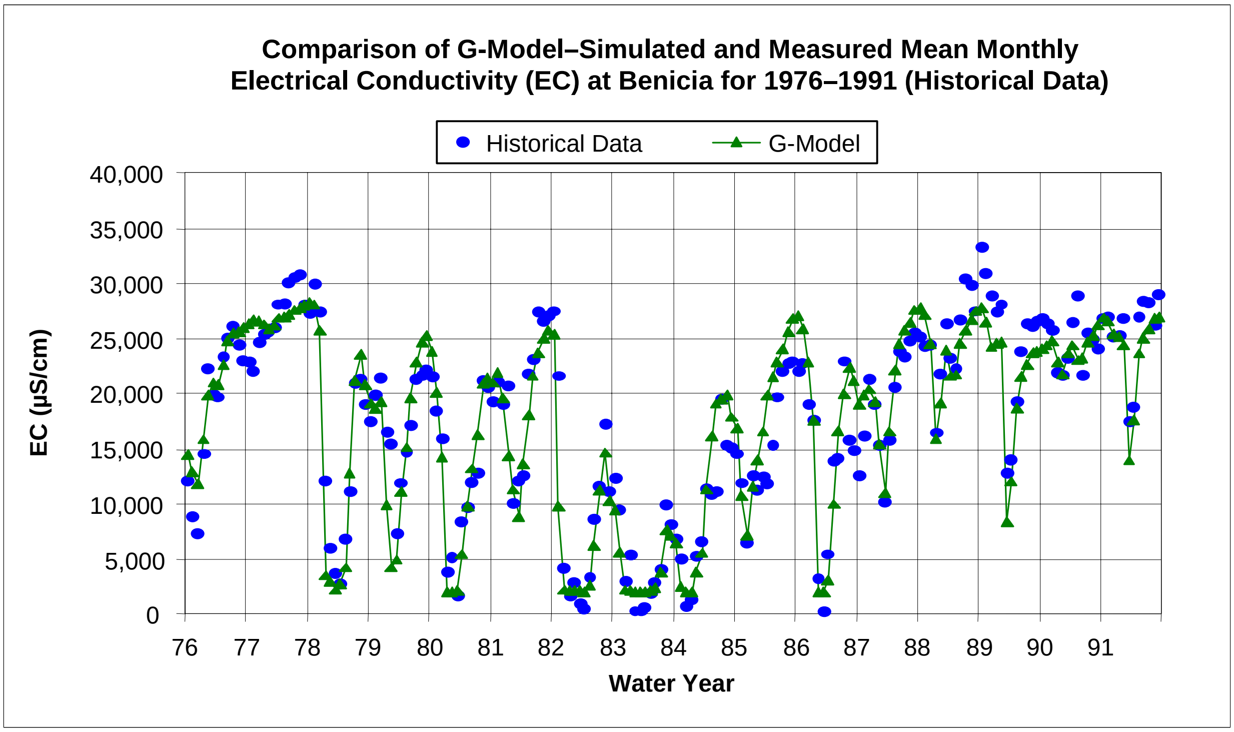
Figure D-135

Adjustments between Monthly CALSIM II Outflow and Effective Outflow for 2001 Baseline and Comparison of the Monthly Historical and 2001 Baseline Effective Outflows for 1976–1991



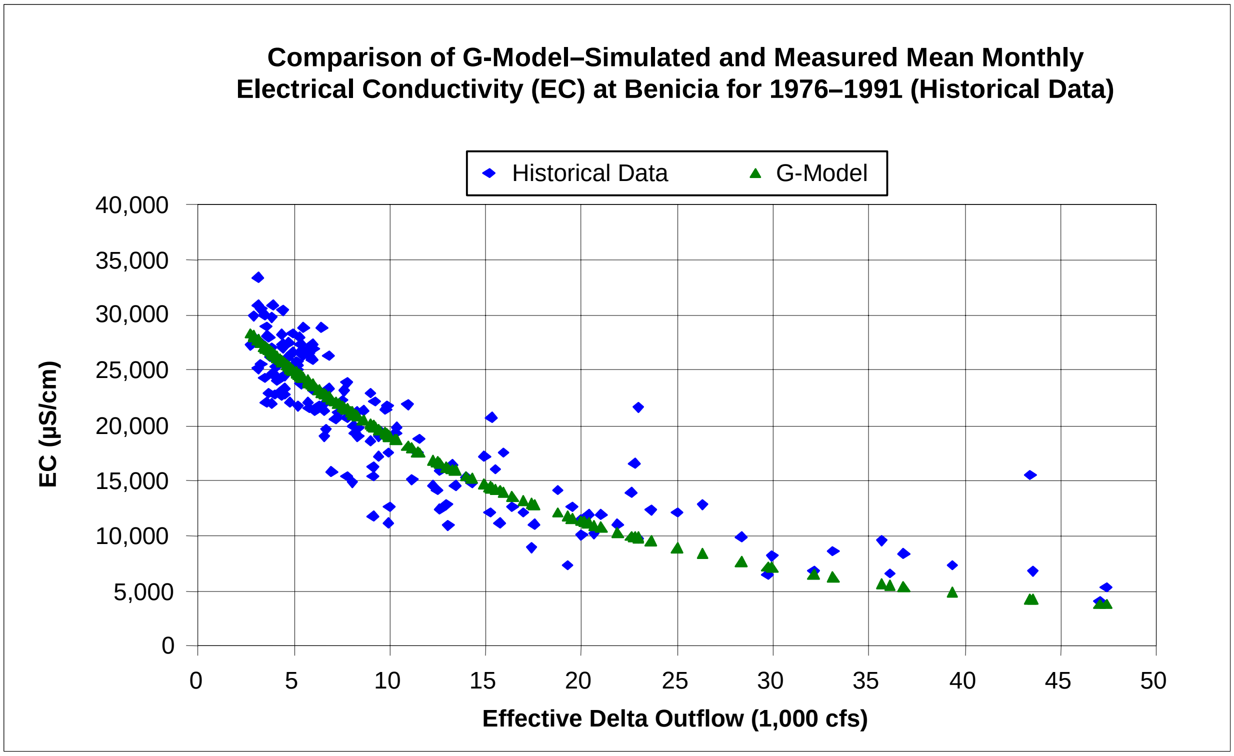


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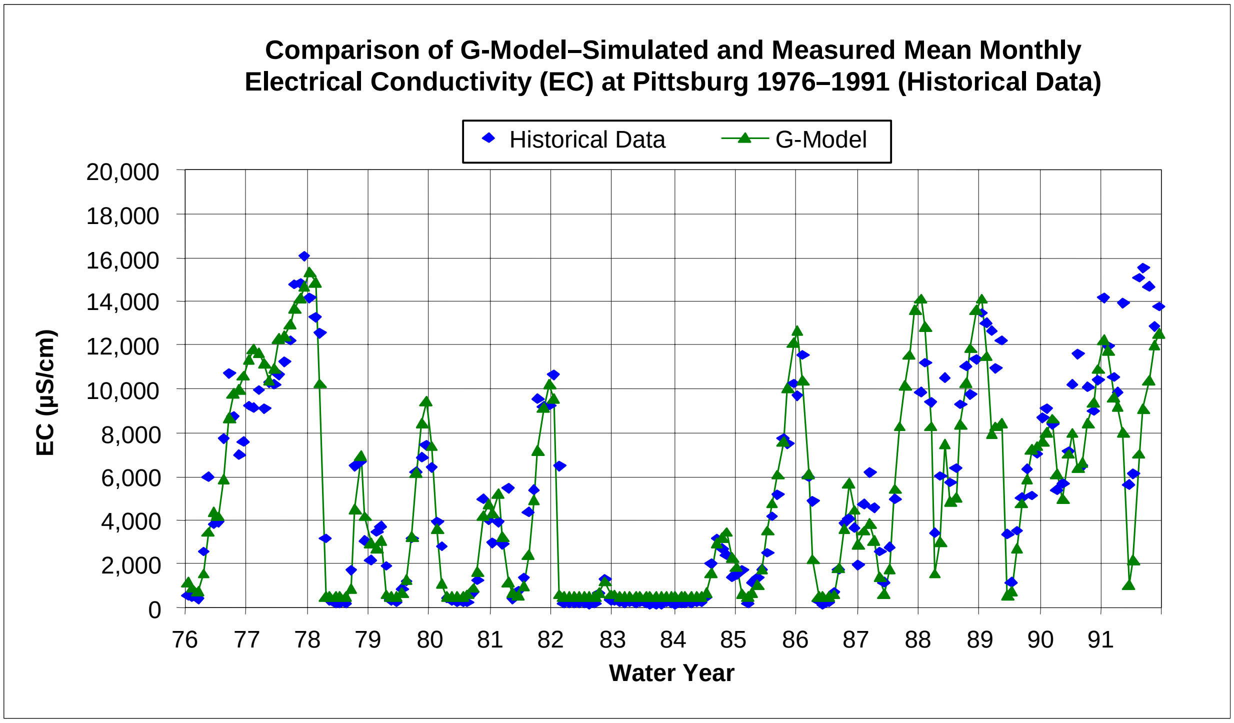
Figure D-136

Comparison of Historical Electrical Conductivity Measurements and Effective Outflow Electrical Conductivity Estimates at Benicia for 1976–1991



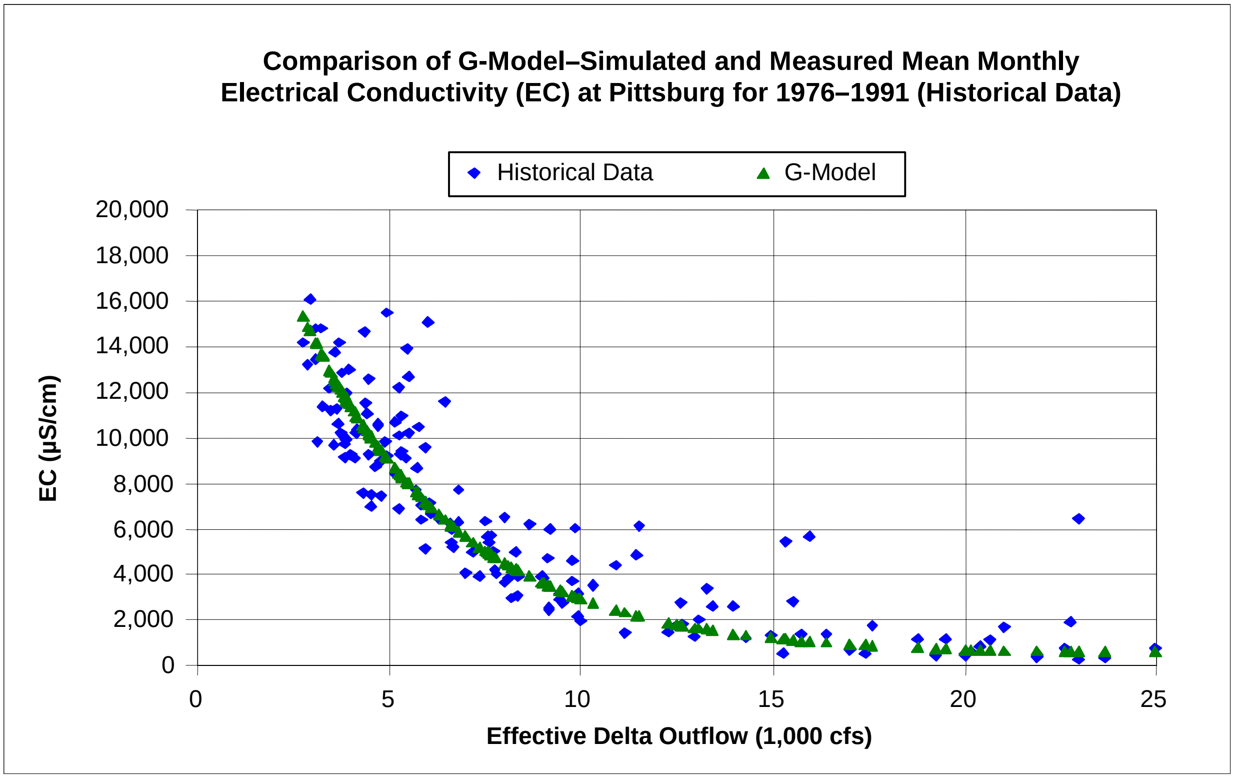


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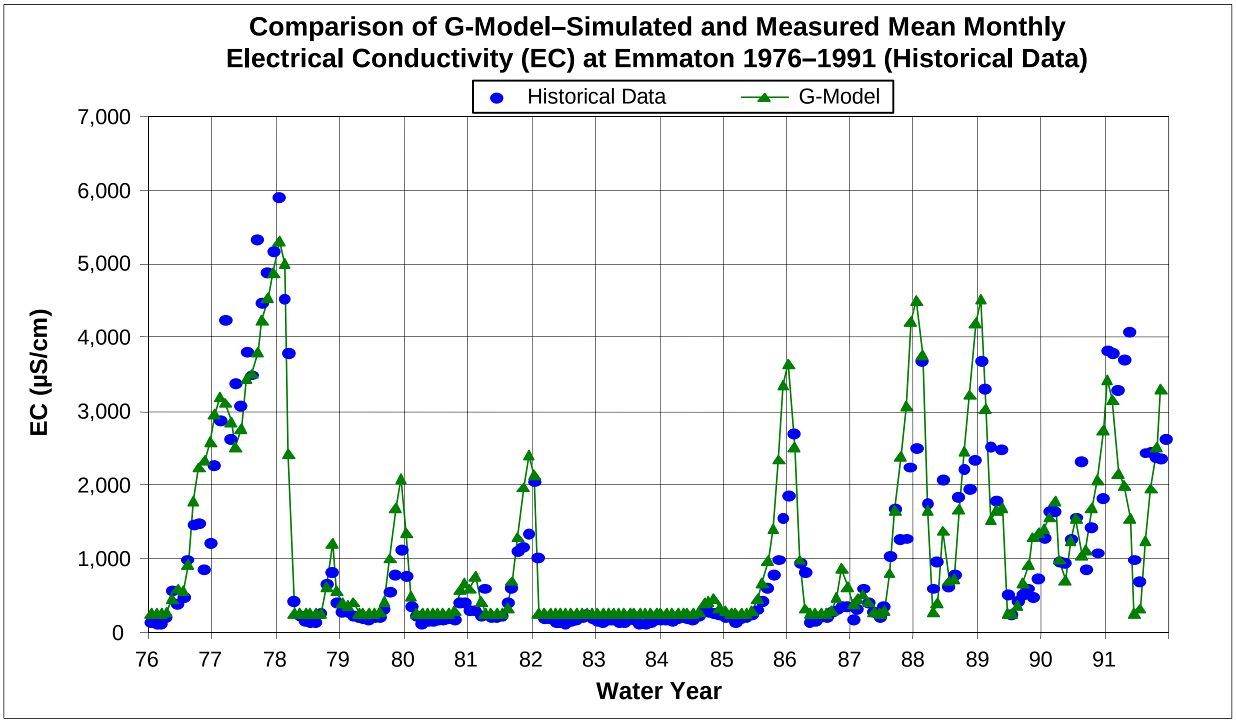
Figure D-137

