Stockton Deep Water Ship Channel Tidal Hydraulics and Downstream Tidal Exchange

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Contents

Tables

Follows Page

Figures

All figures follow report text.

Acronyms and Abbreviations

ADCP	acoustic-doppler current profiler
af	acre-feet
BOD	biochemical demand
cfs	cubic feet per second
CVP	Central Valley Project
DO	dissolved oxygen
DSM2	Delta Simulation Model
DWR	Department of Water Resources
DWSC	Stockton Deep Water Ship Channel
EC	electrical conductivity
HOR	Head of Old River
msl	mean sea level
NPDES	National Pollutant Discharge Elimination System
R&R	Rough & Ready Island
RWCF	Regional Wastewater Control Facility
SJR	San Joaquin River
SWP	State Water Project
TAC	Technical Advisory Committee
USGS	U.S. Geological Survey
UVM	Ultrasonic Velocity Meter
µS/cm	microSiemens per centimeter

Executive Summary

This is the final report for this CALFED Directed Action 2001 Project. This project evaluated the tidal hydraulics (i.e., variations in stage, flow, and velocity) in the Stockton Deep Water Ship Channel (DWSC) and the San Joaquin River (SJR) between the Head of Old River (HOR) located upstream near Mossdale and the DWSC. Preliminary results were summarized in a draft report to the San Joaquin River Dissolved Oxygen TMDL Technical Advisory Committee (TAC) and to the CALFED Peer Review Panel that evaluated the San Joaquin River Dissolved Oxygen Directed Action projects in June 2002. This project has resulted in a summary of the tidal hydraulics in the DWSC that should improve the analyses and evaluations of water quality processes that influence dissolved oxygen (DO) concentrations in the Stockton DWSC.

The dye studies that were originally proposed to evaluate the tidal mixing and exchange near Turner Cut were not conducted. Preliminary analysis of historical data from the City of Stockton river sampling stations and from the Department of Water Resources (DWR) longitudinal DO surveys revealed that the electrical conductivity (EC) of the SJR provided a natural tracer that would more clearly illustrate the tidal exchange near Turner Cut.

Measurements of EC were used to determine the tidal movement of water in the DWSC near Turner Cut. Historical measured EC at the City of Stockton river stations were used to estimate the upstream mixing of low salinity Sacramento River water moving across the Delta to the Central Valley Project (CVP) and State Water Project (SWP) export pumps in the SJR channels (i.e., Columbia Cut and Turner Cut). The tidal exchange of this Sacramento River water into the DWSC near Turner Cut was estimated as a function of the SJR flow through the DWSC and Turner Cut flow.

The tidal flow measurements at the DWR Rough & Ready Island (R&R) station and at the U.S. Geological Survey (USGS) Stockton Ultrasonic Velocity Meter (UVM) station were evaluated and compared to characterize the strength of the tidal flows in the DWSC and the SJR channel upstream of the DWSC. The tidal flow and mixing within the DWSC was also evaluated with the DWR Delta Simulation Model (DSM2). Tidal hydraulics and salinity tracking results were compared for a range of DWSC flows and Turner Cut flows. The general patterns of tidal exchange in the DWSC upstream of Turner Cut were described as a function of the DWSC flow and Turner Cut flow.

The DWSC tidal exchange of Sacramento River water near Turner Cut is very small whenever DWSC flows are greater than 500 cubic feet per second (cfs).

The downstream tidal exchange may increase DO in the DWSC upstream of Turner Cut during periods when the DWSC flow is less than 500 cfs. However, there is never enough tidal exchange at Turner Cut to increase DO concentrations at the DWR R&R DO monitoring station.

Introduction

The Deep Water Ship Channel (DWSC) near Stockton is located in the southern portion of the Sacramento-San Joaquin Delta. Strong tidal flows in the Delta channels produce considerable tidal movement and mixing of the DWSC and may influence the observed water quality patterns. The strong tidal flows in the DWSC may create a significant exchange of water between the San Joaquin River (SJR) downstream of Turner Cut and the upstream portion of the DWSC where low dissolved oxygen (DO) concentrations are generally observed. The tidal exchange at Turner Cut is reduced and becomes less important at higher DWSC flows (i.e., greater than 500 cubic feet per second [cfs]). The tidal exchange is more effective when the Turner Cut net upstream flow is greater. South Delta export pumping and agricultural diversions will increase the net upstream Turner Cut flow.

Because water from the Sacramento River has a higher DO concentration and a lower biochemical oxygen demand (BOD) concentration, this tidal exchange will likely increase the DO in the downstream portion of the DWSC between the DWR R&R DO monitoring station (SJR mile 37.5) and Turner Cut (SJR mile 32.5). This tidal exchange is difficult to measure directly and the effects of tidal exchange on the longitudinal electrical conductivity (EC) profile cannot be easily distinguished from a net reverse flow pattern in the DWSC.

The DWR DSM2 tidal hydraulic flow and salinity model includes the entire Delta and provides an accurate simulation of the DWSC tidal flow and exchange processes. The strength of this tidal exchange for a range of DWSC flows and Turner Cut flows was evaluated. The simulated tidal exchange was generally small unless the net DWSC flow was less than 500 cfs.

The Stockton water quality model assumes a specific tidal exchange rate at the three downstream boundaries of the model that are located on the SJR near Columbia Cut, on 14-mile Slough, and on Turner Cut. The simulated tidal exchange removes water from the downstream end of the DWSC and replaces it with “boundary water” having a lower BOD and a higher DO concentration (specified as model input). The model was calibrated with weekly salinity (EC) measurements from the downstream portion of the DWSC from 1990 and 1991. The simulated tidal exchange rate, however, is uncertain. A net DWSC reverse flow will have the same general effects as tidal exchange on the longitudinal EC profile. Historical EC data cannot distinguish between slightly higher reverse flows and slightly higher tidal exchange rate.

A dye study originally was planned to measure the tidal exchange near Turner Cut but has been replaced with a series of measured longitudinal EC profiles in the vicinity of Turner Cut. The EC of the Sacramento River water is generally about 150 microSiemens per centimeter (µS/cm). As this water flows across the Delta in the SJR channels, the EC increases to about 250 µS/cm near the mouth of the Mokelumne River at San Andreas Landing EC station. The EC of the SJR water in the DWSC is generally between about 500 µS/cm and 750 µS/cm during the irrigation season of April through August. This allows the tidal mixing of these two sources of water to be directly observed along the DWSC in the vicinity of Turner Cut.

Study Methods

Figure 1 shows a map of the DWSC between Stockton and Columbia Cut. The locations of the City of Stockton River sampling stations are indicated. The geometry of the DWSC is very important background information because it controls the movement of water through the DWSC and the tidal exchange and mixing within the DWSC. The residence time is controlled by the volume, and the tidal flows are controlled by the tidal stage variations and the surface area of the DWSC and the tidal portion of the SJR upstream of the DWSC (i.e., between the DWSC and Mossdale).

Table 1 gives the surface widths (area) and cross-sectional areas (volumes) of the DWSC from the upstream end at SJR mile 41.5 (Weber Point) to Turner Cut (SJR mile 32.5). The total surface area is about 750 acres at an elevation of 0 feet mean sea level (msl). The DWSC between the Turning Basin and Turner Cut has a volume of about 15,000 acre-feet (af) at an elevation of 0 feet msl. This geometry table has been estimated from a combination of USGS quad maps and the specified model geometry in the Stockton Water Quality model and the geometry used in the DWR DSM2 model (i.e., Cross-Section Development Program).

Tidal Flow Estimates from Upstream Area

The measured tidal flows at the USGS Stockton Ultrasonic Velocity Meter (UVM) station and the DWR R&R tidal flow station reflect the upstream “tidal prism” that is defined as the difference in upstream volume between low tide and high tide. Assuming a flat surface elevation at high and low tide, the net upstream movement of water must be equal to the upstream area times the change in tidal stage. The volume of water flowing past a tidal flow gage is:

tidal volume (af) = tidal stage change (feet) ∗ upstream area (acres)

The measured tidal flow records suggest that the SJR surface area upstream of the USGS Stockton UVM station is about 400 acres. For a 3-foot flood-tide stage change, the tidal volume moving upstream would be about 1,200 af. This volume corresponds to an average flow of about 2,400 cfs during the 6-hour flood-tide period (i.e., flow (cfs) = volume (af) * 43,560/ [6 * 3600] = 2.01 ∗ af).

Based on the DWR tidal flow records, the surface of the DWSC and the SJR upstream of the DWR R&R tidal station is about 850 acres, so the effective tidal area between the USGS Stockton UVM station and the R&R station is about 450 acres. For a 3-foot tidal stage change, the tidal volume at the R&R station is about 2,550 af (i.e., 3 feet ∗ 850 acres). This represents an average flow of about 5,100 cfs during a 6-hour flood-tide period.

Table 1. Geometry of the San Joaquin River Deep Water Ship Channel

Downstream River Mile	River Location	Average Segment Width (feet)	Segment Area (acres)	Cumulative Area (acres)	Segment Cross Section at 0 feet msl (square feet)	Cumulative Volume at 0 feet msl (acre-feet)
41.5	Weber Point	310	19	19	3,000	120
41.0		350	22	41	4,200	440
40.5	Turning Basin	670	41	81	37,000	1,880
40.0		430	26	108	15,000	2,780
39.5	SJR / R3	590	36	144	12,000	3,500
39.0		550	33	177	14,000	4,340
38.5	R4	590	36	213	16,000	5,300
38.0	Rough & Ready	710	43	256	16,000	6260
37.5	R5	630	38	294	17,000	7,280
37.0		550	33	328	14,000	8,120
36.5		670	41	368	14,000	8,960
36.0		590	36	404	13,000	9,740
35.5	R6	590	36	440	12,000	10,460
35.0		590	36	476	13,000	11,240
34.5		630	38	514	14,000	12,080
34.0		790	48	562	17,000	13,100
33.5		1,380	84	646	16,000	14,060
33.0		950	57	703	16,000	15,020
32.5	Turner Cut	790	48	751	16,000	15,980

The additional DWSC surface area between the R&R station and Turner Cut is also about 450 acres. Therefore, the tidal volume (for a 3-foot stage change) at Turner Cut would be about 3,900 af (i.e., 3 feet ∗ 1,300 acres). This corresponds to an average tidal flow of about 7,800 cfs during the 6-hour flood-tide period.