Comparison of Historical Electrical Conductivity Measurements and Effective Outflow Electrical Conductivity Estimates at Pittsburg (Upstream of Chipps Island) for 1976–1991



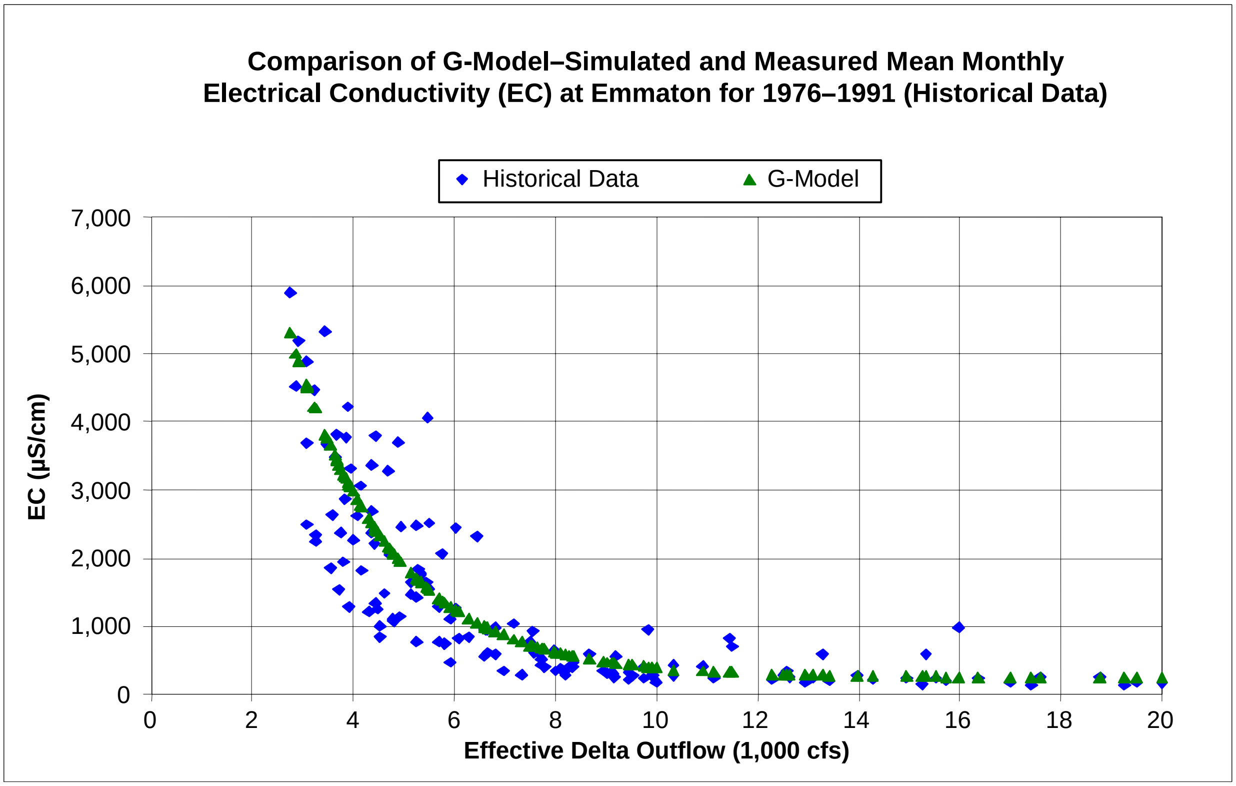


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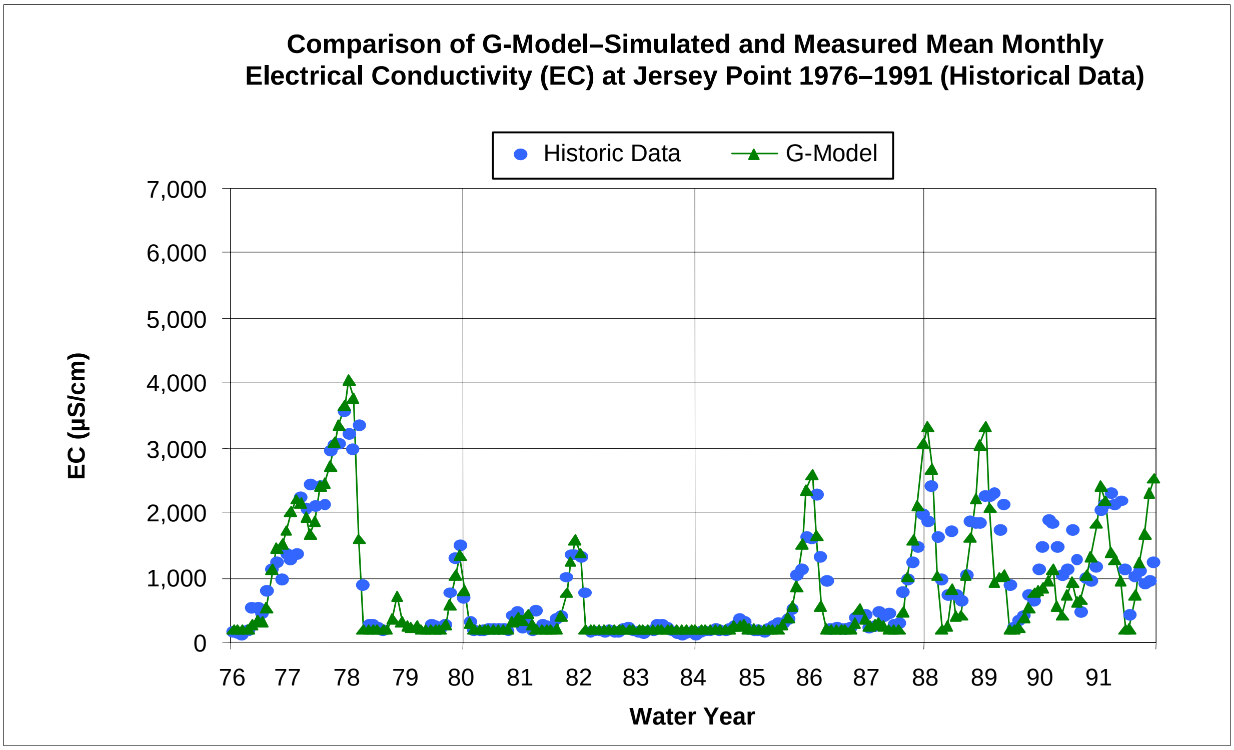
Figure D-138

Comparison of Historical Electrical Conductivity Measurements and Effective Outflow Electrical Conductivity Estimates at Emmaton for 1976–1991



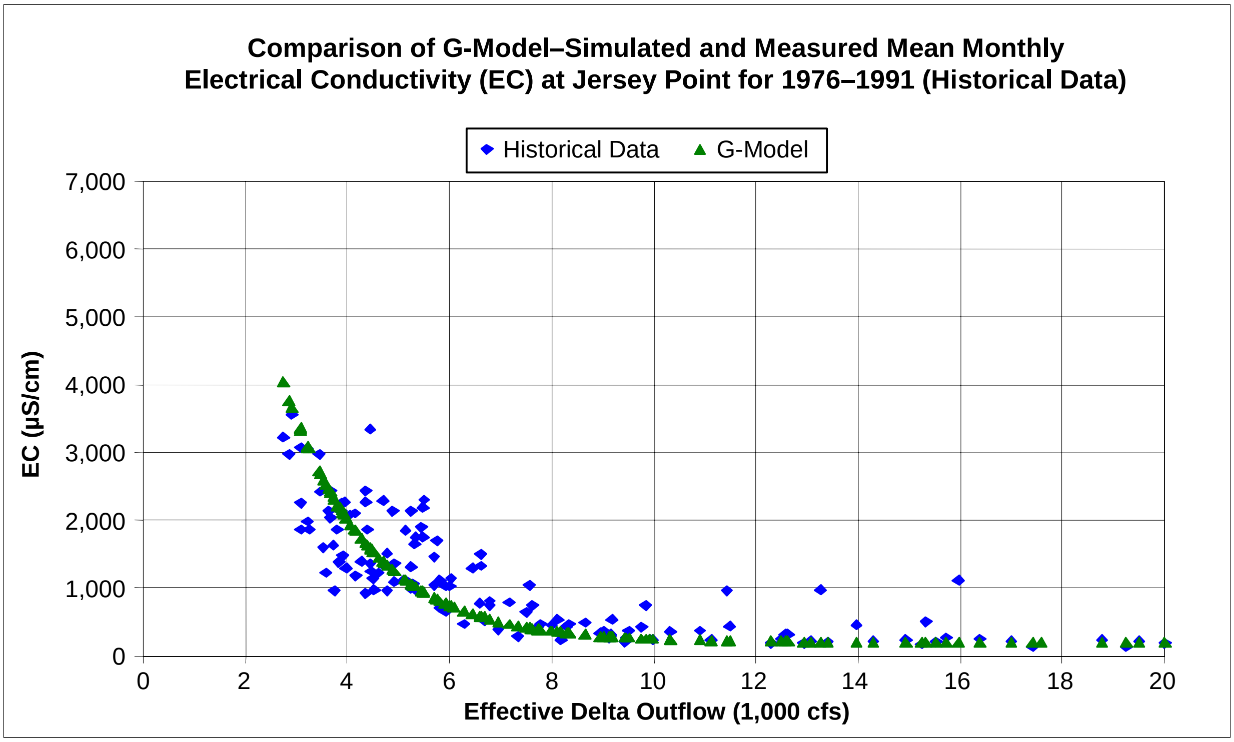


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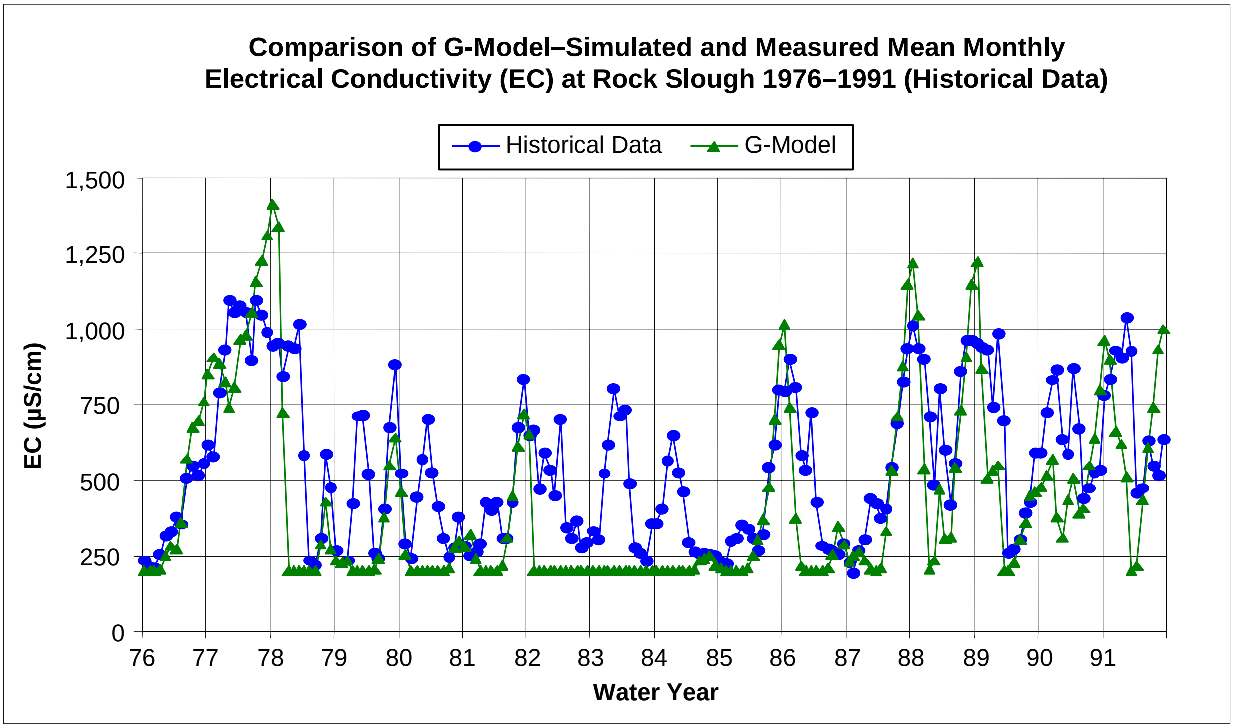
Figure D-139