Historical Deep Water Ship Channel Longitudinal Electrical Conductivity Profiles

This relatively large DWSC tidal flow may produce a considerable exchange of water from downstream of Turner Cut that may originate from the Sacramento River. This exchange was observed in historical EC measurements from 1990 and 1991 at the City of Stockton river sampling stations. The salinity gradient in this portion of the DWSC has been measured for many years by the City of Stockton National Pollutant Discharge Elimination System (NPDES) compliance sampling program. EC measurements during the low flow periods of 1990 and 1991 were examined to determine the combined effects of net SJR flow and downstream tidal exchange on the EC gradient in this portion of the DWSC.

The effects of tidal exchange were evaluated with the measured EC at the City of Stockton sampling station R5 (SJR mile 37.5) near the R&R DO monitor, station R6 (SJR mile 35.5), station R7 (SJR mile 32.5) at Turner Cut, and R8 (SJR mile 30.5) downstream near Columbia Cut.

The flows in 1990 and 1991 were very low, with Vernalis flows of only about 500 cfs measured during the summer months. Flows at Vernalis are generally expected to be higher than this in the future (because of the Vernalis EC objective of 700 µS/cm). Conditions observed in 1990 and 1991 represent worse flow conditions than are generally expected to occur in the future. The low DWSC flows allowed the tidal exchange effects on the longitudinal EC profiles to be more easily observed.

Recent measurements (i.e., 2000 and 2001) from the City of Stockton river sampling stations showed less of a longitudinal EC gradient because DWSC flows were much higher. Vernalis flows in the summer of 2000 were about 2,000 cfs and flows during the summer of 2001 were about 1,500 cfs. To understand the salinity gradient near Turner Cut, the net SJR flow past Stockton and the net flow into Turner Cut both must be evaluated. Both of these may be influenced by the south Delta export pumping. The upstream SJR salinity (i.e., Mossdale EC) and the downstream SJR salinity (i.e., San Andreas Landing EC) also must be considered. Evaluation of these historical EC data suggest that tidal exchange near Turner Cut will not be effective unless net DWSC flow is less than 500 cfs.

Deep Water Ship Channel and San Joaquin River Tidal Flow Measurements

Measurements of tidal stage, velocity, and flow at the DWR R&R station and from the USGS UVM station at the Stockton Regional Wastewater Control Facility (RWCF) discharge located 1.5 miles upstream of the DWSC were evaluated and compared. The tidal flows and velocities that are expected near Turner Cut were estimated to be larger than those measured at R&R and were assumed to be proportional to the upstream DWSC surface area. Some special-study USGS tidal flow measurements in the SJR downstream of Turner Cut and in Turner Cut during 1997 were compared to confirm these estimates of tidal flows near Turner Cut. This tidal flow information was then used to characterize the strength of the tidal exchange (i.e., mixing) within the portion of the DWSC between R&R (R5) and Turner Cut.

DWR DSM2 Tidal Hydraulic Model Simulations

The DWR DSM2 model was used to simulate tidal hydraulics for a 2-month study period (October–November 1996). These historical conditions were then modified slightly to evaluate the tidal exchange resulting from selected combinations of SJR inflow, Delta export pumping, and the HOR barrier placement.

The Hydro module of the DSM2 model simulates the flow, velocity, and stage throughout the Delta. The Qual module of the model simulates water quality throughout the Delta. For the evaluation described here, Qual was used to track the fraction of water from the SJR or the Sacramento River inflow using the EC variable. The primary inputs to the model are stage at Martinez and the flow and water quality of the water entering the Delta (e.g., from river inflows and agricultural drainage).

The current version of the DSM2 model was obtained from the DWR web page: http://modeling.water.ca.gov/delta/models/dsm2/index.html. Instructions for the model are provided in the draft DSM2 tutorial, which is available on the web page. Additional help was obtained from DWR Delta Modeling Section staff. The model input files provided on the web page are set up to simulate historical conditions for October and November of 1996. These files were modified slightly to determine how simulated tidal flows would respond to specified combinations of SJR inflow and CVP/SWP exports. In addition, the effects of the HOR temporary barrier on DWSC flows were evaluated.

Vernalis inflows were specified as constant values of 500 cfs, 1,000 cfs, or 1,500 cfs within the *Boundary.inp* file. Total exports (i.e., CVP at Tracy and SWP at Banks) were specified as 0 cfs, 5,000 cfs (2,300 cfs CVP), or 10,000 cfs (4,600 CVP). The original input for the HOR barrier in the *Gates.in* file represents the historical conditions with the barrier in place from October 2 to November 19, 1996. The model parameters indicate that the barrier was a notched weir (32-foot-wide notch at 0 foot stage) with no pipes.

In each of the scenarios, Vernalis EC was used as a marker to track the movement of SJR water downstream through the DWSC to Turner Cut. The inflow EC from Vernalis was set at 1,000 µS/cm, and EC from all other locations was set to 0. For a few of the cases with low DWSC flow, the Sacramento River inflow EC was used to track Sacramento River water moving upstream past Turner Cut into the DWSC.

The Hydro module of DSM2 comes to equilibrium throughout the Delta after approximately 4 days, so the end-of-October results are sufficient to see the tidal hydraulic effects of changing Vernalis flows, exports, or removing the HOR barrier.

The EC tracking with the Qual module of DSM2 takes longer to reach equilibrium near Turner Cut when the DWSC flows are low. For these evaluations, the 2-month simulation October–November was used to determine the equilibrium EC values in the DWSC.

Measured EC Gradients near Turner Cut

Additional longitudinal EC profiles were measured during October 2001 to provide greater detail in the observed salinity gradient near Turner Cut. Measurements at high tide and low tide were made to confirm the estimated tidal excursion (i.e., movement between high and low tide) near Turner Cut. Because DWSC flows during the period of these EC measurements were greater than 1,000 cfs, the salinity gradient was generally located downstream of Turner Cut. This generally supported the conclusion that the tidal exchange will not be strong enough to affect DO concentrations upstream of Turner Cut if the DWSC net flow is greater than about 500 cfs.

DWR measures water quality in the DWSC from downstream near Prisoner's Point (SJR mile 24.5) to the Turning Basin (SJR mile 40). The temperature and DO values are routinely reported, but the water quality instrumentation also measures pH and EC. Results from the 1999 surveys conducted every 2 weeks from July 27 to December 8 were obtained from DWR and evaluated for this study. The strong EC gradient was located downstream of Turner Cut because the DWSC flows during this period were quite high, ranging from 1,000 cfs in August and September to 500 cfs in October and November. No substantial upstream movement of Sacramento River water was indicated from these 1999 longitudinal EC gradient patterns.

Results

USGS Stockton UVM Tidal Flows

The USGS Stockton tidal flow station was installed during the summer of 1995 in cooperation with the City of Stockton to provide direct measurements of the tidal flow near the Stockton RWCF discharge. The USGS tidal flow station provides 15-minute records of stage, velocity, and flow. These records have been evaluated to determine the net daily flows and the average tidal flows that correspond to the tidal prism volume upstream of the UVM station. The net daily flow can be subtracted from the 15-minute tidal flow records to generally evaluate the average tidal flows. This separation of the tidal flow from the net daily flow is most accurate during periods of relatively low net flow.

Figure 2 shows the 15-minute tidal stage and flow records from the Stockton UVM station for September 1999. The daily average stage and net daily flows are shown with dots. The net daily flow was about 1,000 cfs during September 1999. The 28-day lunar cycle produces some relatively high tides (spring tides) and some relatively lower tides (neap tides). Generally, however, the tidal stage change during a tidal cycle averages about 3 feet at the Stockton UVM tidal flow station. The two flood tides (i.e., rising stage) are very consistent, while the two ebb tides (i.e., falling stage) are often different, with a large stage drop between the high-high and low-low tides, and then a smaller stage drop between low-high and high-low tide each day.

The tidal stage change produces the water surface slope that drives the tidal flows. The tidal flow is positive (i.e., downstream) during falling tides (i.e., ebb tides, stage decreasing). The tidal flow is negative (i.e., upstream) during rising tides (i.e., flood tides, stage increasing). There is generally a delay between the high or low tide stage and the reversal of the flow (i.e., slack tide) because the momentum of the water must be overcome at the beginning of each change in tidal flow direction. This time delay from high tide to slack tide at the Stockton UVM station is about an hour (Jones & Stokes 2001b).

Figure 3 shows the 15-minute tidal volumes at the Stockton UVM station for the first 7 days of September 1999. The net daily flow has been subtracted from the tidal flow records and the tidal flow records are shown as 15-minute flow volumes (af). The tidal stage changes have been calculated from the tidal stage records. The average measured tidal volume was about 1,250 af for September 1999. This indicates that the upstream tidal prism surface area is about 415 acres (i.e., 1250/3). The average measured tidal flow was about 2,500 cfs. The cross section is about 3,000 square feet, so the average tidal velocity was about 0.8 ft/sec.

The tidal excursion (movement between high and low tides) is calculated from the measured tidal velocity and can be estimated by dividing the tidal volume between low tide and high tide (i.e., upstream surface area ∗ tidal stage change) by the channel cross section of the station. The tidal excursion is therefore:

tidal excursion (miles) = upstream area (acres) ∗ stage change (feet) /

cross section (square feet) ∗ 43,560 / 5,280

excursion (miles) = 8.25 ∗ surface area ∗ stage / cross-section area

For an average 3-foot change in stage between high tide and low tide, the tidal excursion distance is about 2.8 miles (based on the UVM cross-sectional area). This suggests that some Stockton RWCF effluent moves upstream 2.8 miles between low tide and high tide. Water from the RWCF effluent that reaches the DWSC during ebb tide (i.e., downstream flow) will slow down once it reaches the DWSC because the cross section of the DWSC is much larger than the SJR at the UVM station. Therefore, the downstream tidal movement will be less than 2.8 miles because the DWSC is only 1.5 miles downstream from the RWCF discharge.

DWR Rough & Ready Island Tidal Flows

The DWR R&R tidal flow station was installed during the summer of 2000 and 2001 as part of the intensive data collection effort for the SJR DO TMDL study program. The R&R tidal flow station was evaluated to determine the net daily flows and the average tidal flows that correspond to the tidal prism volume upstream of the R&R station.

Figure 4 shows the 15-minute tidal stage and flow records from the R&R station for September 2000. The daily average stage change and the net daily flows are shown with the dots. The net daily flow was about 1,500 cfs in September 2000. The 28-day lunar cycle includes some relatively high tides and some relatively lower tides. Generally, however, the tidal stage change averages about 3 feet at the R&R tidal flow station.

Figure 5 shows the 15-minute tidal volumes at the R&R tidal station for the first 7 days of September 2000. The net daily flow has been subtracted from the tidal flow records, and the flow records are converted to 15-minute flow volumes (af). The tidal stage changes have been calculated from the tidal stage records. The average tidal stage change is about 3 feet for September 2000. The average measured tidal volume was about 2,550 af during September 2000. This indicates that the upstream tidal prism surface area is about 850 acres (i.e., 2550/3). The average measured tidal flow was about 5,100 cfs. The cross section is about 16,000 square feet, so the average tidal velocity was about 0.3 ft/sec.

The tidal excursion between low and high tides (i.e., 3-foot stage change) at the R&R station is about 1.25 miles. Water quality measurements at the R&R station may include water from 1.25 miles upstream if collected at low tide, or 1.25 miles downstream if collected on high tide. Grab samples from R5 therefore will represent a 1.25-mile length of the DWSC, centered at R5, if the tidal stage is not considered in the timing of samples. This tidal movement of water in the DWSC also suggests that an aeration device placed at a fixed location along the R&R dock will influence the DO in a zone of water that is 2.5 miles long (1.25 miles upstream and 1.25 miles downstream).

Tidal Flows in the Deep Water Ship Channel upstream of Turner Cut

The DWSC tidal flows near Turner Cut can be estimated from the combination of the measured R&R tidal flows and the additional surface area between the R&R station and Turner Cut. Table 1 indicates that the surface area of the DWSC between the R&R tidal station and Turner Cut is about 450 acres. There may be slightly more tidal surface area associated with Fourteen-Mile Slough. The combined upstream tidal surface area is therefore about 1,300 acres at Turner Cut. Assuming an average tidal stage change of about 3 feet, the tidal volume at Turner Cut should be about 3,900 af. The average tidal flow therefore will be about 7,800 cfs. This large tidal flow that moves back and forth near Turner Cut may create substantial tidal exchange in this portion of the DWSC.

The tidal excursion (average distance between high tide and low tide) near Turner Cut can be estimated by dividing the tidal volume by the cross-sectional area near Turner Cut. The DWR DSM2 geometry data indicate that the DWSC cross section near Turner Cut has an area of about 16,000 square feet (same as R&R tidal station). The average tidal excursion at Turner Cut is therefore expected to be about 2.0 miles.

Measured Tidal Excursion at Turner Cut

Longitudinal EC profiles were measured at high and low tides on October 15, 2001, and October 26, 2001. The distance between the locations of the salinity gradients is a direct measurement of the tidal excursion corresponding to the tidal stage changes on these two days. Figure 6 shows the measured tidal stage during October 2001 at Venice Island, located on the SJR downstream of Columbia Cut. The high and low tidal stages on the days of the tidal excursion surveys are listed. The measured low tide on October 15 was 0.05 foot msl and the measured high tide was 2.83 feet msl, giving a tidal stage change of about 2.8 feet. The low tide on October 26 was -0.57 feet msl and the high tide was 2.38 feet msl, giving a tidal stage change of about 3.0 feet.

Figure 7 shows the surface and bottom EC measurements from October 15 and October 26, 2001. The longitudinal separation of the EC gradients measured at low tide and high tide on these two days was about 3 miles. This is greater than the estimated tidal excursion of 2.0 miles near Turner Cut for a 3-foot stage change.

The location of the high tide EC gradient on both days is just downstream of Turner Cut (SJR mile 32.5). Because there is a substantial tidal flow into Turner Cut, this tidal volume moving into Turner Cut must be added to the calculated tidal volume for the DWSC at Turner Cut to match the 3.0 mile tidal excursion measured downstream of Turner Cut.

Measured USGS Tidal Flows in the San Joaquin River and in Turner Cut

Tidal flows were measured by USGS with portable (temporary) acoustic-doppler current profiler (ADCP) equipment from May through July 1997, as part of dye studies and flow evaluations of the HOR fish protection barrier and agricultural barriers in the south Delta (Oltmann 1998). Tidal flows were measured in the SJR downstream of Turner Cut and in Turner Cut itself. Subtracting the Turner Cut tidal flow from the downstream SJR tidal flow provides an estimate of DWSC tidal flows upstream of Turner Cut.

Figure 8 shows the measured tidal flows in the SJR downstream of Turner Cut and in Turner Cut during May 1997. The Turner Cut flow was subtracted from the SJR tidal flow to estimate the DWSC tidal flow just upstream of Turner Cut. The tidal flows in Turner Cut indicated that an average net flow of 800 cfs was moving upstream (i.e., negative) from the DWSC toward Middle River and the south Delta pumping plants near Tracy. The tidal flow in Turner Cut (after subtracting the net flow) during the month of May 1997 averaged 3,600 cfs. The average measured tidal volume was about 1,800 af during each 6-hour flood or ebb tide. The tidal prism area upstream of Turner Cut for an assumed average 3-foot stage change is about 600 (i.e., 1800/3) acres.

This additional tidal volume should increase the tidal excursion observed downstream of Turner Cut by about 0.9 mile. The expected tidal excursion downstream of Turner Cut is therefore about 2.9 miles. The EC measurements at high and low tides on October 15, 2001, and October 26, 2001, generally confirm this estimate of the tidal excursion just downstream of Turner Cut.

Simulated Turner Cut Net Flows

Figure 9 shows the simulated Turner Cut net daily flow results from the RMA Delta hydrodynamic model (earlier version of the DSM2 model) for a range of SJR and Delta export pumping conditions. The DWR DSM2 model gives similar results for the combinations of SJR flows and export pumping simulated for this study. The SJR flow does not appear to have much effect on the net Turner Cut flows, except that the SJR flows through HOR will reduce the effective export pumping flow from the Old and Middle Rivers (including Turner Cut). The Turner Cut flow appears to be about 10% of the total export pumping. This suggests that about 10% of the net flow moving toward the export pumping plants travels through Turner Cut. These results from the RMA hydrodynamic model indicate that higher export pumping will draw more water from the lower end of the DWSC and therefore may increase the tidal exchange rate.

The USGS tidal flow measurements in May 1997 indicated a net upstream flow of about 800 cfs in Turner Cut. The combined export pumping was about 3,000 cfs for May 1997, which suggests that the Turner Cut flow was about 25% of the total exports. This is higher than the RMA model indicated. The HOR barrier was installed until May 15, 1997, and the SJR flows were relatively high (e.g., 6,000 cfs). This may partially explain the higher fraction of the export flow moving down Turner Cut.

Table 2 gives a summary of the DSM2 tidal and net flows for the 10 cases that were simulated for this study. The DSM2 results in table 2 indicate that the upstream Turner Cut flow can be estimated as

upstream Turner Cut net flow (cfs) = 125 + 0.075 ∗ [exports - HOR + ag div]

Exports of 5,000 cfs will produce a Turner Cut flow of 400–500 cfs depending on the HOR flow and agricultural diversions. Exports of 10,000 cfs will produce

Table 2. Summary of DSM2 Simulated Net Flows in the SJR and DWSC (cfs)

Case	1	2	3	4	5	6	7	8	9	10
HOR Barrier	Out	Out	Out	In	Out	In	Out	In	Out	Out
Exports	5,000	10,000	0	0	5,000	5,000	10,000	10,000	5,000	5,000
Vernalis	500	500	1,000	1,000	1,000	1,000	1,000	1,000	1,500	1,500
HOR	495	495	995	995	995	995	995	995	1,495	1,495
HOR Diversion	557	785	636	259	869	326	1,065	375	1,461	1,314
Below HOR	-64	-292	361	736	128	665	-68	619	356	179
R&R Island	-85	-314	341	716	107	644	-90	598	335	157
14-mile Diversion	-34	-68	20	40	-21	12	-53	-13	0	-37
Turner Cut	-54	-249	321	672	124	629	-40	608	336	191
Turner Cut Diversion	480	816	113	161	468	537	808	902	461	803
Below Turner Cut	-539	-1,069	204	507	-348	87	-852	-298	-129	-617
Estimated Stockton Flow[1]	0	-250	500	750	250	700	0	650	500	250
Estimated Turner Cut Flow[2]	488	846	107	136	465	506	825	877	420	806

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[1] Stockton Flow = Vernalis (0.5–0.05 Exports)

[2] Turner Cut Flow = 125 + 0.075 (Exports – HOR Diversion + 400)

a Turner Cut flow of 800–900 cfs depending on the HOR flow and agricultural diversions. The fraction of the Turner Cut net flow originating from the DWSC upstream of Turner Cut will depend on the net flows upstream and downstream of Turner Cut. The tidal flows in the DWSC and in Turner Cut will not change much for this range of relatively low SJR flows. There are three basic cases to consider.