Comparison of Historical Electrical Conductivity Measurements and Effective Outflow Electrical Conductivity Estimates at Jersey Point for 1976–1991



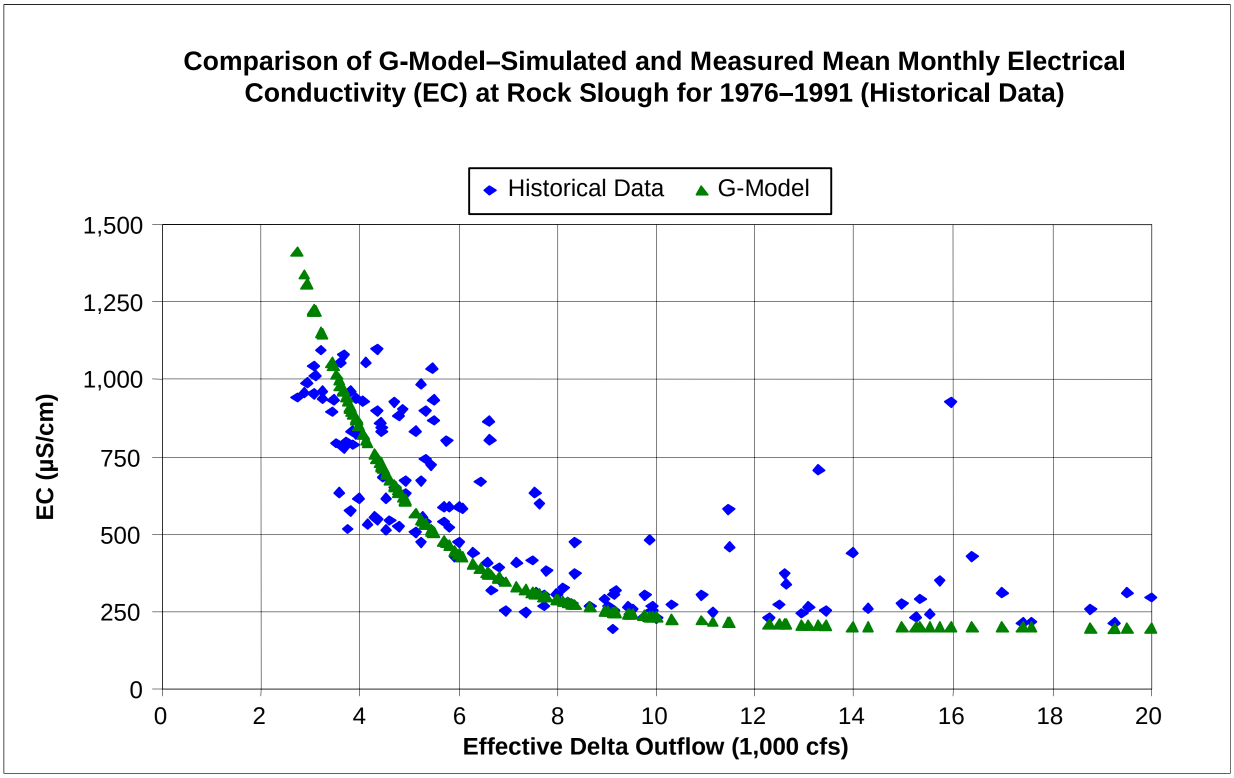


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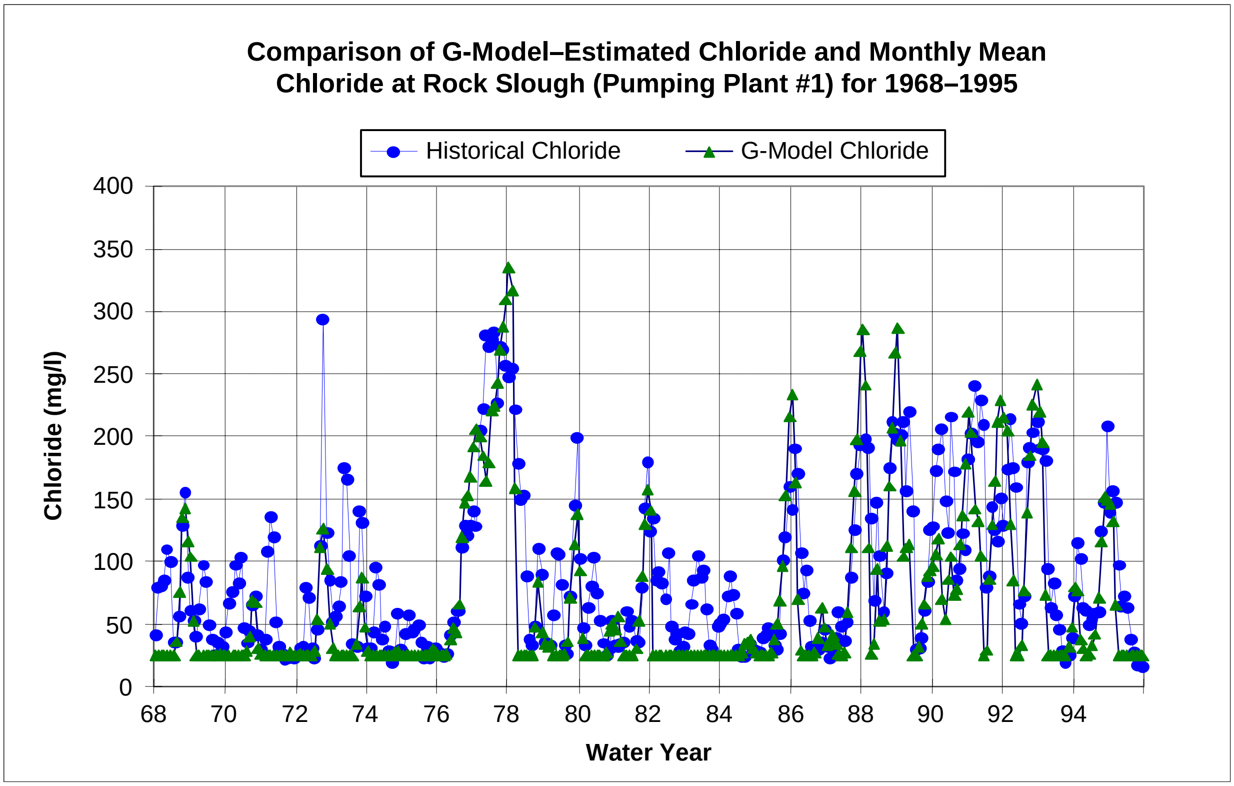
Figure D-140

Comparison of Historical Electrical Conductivity Measurements and Effective Outflow Electrical Conductivity Estimates at Rock Slough for 1976–1991



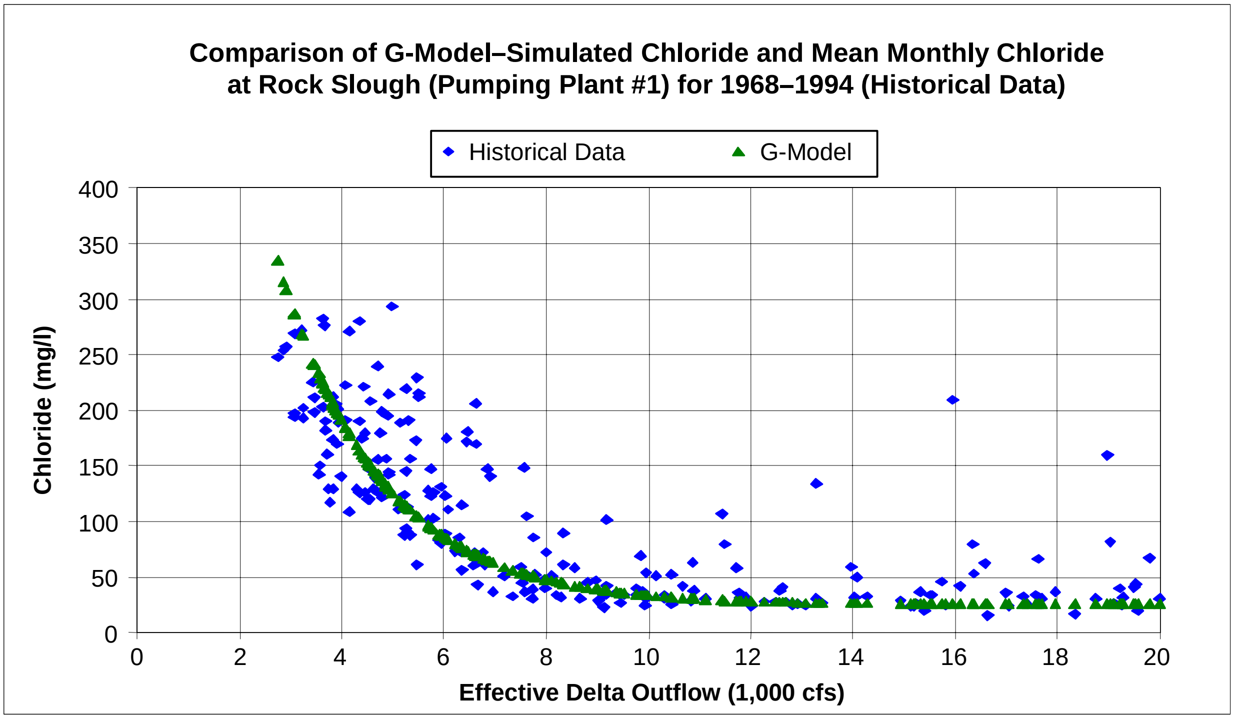


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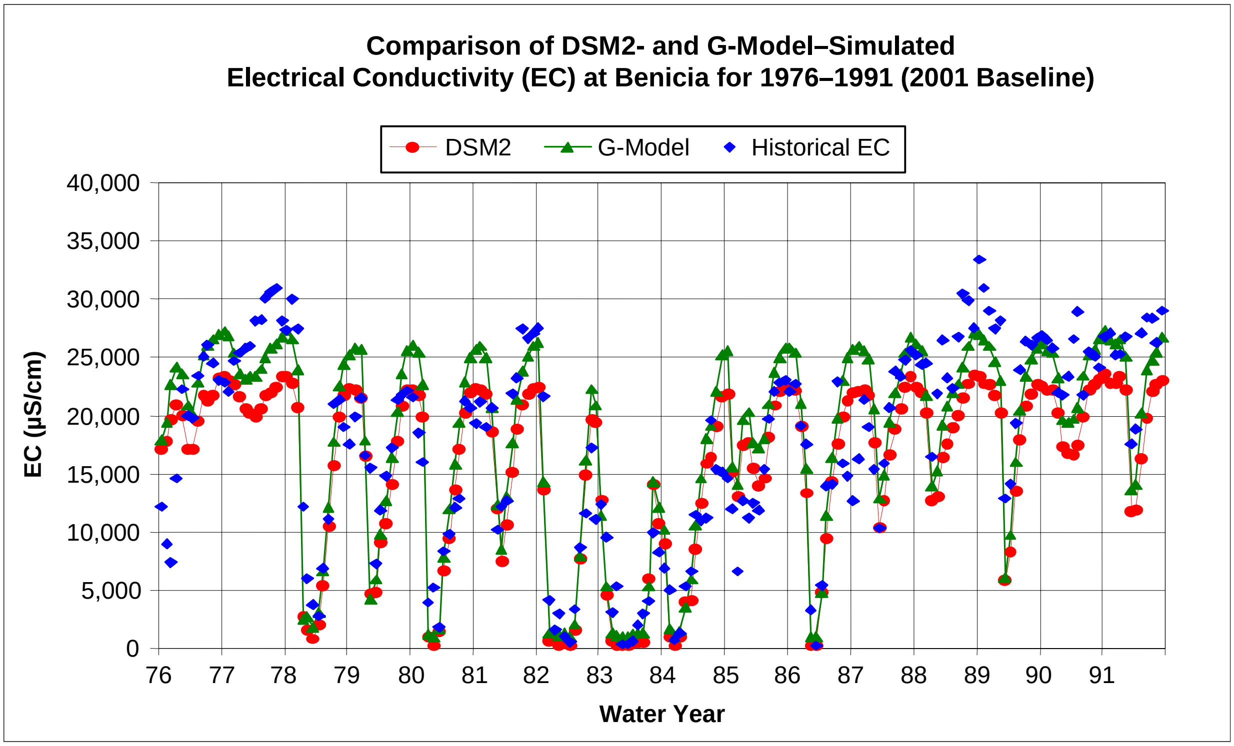
Figure D-141