1. If the DWSC net flow upstream of Turner Cut is large (i.e., greater than 500 cfs), the tidal exchange near Turner Cut is not expected to change the water quality upstream of Turner Cut. Although some water from the DWSC upstream of Turner Cut will be diverted into Turner Cut, the net flow downstream of Turner Cut will remain positive, and very little Sacramento River water will be tidally mixed into the DWSC upstream of Turner Cut. Moderate DWSC net flows (500 to 1,000 cfs) with large Turner Cut flows (high exports) may produce a net upstream movement of Sacramento River water toward Turner Cut. However, the DWSC net flow will position the relatively strong EC gradient downstream of Turner Cut.
2. If the DWSC net flow is small (i.e., less than 500 cfs) and the Turner Cut net flow is greater, tidal exchange near Turner Cut may change the water quality upstream of Turner Cut. Because the net flow downstream of Turner Cut will be negative, a considerable amount of Sacramento River water will be moving upstream to Turner Cut and may be mixed into the DWSC upstream of Turner Cut.
3. If the DWSC net flow is negative (moving upstream) the water quality of the DWSC will be changed to approach the Sacramento River water quality. Although the time required for Sacramento River water to influence water quality in the DWSC will depend on the magnitude of the net reverse flow, eventually the DWSC salinity and other water quality variables will reflect Sacramento River water.

Longitudinal EC profiles measured in October 2001 fall in category 1 with relatively high DWSC flows. Very little dilution of the SJR EC was measured upstream of Turner Cut. The location of the gradient between SJR EC and Sacramento EC was downstream of Turner Cut.

Measured Electrical Conductivity Gradients between River Stations R5 and R8

The historical EC measurements from City of Stockton river sampling stations during the low flow periods of 1990 and 1991 can be used to illustrate the effects of the tidal exchange near Turner Cut on DWSC water quality. Table 1 indicates that station R8 is located at SJR mile 30.5, 2 miles downstream of Turner Cut. Station R7 is located at SJR mile 32.5, at Turner Cut. Station R6 is located at SJR mile 35.5, 3 miles upstream of Turner Cut. Station R5 is located at SJR mile 37.5, 5 miles upstream of Turner Cut near the DWR R&R water quality monitoring station.

Figure 10 shows the measured EC data during 1990. The SJR flow at Vernalis was about 1,000 cfs during the July-through-September period when weekly EC measurements were taken in the DWSC. The daily average EC at the DWR R&R water quality station was about 800 µS/cm at the beginning of July, dropped to 500 µS/cm in August and early September, and then increased to 800 µS/cm again at the end of September. The station R5 EC values generally follow the R&R monitoring station data.

The EC values at R8 were about 300 µS/cm less than the R5 EC data throughout the summer period. The R7 (Turner Cut) EC values were about equal to the R8 EC values. The R6 EC data were generally closer to the R5 value than to the R7 value. During August 1990, the R6 EC was about midway between the R5 and R7 values, indicating that the area of exchange between the two water types was upstream of Turner Cut. Although the DWSC flows were not measured, the Vernalis flow of 1,000 cfs suggests that the DWSC flow might have been only 250 cfs (25% of Vernalis). On September 10, 1990, the HOR barrier was installed and the DWSC flows likely increased to at least 75% of the Vernalis flows. The EC values at R6 increased to the EC measurements at R5 during September, suggesting that the effects of tidal exchange at Turner Cut were reduced as the flow increased above 500 cfs.

The data from 1991 are similar. The station R5 EC data follow the R&R daily average EC data. The R8 and R7 EC data are always lower than the R5 data, suggesting that a longitudinal EC gradient existed upstream of Turner Cut. SJR flow at Vernalis was only 500 cfs during the summer of 1991. Nevertheless, the EC data from R6 were generally closer to the R5 values than to the R7 values. This suggests that even during this period when the DWSC flows must have been less than 250 cfs, the tidal exchange was only moderately influencing the EC gradient between Turner Cut and the R&R EC monitor. The HOR barrier was installed on September 9, 1991. The EC at station R6 increased to about the EC at R5, suggesting that the flow of about 500 cfs was enough to move the EC gradient caused by tidal exchange at Turner Cut to a location somewhat downstream of R6 (within 3 miles of Turner Cut).

Figure 11 shows the EC measurements from 2000 and 2001. During 2000 the SJR flow at Vernalis was greater than 2,000 cfs. Only small differences in EC values were measured between R5 and R7. The major drop in EC was consistently downstream of Turner Cut at R8. EC measurements in 2001 showed a similar location for the EC gradient. The largest difference in EC was measured between R7 and R8, downstream of Turner Cut.

The tidal exchange from Turner Cut is not expected to influence DO concentrations at station R5 because the EC gradient has never been observed to extend this far upstream from Turner Cut. The DO concentrations at station R6 (SJR mile 35.5) may be slightly influenced if the DWSC flow is less than 500 cfs. No effects on DO concentration are expected upstream of Turner Cut if the DWSC flow is greater than about 500 cfs.

Department of Water Resources Longitudinal Electrical Conductivity Profiles in 1999

DWR conducts longitudinal water quality surveys in the late summer and fall of most years to evaluate the effects of the HOR barrier placement on DO concentrations in the DWSC. The EC measurements taken in 1999 were examined to indicate the location of the EC gradient. Stockton UVM flow measurements indicated DWSC net flows of about 750–1,000 cfs from July through September, and flows of 250–500 cfs from October through December. Although exports were high during this period, Turner Cut flows are estimated to have been higher than the DWSC flows, and SJR net flow was negative downstream of Turner Cut, moving Sacramento River water upstream toward Turner Cut. These flow conditions suggest that the EC gradient would be quite strong but located downstream of Turner Cut for the fall of 1999.

Figure 12 shows the measured EC gradient from Prisoners Point (SJR 25) to the Turning Basin (SJR 40) on several of the longitudinal water quality survey dates in 1999. The EC gradients were generally located downstream of Turner Cut and extended over a distance of about 2 miles. The DWSC flows were high (750–1,000 cfs) and, although the estimated Turner Cut flows were greater, the EC gradient remained downstream of Turner Cut. These data suggest that although Sacramento River water was moving upstream toward Turner Cut, the tidal exchange would not have increased DO concentrations upstream of Turner Cut because of the large DWSC net flows.

Figure 12 shows that the EC gradients in October and November were also located downstream of Turner Cut, although the DWSC flows were much lower (250–500 cfs) and the net SJR flows downstream of Turner Cut were more negative. These data suggest that DWSC net flows of less than 500 cfs with a large Turner Cut flow (i.e., high exports) are the only conditions that will produce substantial tidal exchange upstream of Turner Cut.

Deep Water Ship Channel Geometry Characteristics

The geometry of the DWSC influences all of the tidal flow parameters and travel time calculations used in modeling and interpreting observed water quality patterns in the DWSC. The surface area can be seen on maps of the Delta channels, but it is more difficult to visualize the cross sections of the channel. DWR maintains a GIS database of available geometry measurements (i.e., cross-section surveys) for the Delta channel sections, called the Cross-Section Development Program.

Figures 13 and 14 show several representative sections along the DWSC. These cross-section areas are listed in table 1. Figure 13 shows the section for the Turning Basin that is upstream of the SJR channel entrance to the DWSC. The width is about 1,100 feet, because tugboats turn the ships around in the Turning Basin. The maximum depth of the Turning Basin is about 40 feet and the average depth is about 35 feet. The cross-section area is 37,000 square feet at a water elevation of 0 feet msl. The DWSC section along R&R is shown at the bottom of figure 13. This section has a width of about 700 feet, with a maximum depth of 35 feet. The cross-section area is about 16,000 square feet at an elevation of 0 feet msl. There is a slightly shallower area on the right side (200 feet wide) that is outside the navigation channel.

Figure 14 shows the channel section at the DWR R&R tidal flow and water quality monitoring station. It is very similar to the section shown at the bottom of figure 13. The width of the channel is about 700 feet and the depth is 35 feet, and the area is about 17,000 square feet at an elevation of 0 feet msl. The DWSC cross section just upstream of Turner Cut is shown at the bottom of figure 14. The section upstream of Turner Cut is approximately 700 feet wide with about 100 feet of the width representing a relatively shallow area on the right bank. The depth of this section is about 37 feet and the cross-sectional area at a water level of 0 feet msl is approximately 16,000 square feet.

These channel cross sections illustrate the general shape of the DWSC. It is a relatively simple channel shape, but exhibits relatively complex water quality patterns. The volume characteristics can be accurately measured and are already included in the DSM2 model. The interaction of the DWSC geometry with the tidal flows, SJR flows, temperature stratification, salinity gradients, and side channels make this a complex hydrodynamic environment. Adding the settling and resuspension of organic particles and the growth and decay of algae, nitrification of ammonia, and decay of both dissolved and particulate organic materials creates a very complicated “reactor.” Accurately describing the tidal flows and downstream tidal exchange effects will provide another step in adequately understanding and managing water quality in this portion of the Delta.

Deep Water Ship Channel Tidal Hydraulic Evaluation with DSM2 Model

The DSM2 model includes the entire network of Delta channels. The portion of the SJR that is most directly involved in the observed low-DO conditions in the DWSC has been separated from the remainder of the Delta by considering the SJR between the HOR (SJR 53.5) and Turner Cut (SJR 32.5). The flow split that occurs at the HOR is an important boundary condition for the DWSC evaluation (e.g., upstream boundary for the Stockton Water Quality model).

Head of Old River Tidal Flow Diversion

The SJR near the HOR is tidal (i.e., reversing flows) unless the SJR flows are greater than about 5,000 cfs, when the river stage is raised and the downstream flow is large enough to prevent any upstream tidal flows. The SJR flow will be partially diverted at the HOR into the Old River channel toward Tracy. Higher CVP and SWP export pumping will increase this flow diversion. The tidal flows near the HOR must be accounted for to properly understand this HOR diversion. Only the portion of the SJR flow that continues past the HOR will flow past the Stockton UVM station and past the Stockton RWCF discharge into the DWSC. The SJR volume between the HOR and the DWSC is estimated to be about 2,500 af, with a surface area of 300 acres at 0 feet msl. The channel width increases from about 150 feet at the HOR to about 250 feet at the confluence with the DWSC. The average depth is about 8 feet. The travel time can be estimated from the net flow past the Stockton UVM station as:

$$\text{travel time (days)} = \text{flow (cfs)} * 2/\text{river volume (af)} = \text{flow (cfs)} / 1{,}250$$

A flow of 1,000 cfs corresponds to a travel time of 0.8 day. A flow of 500 cfs will require 1.5 days to travel from the HOR to the DWSC. A flow of 250 cfs will require a travel time of 3 days.

Figure 15 shows the DSM2 simulated tidal flows in the SJR and in Old River at the HOR for a Vernalis flow of 1,000 cfs with 0 cfs exports and with 10,000 cfs exports. One week of simulation from the end of October 1996 is shown to illustrate the tidal flow patterns. The timing of these tidal flows is nearly identical so that there is a flow condition on ebb tide (falling stage) and another flow condition on flood tide (i.e., rising stage). With no exports (top panel), the simulated overall net flow split is about 65% into Old River and 35% continuing past Stockton. The tidal flows that produce this overall net flow split should be considered. During the ebb tide, the downstream SJR flows are about 2,000 cfs. About 60% of this ebb tide flow moves downstream past HOR, and about 40% flows into Old River. However, during flood tide the positive flow from upstream continues for several hours, with the majority moving into Old River. Upstream flow from Stockton of about -1,000 cfs also moves into Old River, so the Old River flow is relatively high (i.e., 1,000 cfs) during flood tide and remains positive from SJR toward Tracy until the last couple of hours of flood tide. The net result is that about 65% of the Vernalis flow is diverted into Old River (table 2).

Figure 15 (bottom panel) shows the simulated effects of 10,000 cfs export pumping on the tidal flows at the HOR. The simulated stage at the HOR flow junction is reduced by the high exports. The tidal flow variations upstream of the HOR are also reduced. During ebb tide, about half of the 1,500 cfs downstream flow is diverted into Old River, so the Old River flow is about 750 cfs. During flood tide, the reverse flow of -1,000 cfs in the SJR downstream of the HOR is almost completely diverted into the HOR. Some remaining downstream flow from upstream of the HOR is also diverted, so the HOR flow is about 1,500 cfs downstream during flood tide. The net result is that the entire SJR flow is diverted into HOR, and the downstream flow is simulated to be reversed (flowing upstream) at -68 cfs (table 2).

These DSM2 model simulated tidal flow diversions into Old River are slightly higher than the measured Stockton UVM data indicate (Jones & Stokes 2001a). Nevertheless, the effects of export pumping on the fraction of SJR flow that moves past the HOR and past the RWCF discharge and into the DWSC can be described with the following approximate regression equation:

$$\text{Stockton/Vernalis fraction} = 0.5 - 0.05 * \text{exports/Vernalis}$$

The DSM2 model gives a Stockton fraction of only 35% (with no exports). The DSM2 Stockton/Vernalis fractions for each of the cases simulated for this study are compared to the regression estimates in table 2.

DSM2 Simulated Stockton Ultrasonic Velocity Meter Tidal Flows

Figure 16 shows the simulated tidal flows at the Stockton UVM station for the case of 1,000 cfs Vernalis flow and 10,000 cfs export pumping. As discussed above, the net flow downstream of the HOR was slightly negative. Figure 16 (top panel) indicates that the average simulated tidal flow was about 2,000 cfs. This is slightly less than the measured UVM data indicates (e.g., average tidal flow of 2,500 cfs). Figure 16 (bottom panel) shows the simulated tidal excursion for these characteristic tidal flows. The flood tide excursions are very consistent, with an average upstream movement of about 15,000 feet (2.8 miles). The ebb tide excursions show a large tidal movement and a shorter movement, because the stage change from high-high tide to low-low tide is usually much greater than the stage change from low-high to high-low tide. This simulated tidal excursion pattern is very close to that measured at the Stockton UVM station.

DSM2 Simulated Deep Water Ship Channel Tidal Flows at the Rough & Ready Island Station

Figure 17 shows the simulated tidal flows at the R&R station for the case of 1,000 cfs Vernalis flow and 10,000 cfs export pumping. As discussed above, the net flow downstream of the HOR was slightly negative. Figure 17 (top panel) indicates that the average simulated tidal flow at the R&R station was about 4,000 cfs. This is about the same as the measured DWR tidal flow data indicates. Figure 17 (bottom panel) shows the simulated tidal excursion for these characteristic tidal flows. The flood tide excursions are very consistent, with an average upstream movement of about 5,000 feet. The ebb tide movement shows a large tidal movement and a shorter movement, because the stage change from high-high tide to low-low tide is usually much greater than the stage change from low-high to high-low tide. This simulated tidal excursion pattern is similar to that measured at the R&R tidal flow station.

DSM2 Simulated Deep Water Ship Channel Tidal Flows near Turner Cut

Figure 18 shows the simulated tidal flows upstream and downstream of Turner Cut and the tidal flow in Turner Cut (positive downstream) for the case of 1,000 cfs Vernalis flow and 0 cfs export pumping. The simulated net flow in the DWSC was about 320 cfs at Turner Cut and the simulated Turner Cut net diversion flow was 113 cfs (net upstream flow). Figure 18 (top panel) indicates that the average simulated tidal flow was about 8,500 cfs upstream of Turner Cut, and about 11,000 cfs downstream. The simulated Turner Cut tidal flow was about 2,500 cfs. This is similar to the measured USGS tidal flow data. Figure 18 (bottom panel) shows the simulated tidal excursion upstream of Turner Cut for these characteristic tidal flows. The flood tide excursions are very consistent, with an average upstream movement of about 9,000 feet (1.7 miles). The ebb tide movement shows a large tidal movement and a shorter movement, because the stage change from high-high tide to low-low tide is usually much greater than the stage change from low-high to high-low tide. This simulated tidal excursion distance is somewhat less than that measured during the October high tide and low tide EC profiles.

Summary of DSM2 Simulated Deep Water Ship Channel Tidal Flows

The tidal flows in the DWSC and in the SJR upstream of the DWSC can be approximated as tidal filling and draining of the channel. The effective upstream area times the change in stage is the approximate volume that is filled or drained in each 15-minute tidal increment. This concept was introduced to evaluate the measured tidal records from the USGS Stockton UVM station and the DWR R&R station. The DSM2 simulated tidal flows in the DWSC and the tidal portion of the SJR have also been evaluated with this effective upstream area concept (i.e., flat pool assumption).

Figure 19 (top panel) shows the DSM2 tidal flows from upstream of Turner Cut compared with the estimated flow calculated from the simulated 15-minute tidal stage change and the effective upstream area (estimated to be 1,300 acres). The agreement between the simulated flows and the effective upstream area estimate is quite remarkable. Although there is a slight deviation at the beginning of each tide, the greatest change in stage and the highest tidal flow occur about 1 hour after the tide changes (high tide or low tide). The simulated tidal flow is then relatively steady until about an hour before the next high or low tide. The DSM2 model indicates that the simulated stage changes and simulated tidal flow upstream of Turner Cut are almost perfectly matched. The tidal flow averages about 10,000 cfs during both flood- and ebb-tide periods.

Figure 19 (bottom panel) shows the DSM2 tidal flows from the DWR R&R tidal station compared with the estimated flow calculated from the simulated 15-minute tidal stage change and the effective upstream area (estimated to be 800 acres). The agreement between the simulated flows and the effective upstream area estimate is good except for the first 2 hours after each tide change, when the stage changes are larger than the simulated flows. This relatively large deviation at the beginning of each tide suggests that there is a resistance to changing the flow momentum. This flow resistance is thought to be caused by the relatively shallow and high-velocity flow in the SJR upstream of the DWSC. The simulated tidal flow is then relatively steady until about an hour before the next high or low tide. The DSM2 model indicates that the simulated stage changes and simulated tidal flow at the R&R station are well matched except for the initial period of each tide when the flow momentum is reversing. The tidal flow averages about 5,000 cfs during both flood- and ebb-tide periods.

DSM2 Simulated Deep Water Ship Channel Electrical Conductivity Gradients near Turner Cut

The DSM2 model was used to track the tidal exchange of SJR water with Sacramento River water near Turner Cut. The Qual module of DSM2 was used to simulate the fraction of SJR water (tracked with an EC of 1,000 µS/cm) in each model segment near Turner Cut. DSM2 model segment 18 is located where the SJR enters the DWSC at SJR mile 40. Segment 25 is just upstream of Turner

Cut and segment 30 is just downstream of Turner Cut. The EC in all segments was set at 0 and only the SJR inflow at Vernalis had an inflow EC of 1,000 µS/cm. All other inflows had an EC of 0.

Figure 20 shows the development of the EC gradient in the DWSC during the simulated period of October and November 1996. The Vernalis inflow has been specified at 1,000 cfs, and the export pumping has been set to 0 cfs. The daily average EC in segment 18 reaches 500 µS/cm on day 13 and reaches a maximum value of about 950 µS/cm on day 26. This delay for the SJR inflow EC to reach segment 18 is caused by the time needed to fill this upstream volume at the simulated net SJR flow of 360 cfs downstream of HOR. The top panel indicates that additional time is required for segments along the DWSC to reach their maximum EC values characteristic of a "steady-state" EC gradient. This response time will lengthen as the net DWSC flow is reduced and will shorten as the DWSC net flow increases.