Comparison of Historical Chloride Measurements and Effective Outflow Chloride Estimates at Rock Slough for 1976–1991



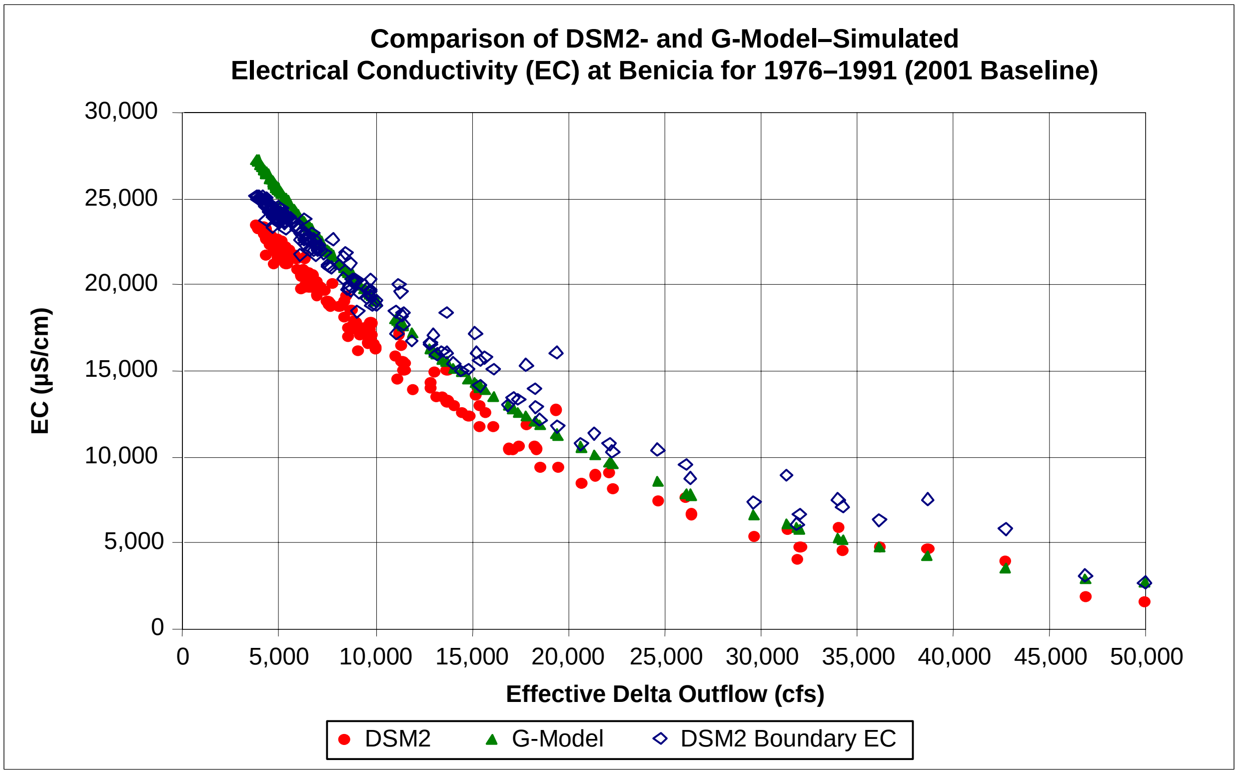


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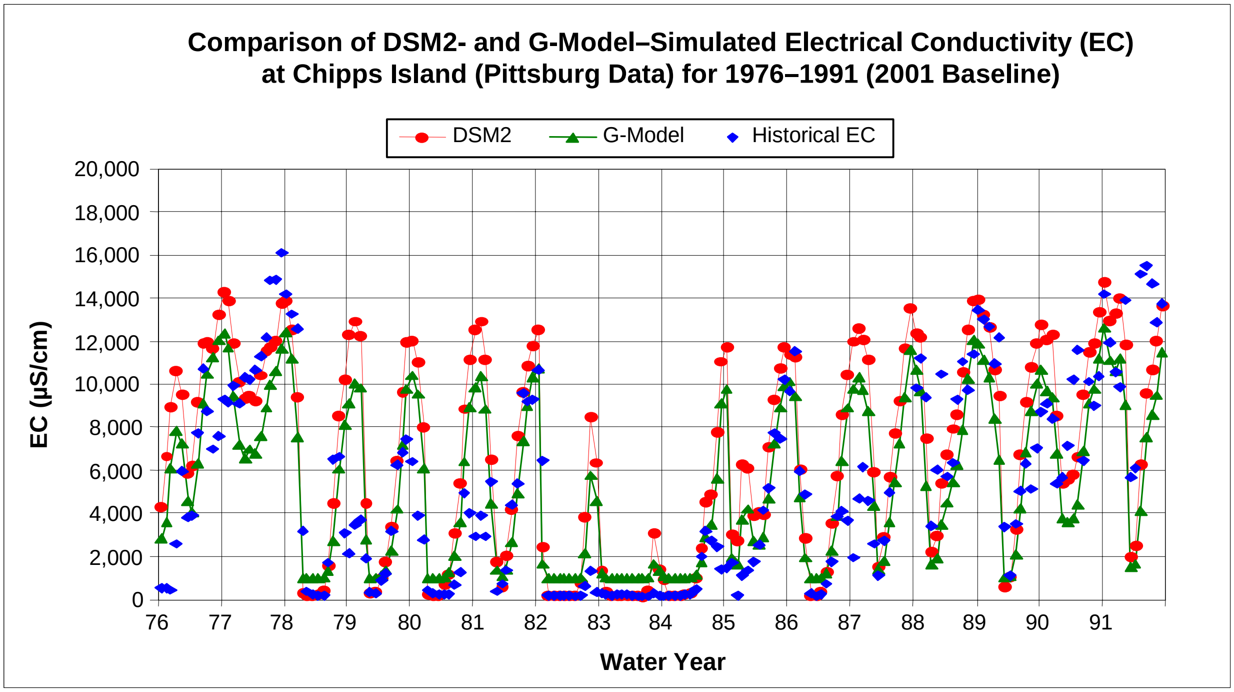
Figure D-142

Comparison of DSM2-Simulated Electrical Conductivity (EC) at Benicia and EC Estimates from Effective Outflow for 2001 Baseline with Historical EC for 1976–1991



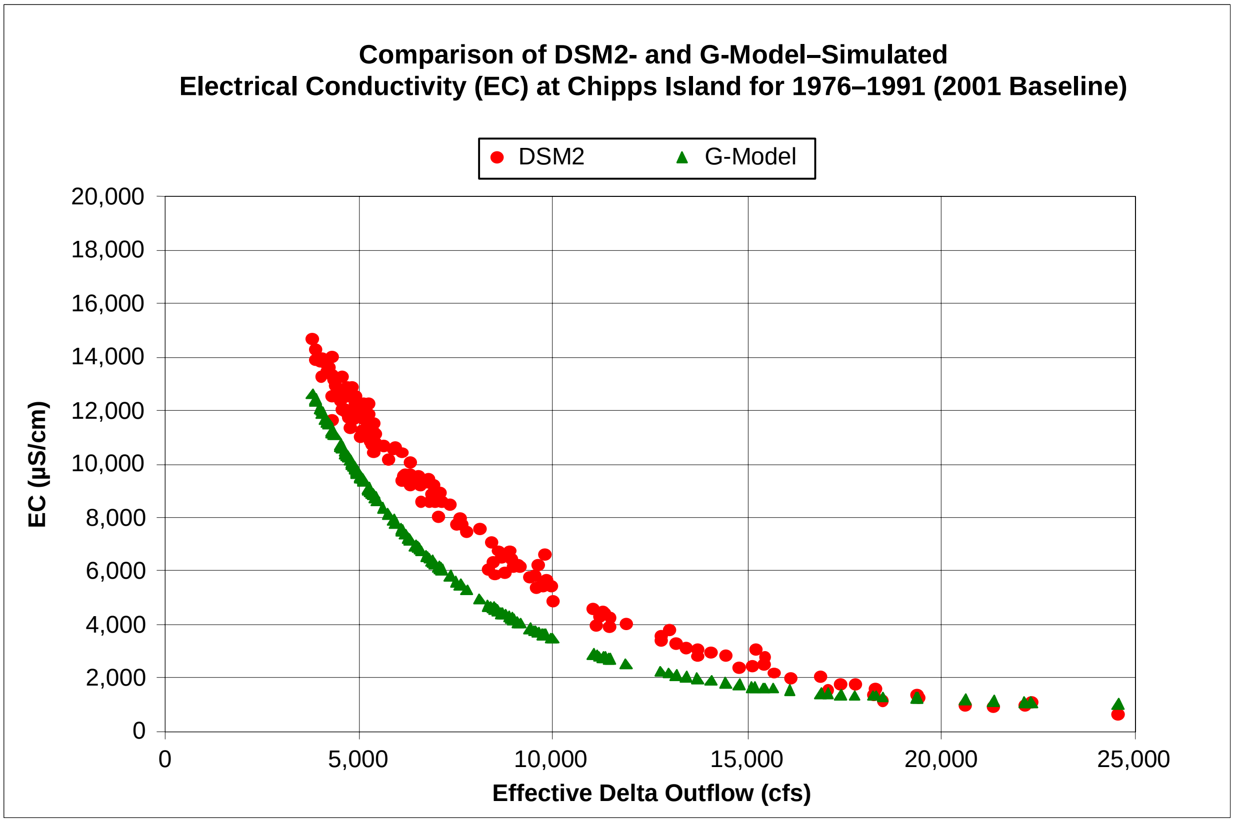


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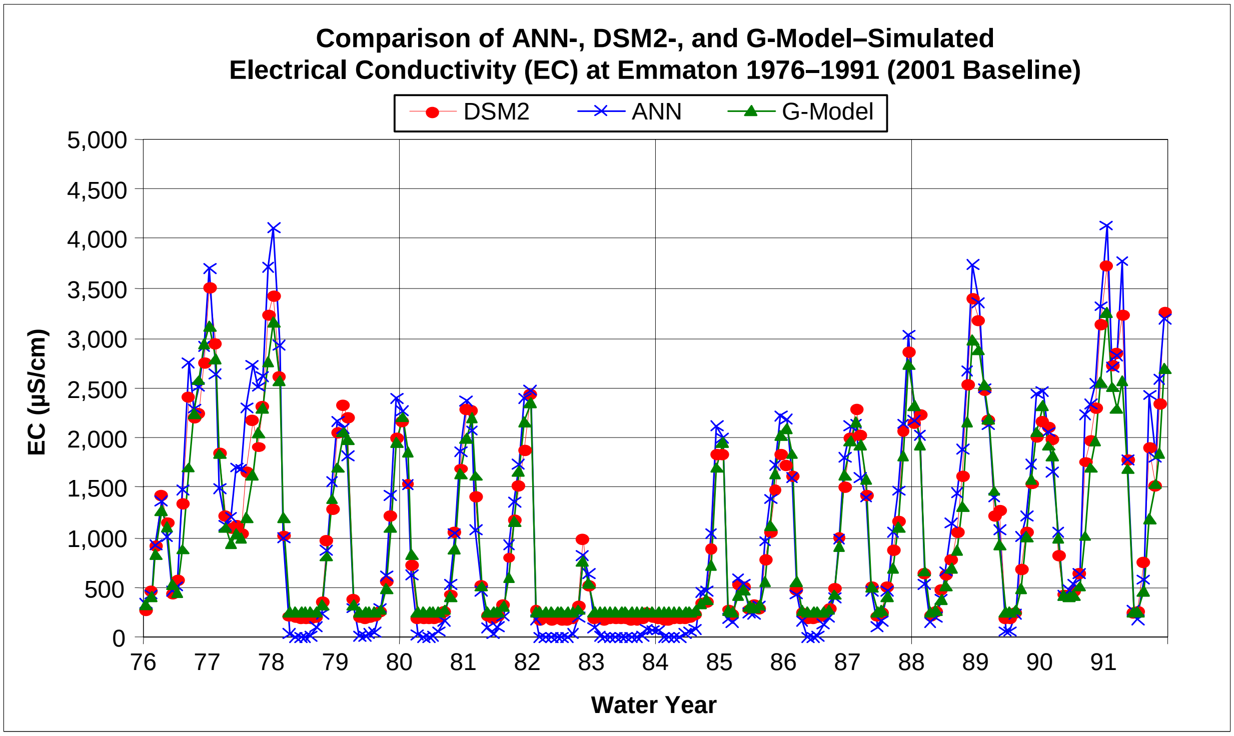
Figure D-143

Comparison of DSM2-Simulated Electrical Conductivity (EC) at Chipps Island and EC Estimates from Effective Outflow for 2001 Baseline with Historical EC for 1976–1991