The bottom panel of figure 20 indicates that the steady-state DWSC EC gradient near Turner Cut will be established after about 40 days for the DWSC flow. The longitudinal EC gradient that develops at the end of the 60-day simulation period is the result of the net flows and tidal exchange upstream and downstream of Turner Cut. For this simulation case, the DWSC flows were about 320 cfs and the Turner Cut net diversion flow was 113 cfs, so the net flow downstream of Turner Cut was 204 cfs. The simulated EC in Turner Cut was about 60% of the EC in segment 18, suggesting that 60% of Turner Cut flow was coming from the SJR and 40% was coming from the Sacramento River. This mixture is a combination of the net flow and the tidal exchange processes. The Turner Cut flow mixture of SJR and Sacramento River water cannot be easily calculated from the net flows alone.

The tidal exchange upstream of Turner Cut can be identified from the simulated EC gradient in the segments upstream of Turner Cut. For this case, segment 25 had an EC that was about 65% of the segment 18 reference value, indicating that segment 25 had 65% SJR water and 35% Sacramento River water. Segment 24 had an EC that was about 75% of the reference value, indicating it was 75% SJR water and 25% Sacramento River water. Segment 23 had an EC that indicates it was 91% SJR water. Segment 22 was 93% SJR water, segment 21 was 94% SJR water, and segment 20 (DWR R&R station) was 96% SJR water. Table 3 gives these relative EC values in each model segment for each case simulated. Although there is strong tidal exchange near Turner Cut, very little of the Sacramento River water will be mixed upstream to the R&R station if the net flow in the DWSC is more than 250 cfs.

Figure 21 shows a second case with a Vernalis flow of 1,500 cfs and exports of 5,000 cfs. The simulated DWSC net flow was about 335 cfs, but the Turner Cut flow was higher (461 cfs) because of higher exports, so the SJR flow downstream of Turner Cut was reversed and more Sacramento River water was moving to Turner Cut. Figure 21 (top panel) shows the results from tracking SJR water with an EC of 1,000 µS/cm. Segment 25 had about 48% SJR at the end of the 60-day simulation period, but Turner Cut had only about 50% SJR water, and the downstream segments had very little SJR water. Segment 30 had only 21% SJR water, and segment 31 had only 12% SJR water. These reduced SJR fractions downstream of Turner Cut are caused by higher Turner Cut flows that draw the majority of the SJR water toward the export pumps.

Figure 21 (bottom panel) shows the same simulated tidal exchange EC gradient near Turner Cut. But the Sacramento River EC was set at 1,000 μS/cm to illustrate the Sacramento River fraction in each model segment. The values are given in table 2 and are generally similar, although the initial EC of the Delta water was set at 0. Because some of this water remains at the end of the 60-day simulation, the Sacramento fraction and the SJR fraction do not quite add to 100%. The simulated pattern of tidal exchange of Sacramento River water upstream of Turner Cut is similar. The results indicate that only 36% of segment 25 was Sacramento River water, 23% of segment 24 was Sacramento River water, and only 2% of segment 23 was Sacramento River water. There will therefore be very little effect from tidal exchange of Sacramento River water at the R&R station when the DWSC flow is greater than 250 cfs. Table 3 indicates that even with a DWSC flow of 125 cfs (Vernalis flow of 1,000 cfs with exports of 5,000 cfs), segment 25 will be 65% Sacramento River water, but segment 20 will be less than 1% Sacramento River water.

Stockton Water Quality Model Simulation of 2001 Conditions

The San Joaquin River Dissolved Oxygen TMDL Technical Advisory Committee (TAC) directed some of the money in this CALFED Directed Action Project to be used for preliminary data analysis and simulation of 2001 water quality conditions in the DWSC. Systech Engineering used the improved SJR water quality model developed under the 2000 CALFED Grant to accomplish the modeling. This modeling work was accomplished in February 2002 by Systech Engineering to support the preliminary analysis of 2001 data that was requested by the TAC. Documentation for this 2001 modeling is included as appendix A in this final CALFED project report.

Table 3. Summary of DSM2 Simulated Net Tidal Exchange Fractions (%) near Turner Cut

Case	1	2	3	4	5	6	7	8	9	10
A. Net Flows										
HOR Barrier	Out	Out	Out	In	Out	In	Out	In	Out	Out
Exports	5,000	10,000	0	0	5,000	5,000	10,000	10,000	5,000	5,000
Vernalis	500	500	1,000	1,000	1,000	1,000	1,000	1,000	1,500	1,500
HOR	495	495	995	995	995	995	995	995	1,495	1,495
HOR Diversion	557	785	636	259	869	326	1,065	375	1,461	1,314
Turner Cut	-54	-249	321	672	124	629	-40	608	336	191
Turner Cut Diversion	480	816	113	161	468	537	808	902	461	803
Below Turner Cut	-539	-1,069	204	507	-348	87	-852	-298	-129	-617

B. Tidal Exchange Fraction

DSM2 Segment	Percent SJR	Percent SJR	Percent SJR	Percent SJR	Percent Sac	Percent SJR	Percent SJR	Percent SJR	Percent SJR	Percent Sac
18		Not Simulated[1]	100	100	0	100	Not Simulated[1]	100	100	0
19			99	100	0	100		100	99	0
20			96	98	0	98		98	96	0
21			94	98	2	98		97	94	1
22			93	97	9	97		96	92	8
23			91	97	17	97		95	90	14
24			75	95	51	91		84	64	51
25			65	94	64	83		70	48	66
Turner Cut			64	88	61	83		68	51	67
30			41	81	81	56		30	21	84
31			28	64	86	35		14	12	87

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[1] Cases with reverse DWSC net flows were not simulated for tidal exchange evaluations.

References

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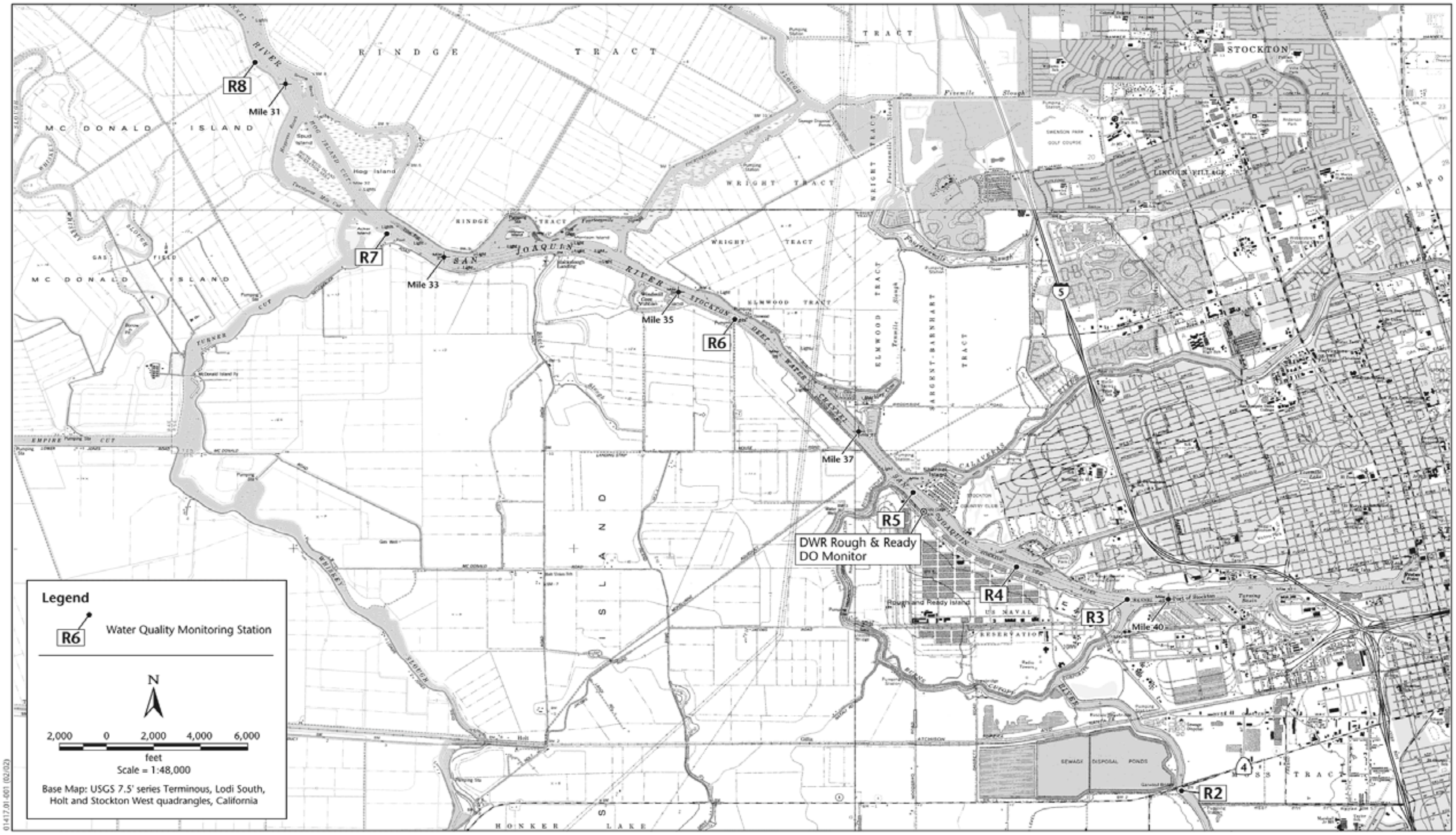
Jones & Stokes. 2001a. Evaluation of San Joaquin River flows at Stockton. Prepared for City of Stockton Department of Municipal Utilities.

Jones & Stokes. 2001b. Tidal dilution of the Stockton Regional Wastewater Control Facility discharge into the San Joaquin River. Prepared for City of Stockton Department of Municipal Utilities.

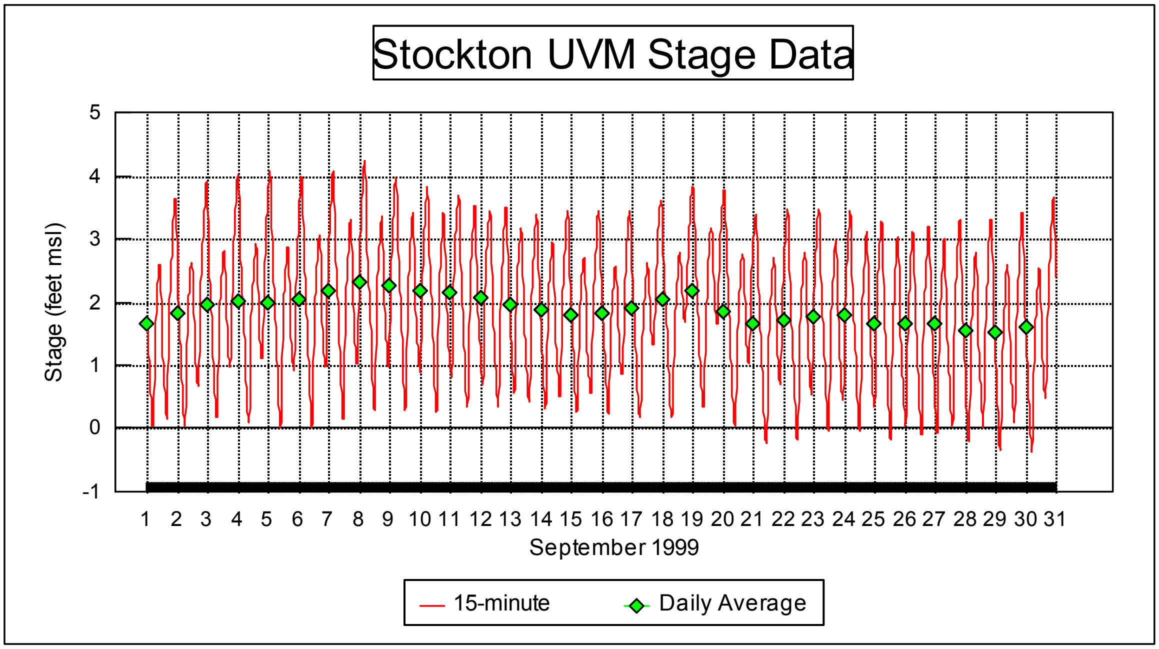
Figure 1. Map of San Joaquin River DWSC between Stockton and Columbia Cut



Jones & Stokes

Figure 1
Stockton Deep Water Ship Channel Water Quality Stations

Figure 2. Tidal Flow Records from USGS Stockton UVM Station in September 1999



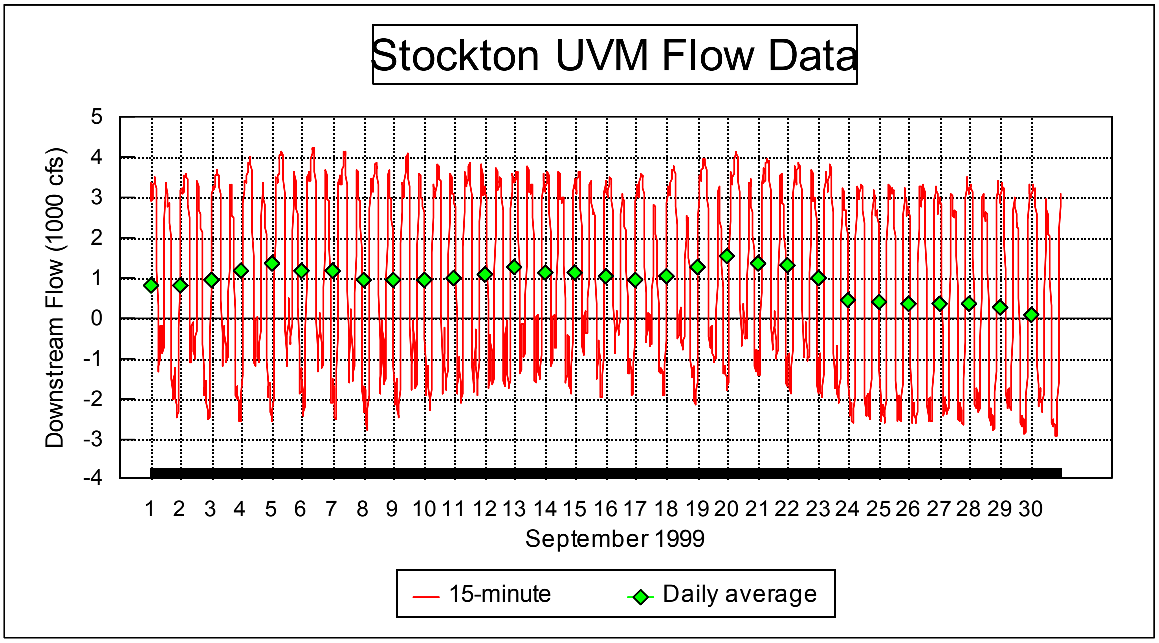


Figure 3. Tidal Flow Volume and Stage Changes at Stockton UVM Station

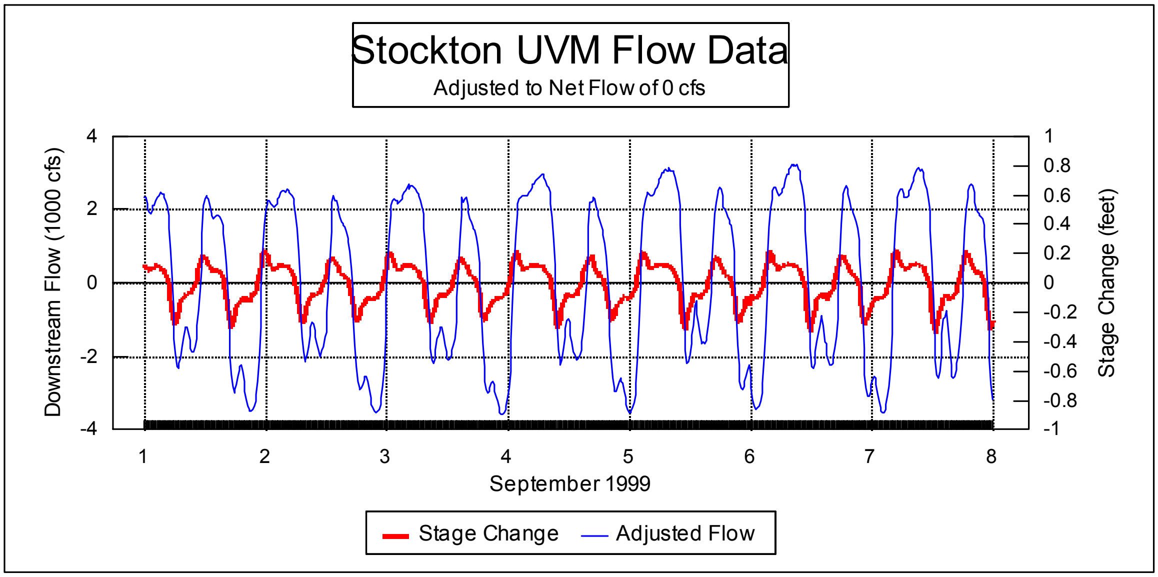
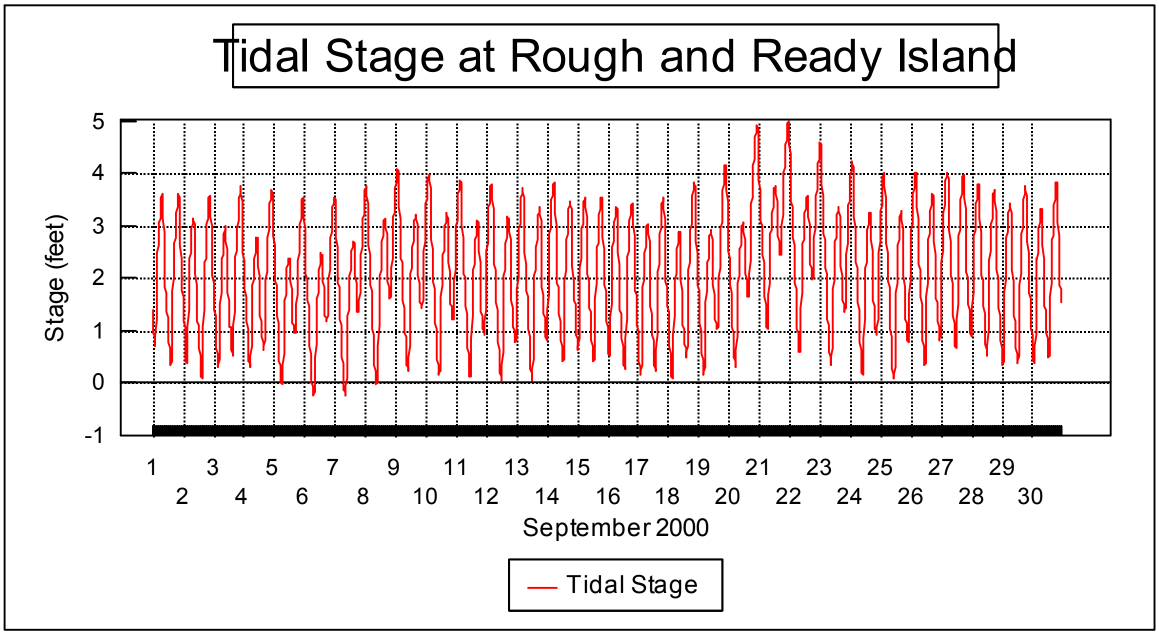


Figure 4. Tidal Flow Records from DWR Rough & Ready Tidal Flow Station for September 2000