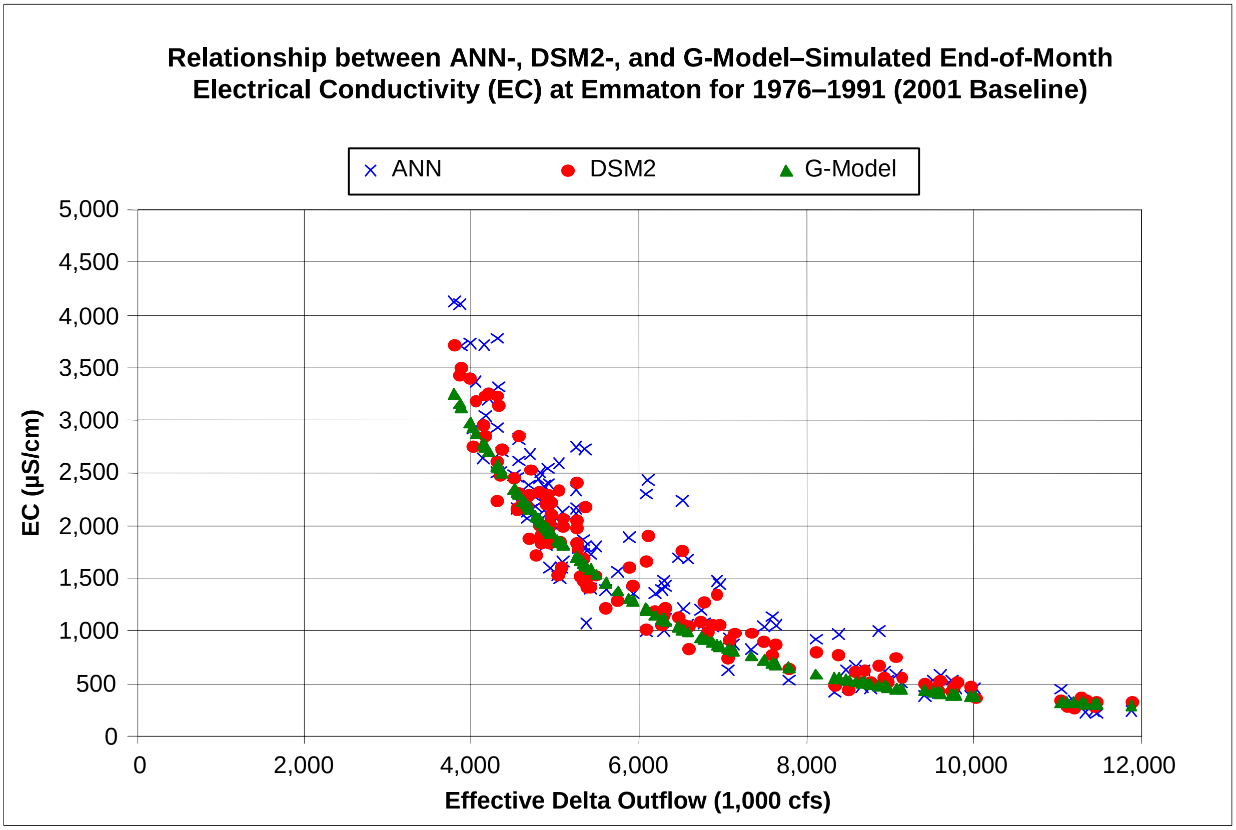


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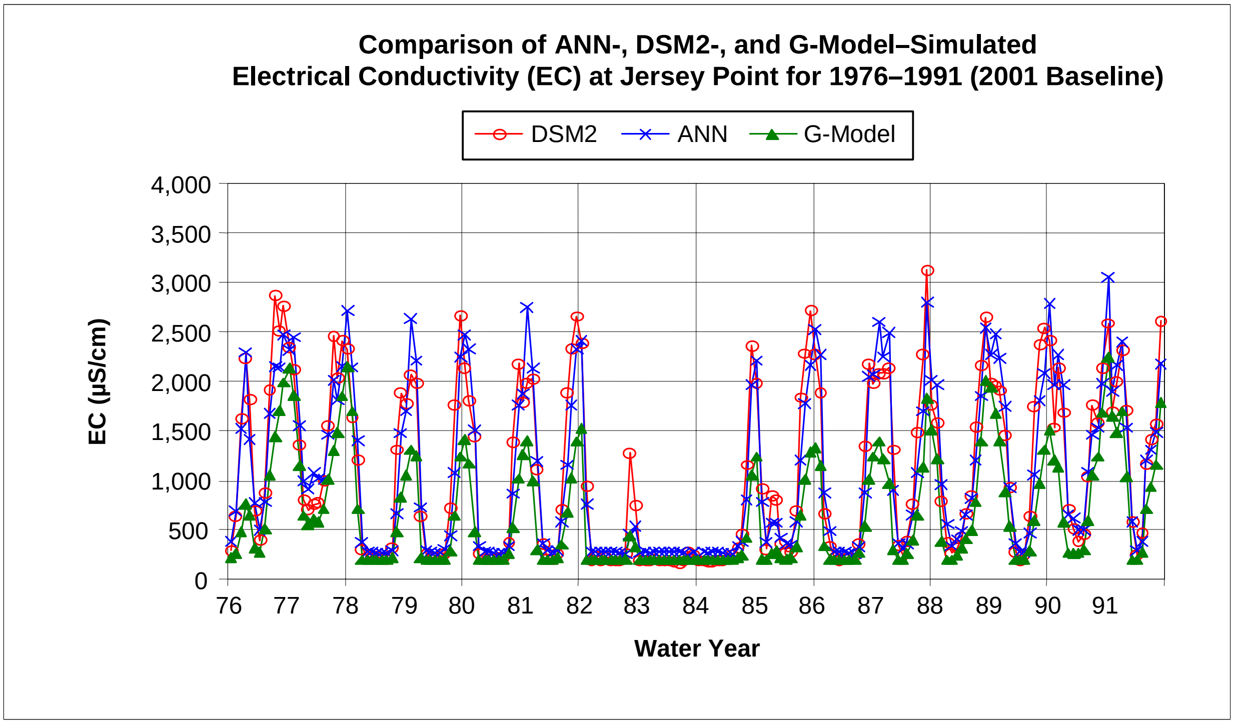
Figure D-144

Comparison of DSM2-Simulated Electrical Conductivity (EC) at Emmaton and EC Estimates from Effective Outflow and CALSIM-ANN for 2001 Baseline for 1976–1991



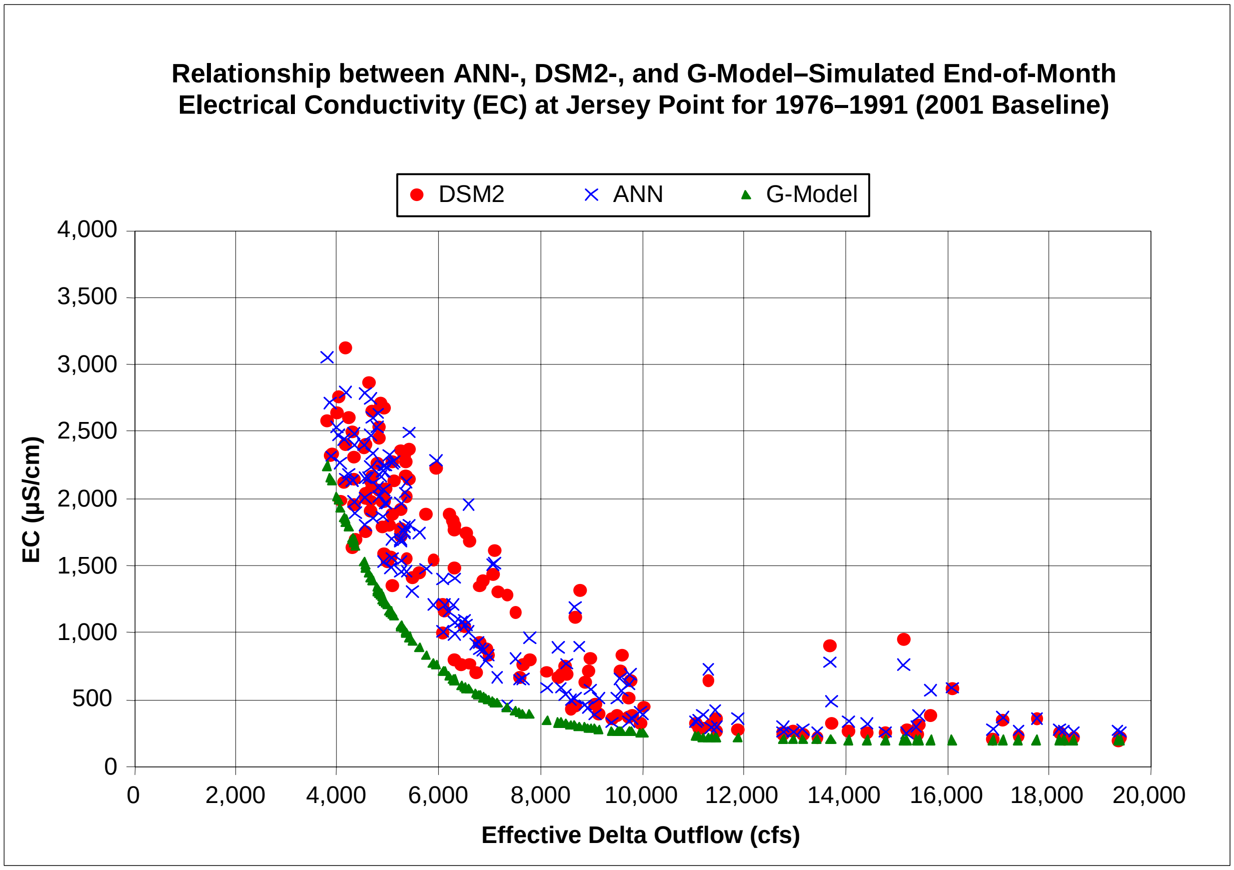


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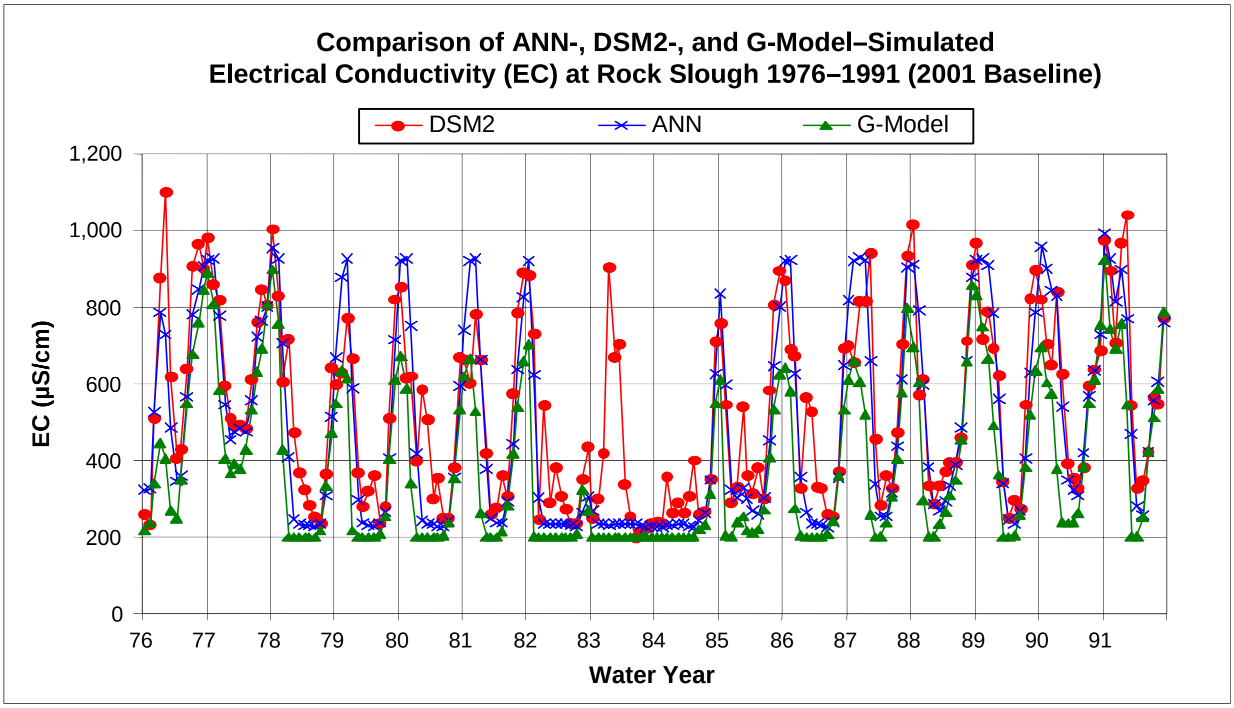
Figure D-145

Comparison of DSM2-Simulated Electrical Conductivity (EC) at Jersey Point and EC Estimates from Effective Outflow and CALSIM-ANN for 2001 Baseline for 1976–1991



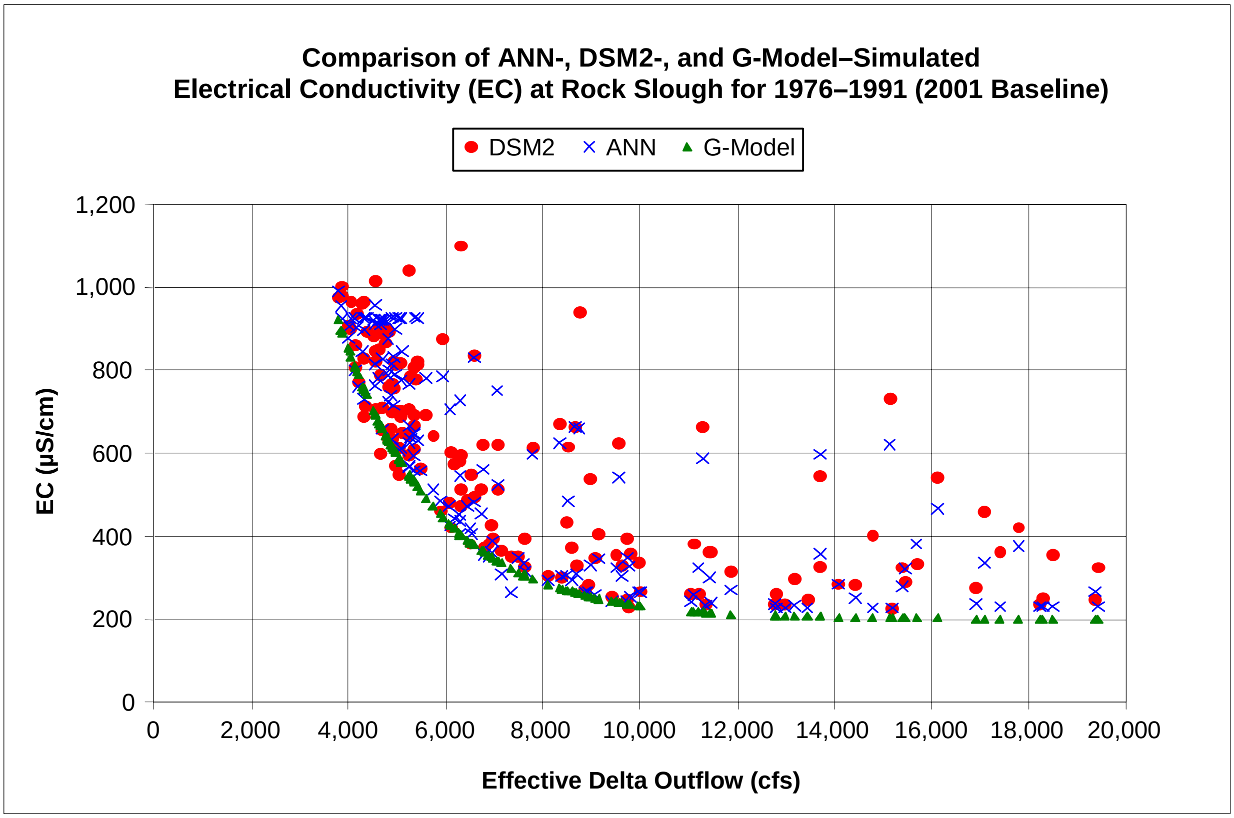


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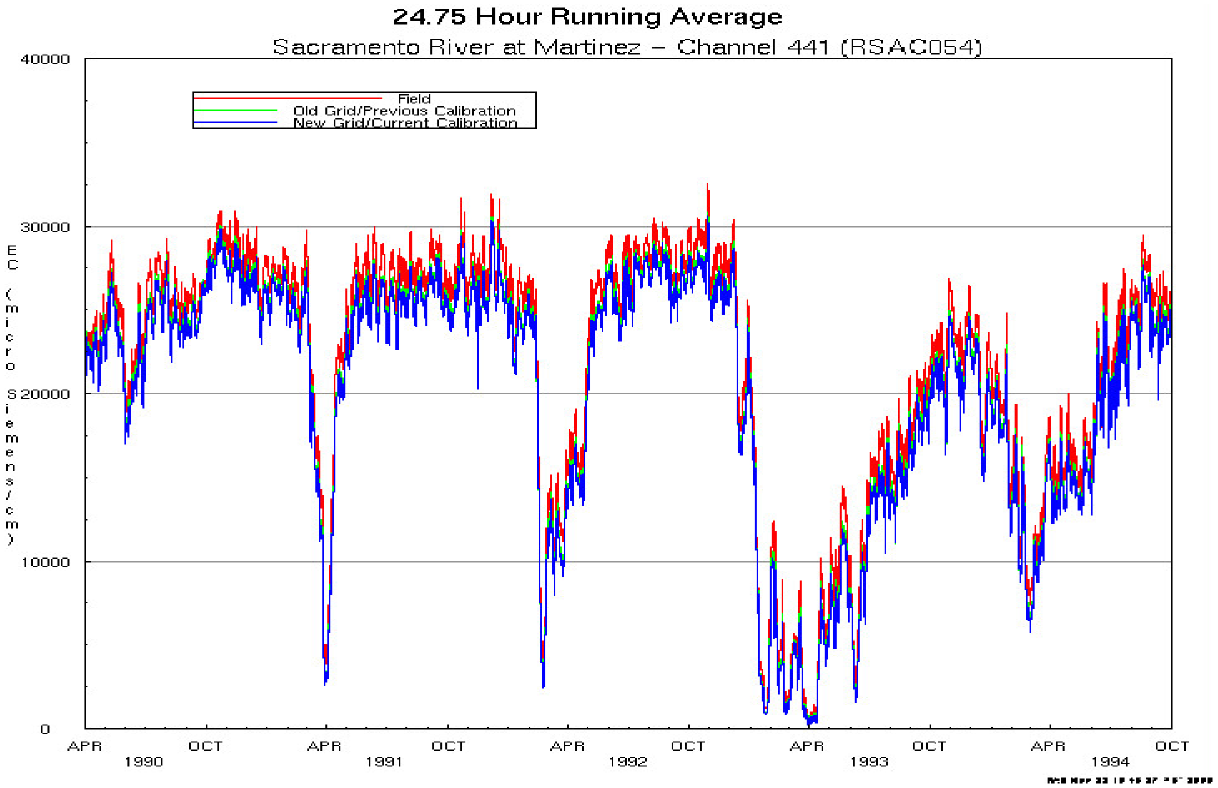
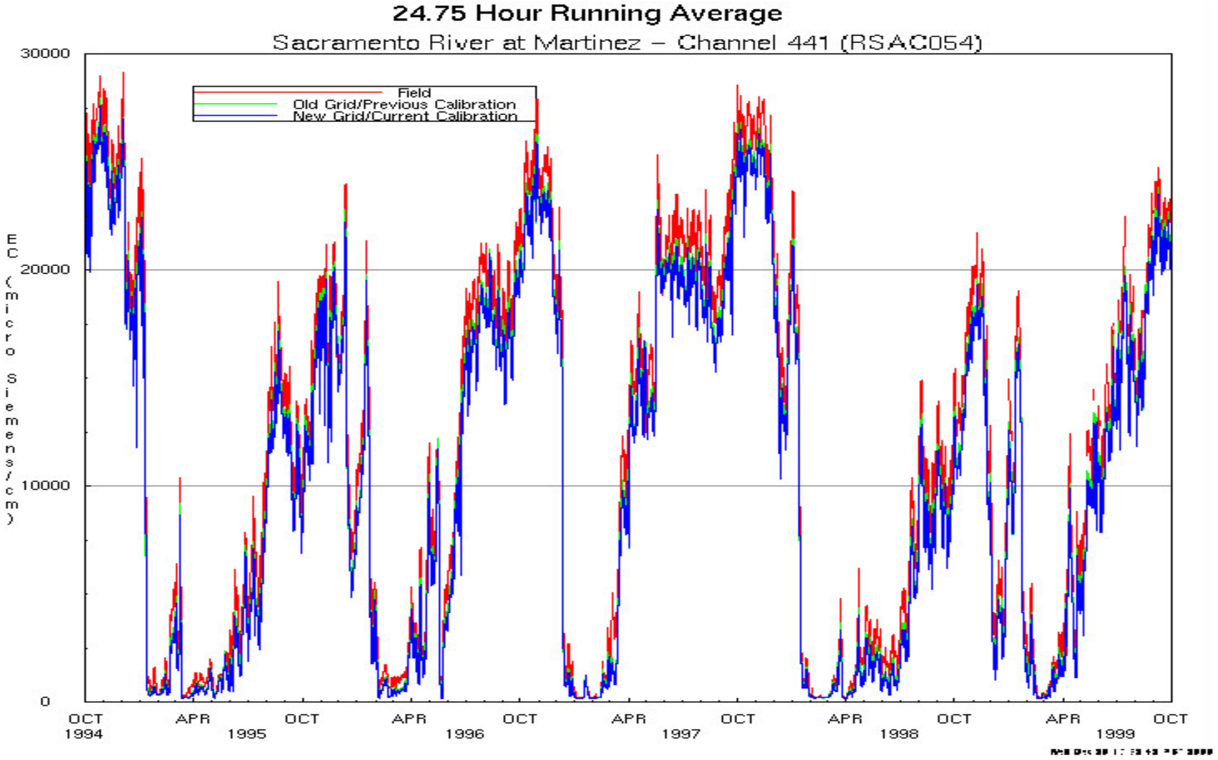
Figure D-146

Comparison of DSM2-Simulated Electrical Conductivity (EC) at Rock Slough and EC Estimates from Effective Outflow and CALSIM-ANN for 2001 Baseline for 1976–1991





Note: Martinez is the downstream model boundary.

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Figure D-147

DSM2-Simulated Daily Electrical Conductivity (EC) at Martinez

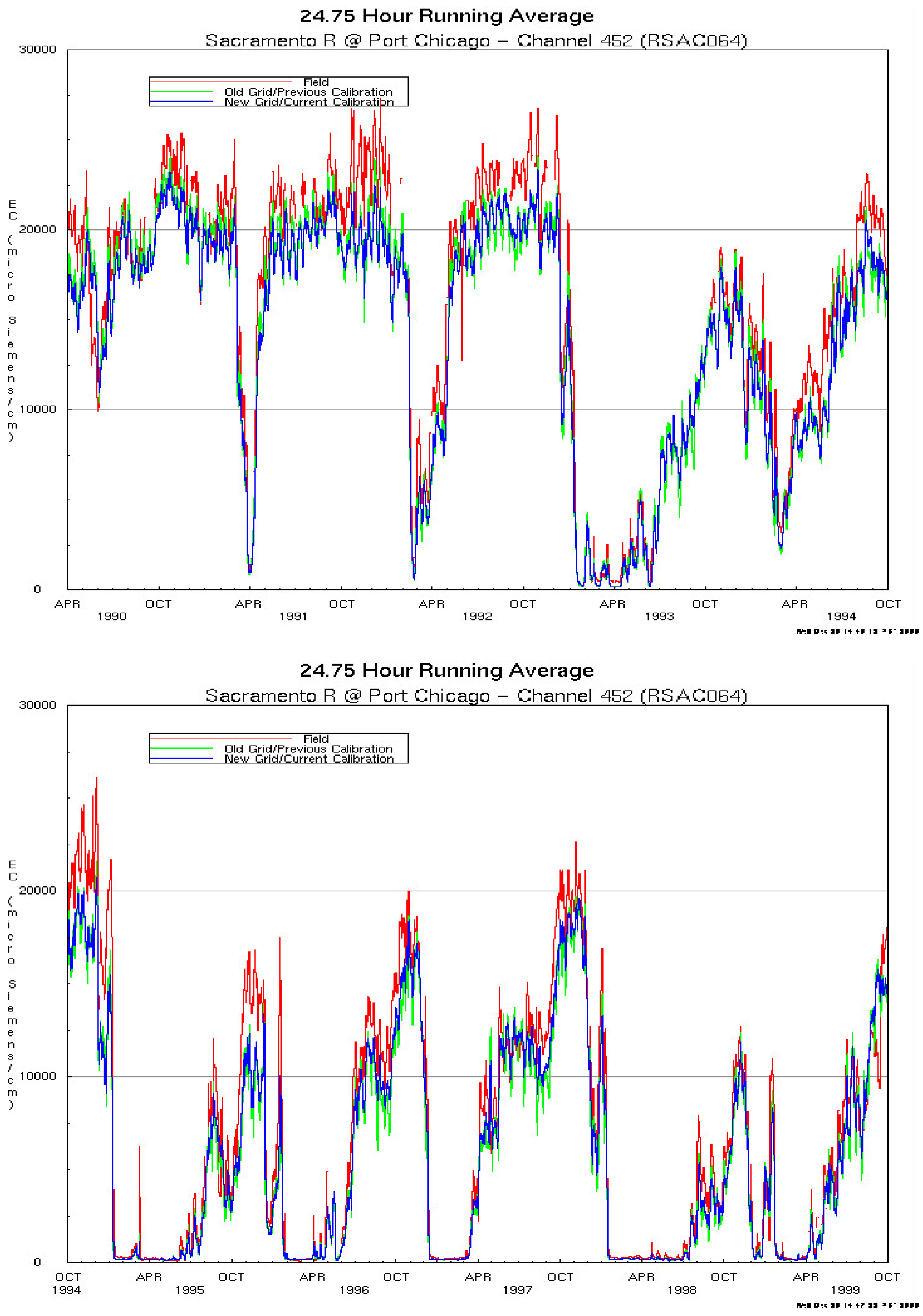

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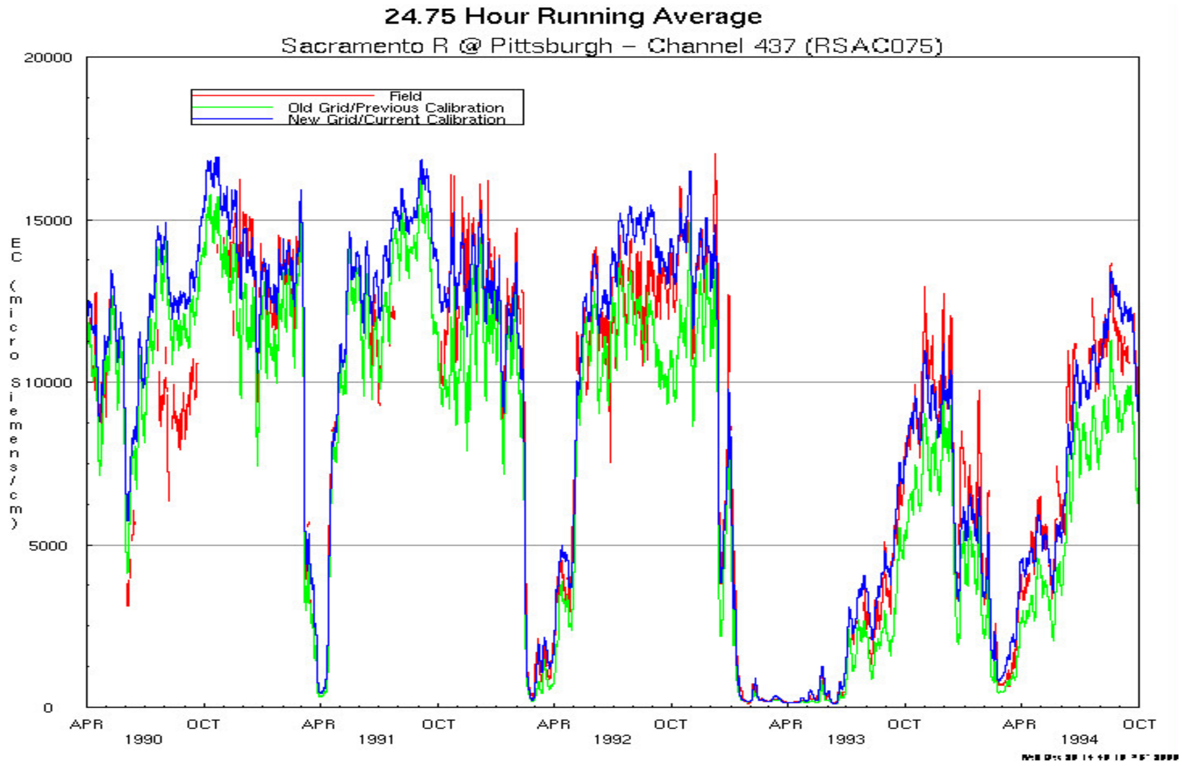
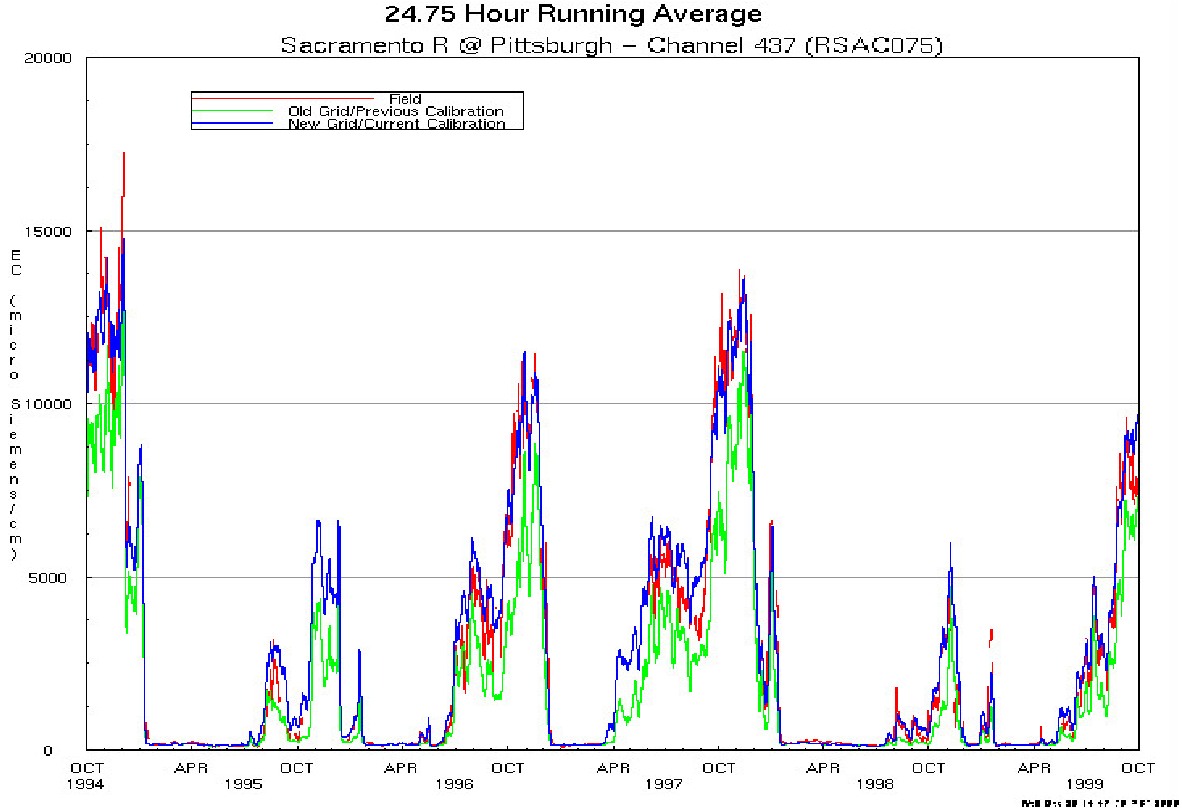
Figure D-148

DSM2-Simulated Daily Electrical Conductivity (EC) at Port Chicago for 1990–1999



24.75 Hour Running Average

Sacramento R @ Pittsburgh – Channel 437 (RSAC075)



24.75 Hour Running Average

Sacramento R @ Pittsburgh – Channel 437 (RSAC075)

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Figure D-149

DSM2-Simulated Daily Electrical Conductivity (EC) in the Sacramento River at Mallard Slough for 1990–1999

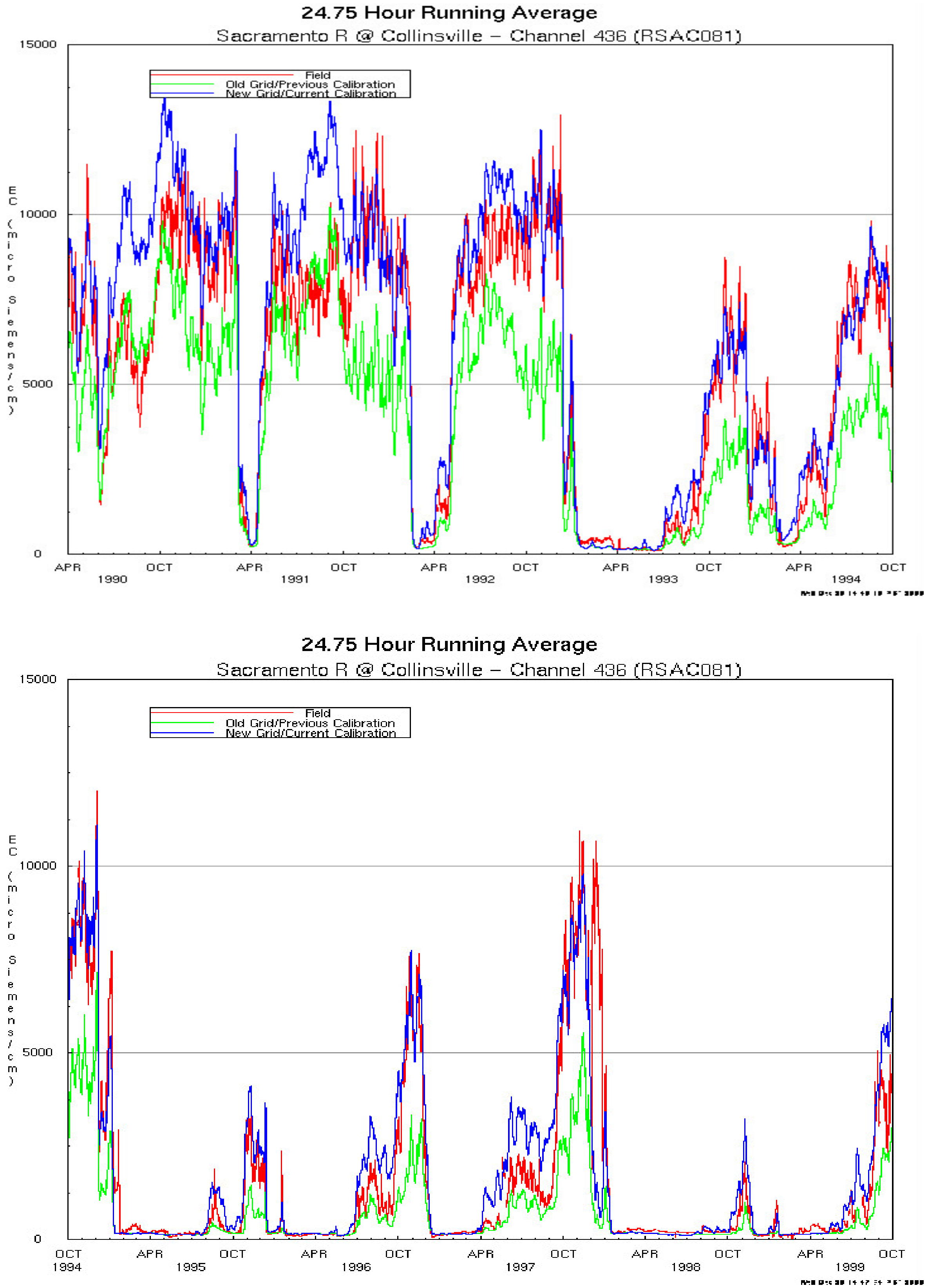

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Figure D-150

DSM2–Simulated Electrical Conductivity (EC) in the Sacramento River at Collinsville for 1990–1999

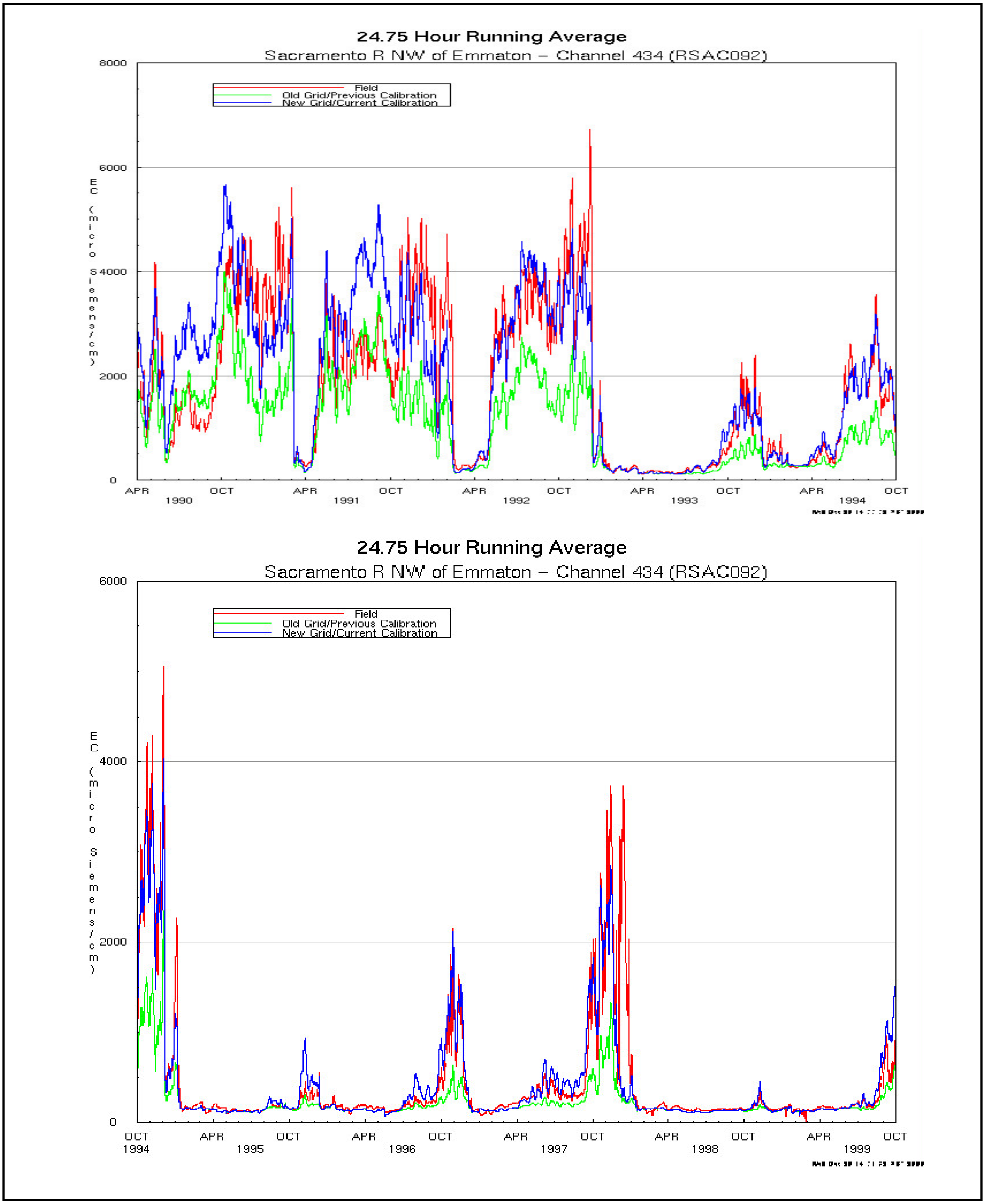

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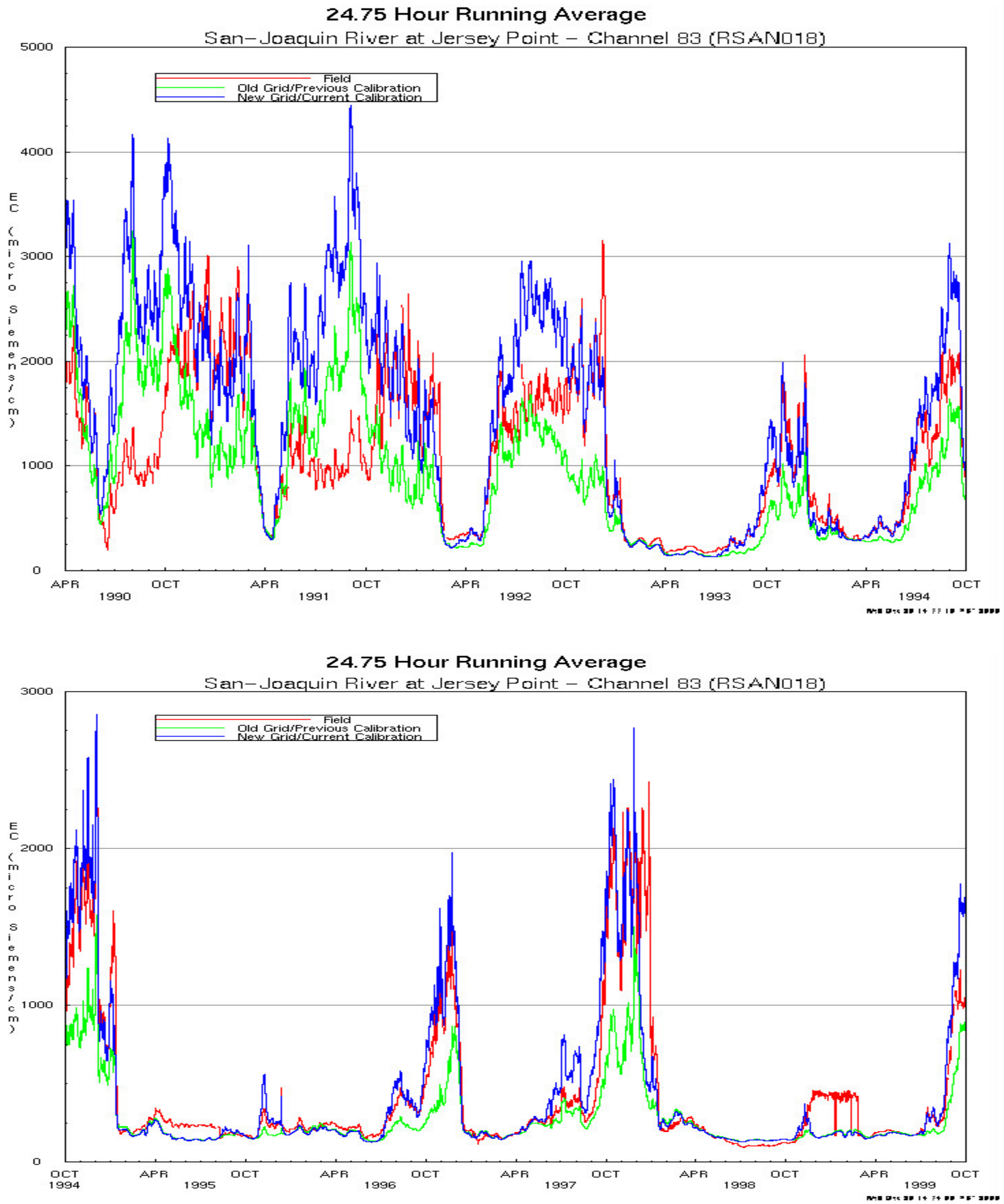
Figure D-151

DSM2-Simulated and Measured Daily Average Electrical Conductivity (EC) in the Sacramento River at Emmaton for 1990–1999



Note: The DSM2-Simulated daily electrical conductivity at Jersey Point for 1990–1999 did not match well in low-flow years of 1990–1992.

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Figure D-152

DSM2-Simulated Daily Electrical Conductivity (EC) in the Sacramento River at Jersey Point for 1990–1999

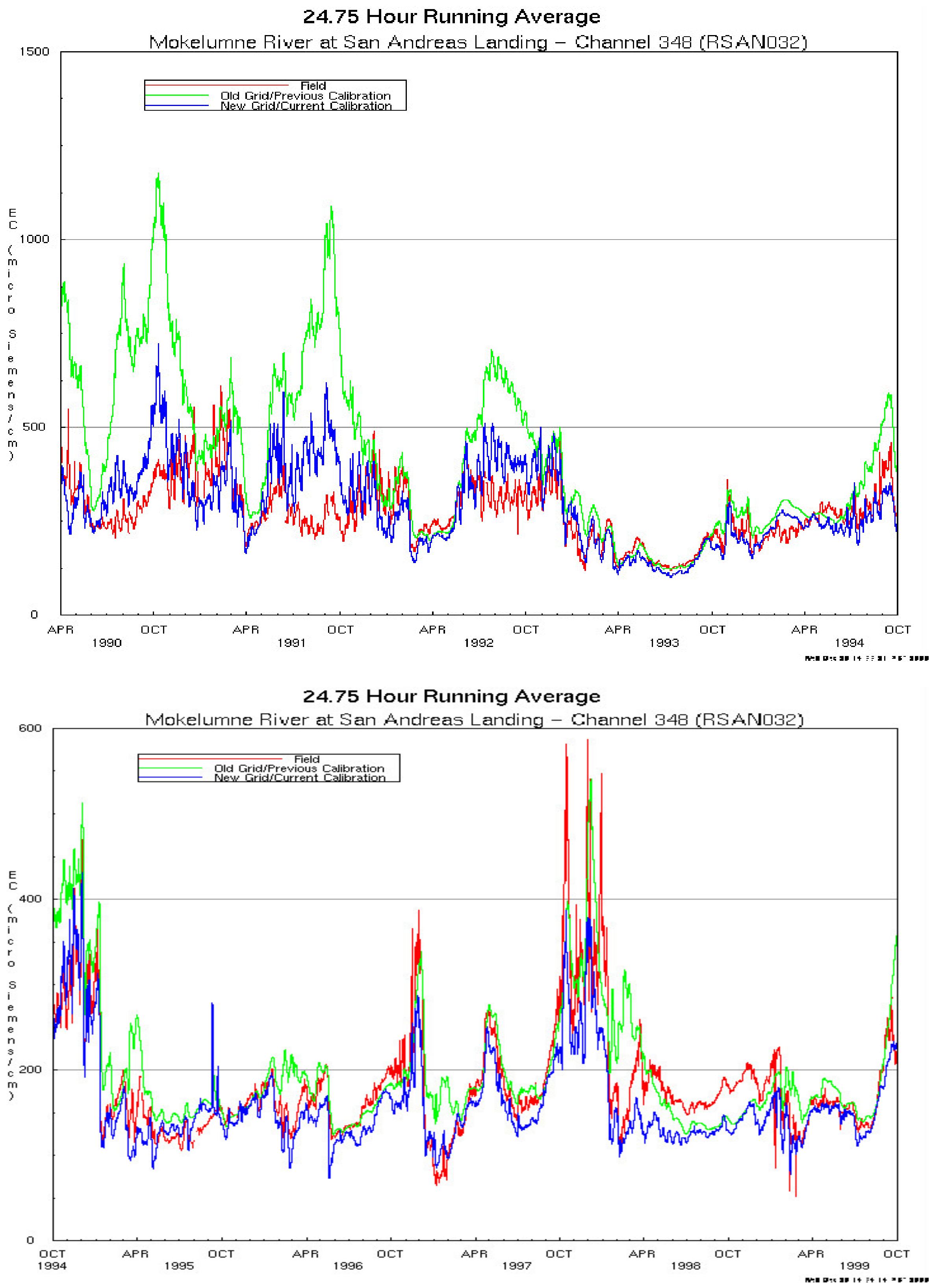

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Figure D-153

**DSM2-Simulated Daily Electrical Conductivity (EC)
in the San Joaquin River at San Andreas Landing
(Downstream of Mokelumne River)**

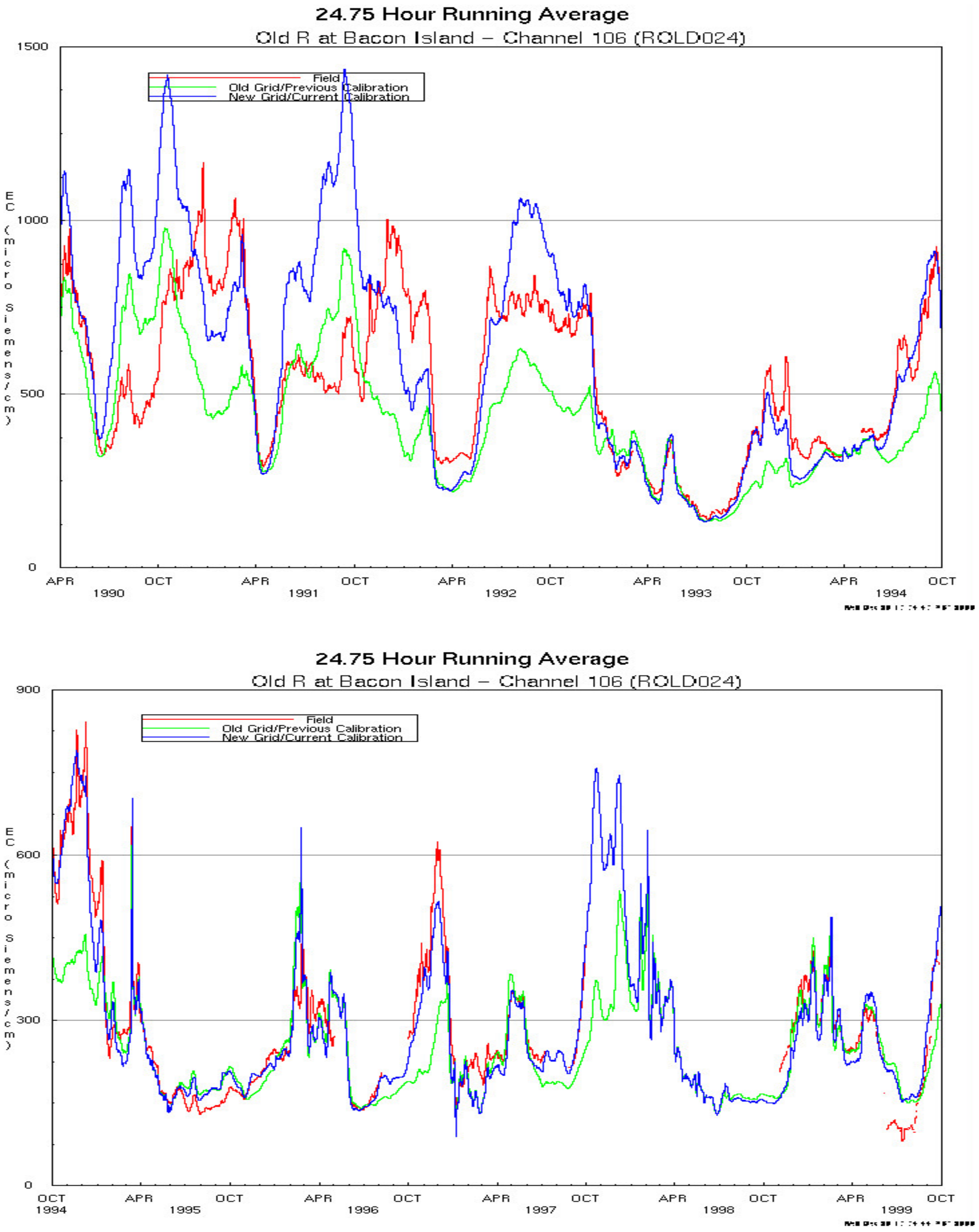

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Figure D-154

DSM2-Simulated Daily Electrical Conductivity (EC) in Old River at Bacon Island (near Rock Slough) for 1990–1999