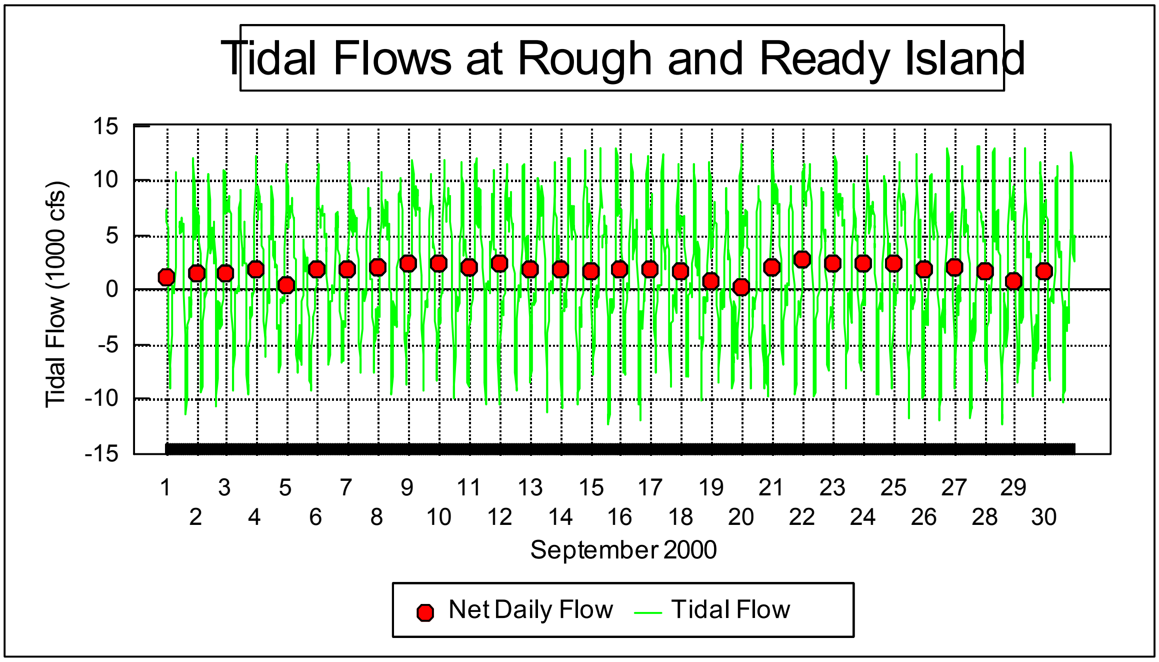
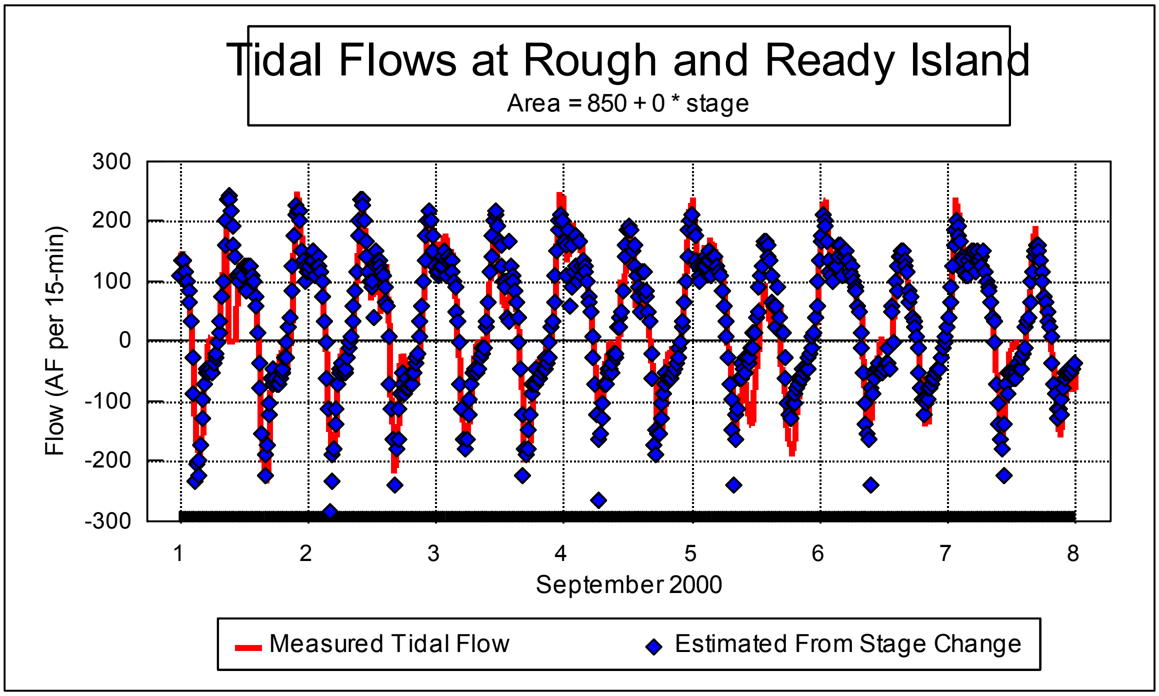


Figure 5. Tidal Flow Volumes and Stage Changes at Rough & Ready Station



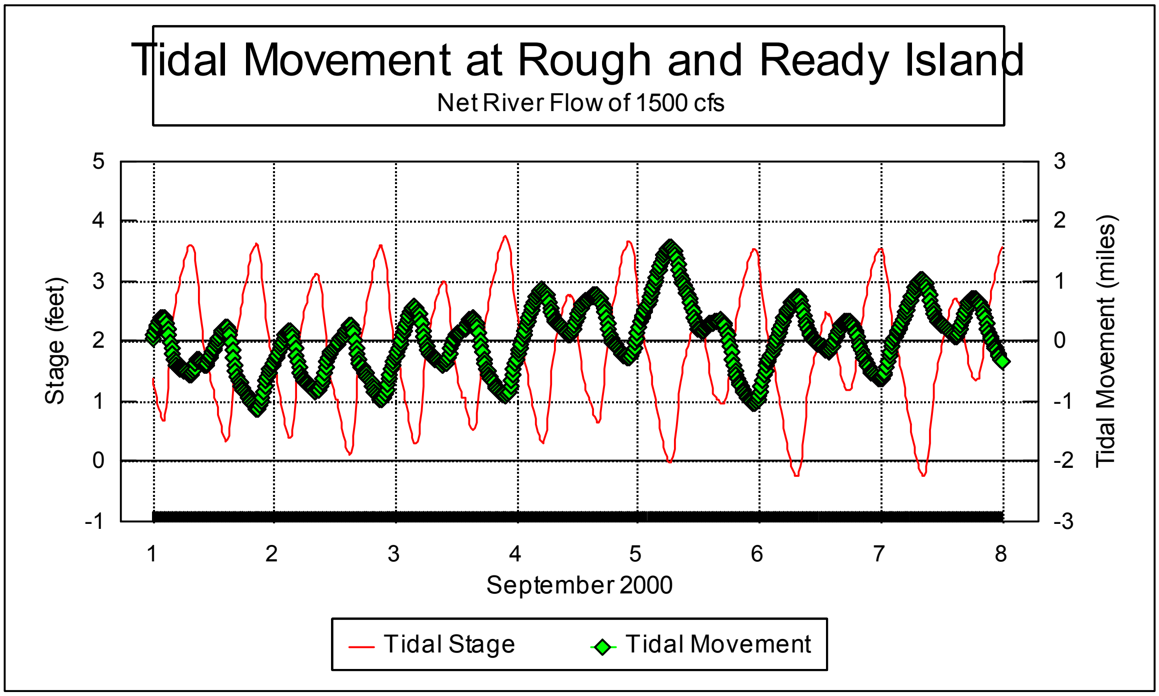


Figure 6. Venice Island Tidal Stage Records for October 2001

	Oct 15	Time	Oct 22	Time	Oct 24	Time	Oct 26	Time	Oct 29	Time	Date
High stage during sampling	2.83	6:00 PM	2.33	12:00 PM	1.97	2:00 PM	2.38	4:00 PM	2.53	4:00 PM	
Low stage during sampling	0.05	11:00 AM					-0.57	9:00 AM			
Difference	2.78	7 Hrs	2.33		1.97		2.95	7 Hrs	2.53		

1

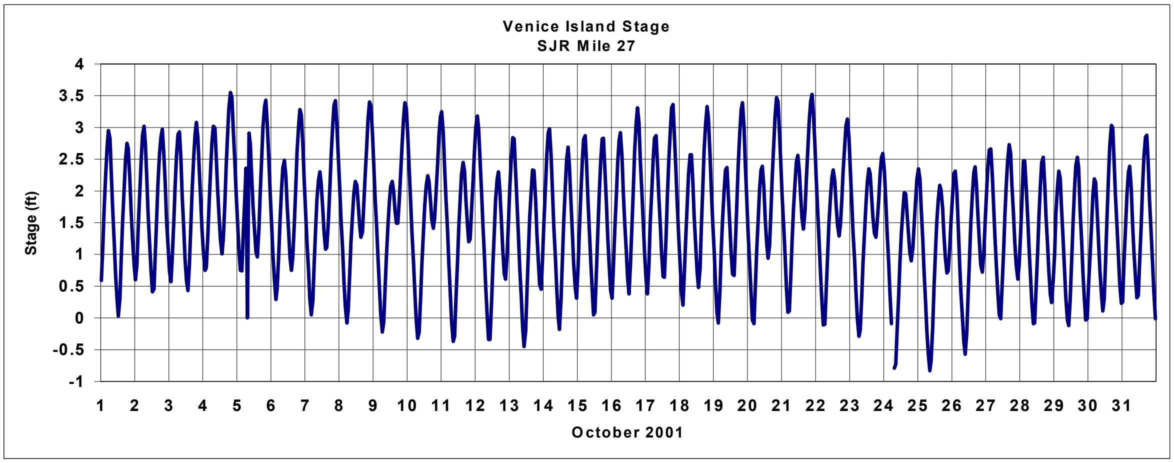


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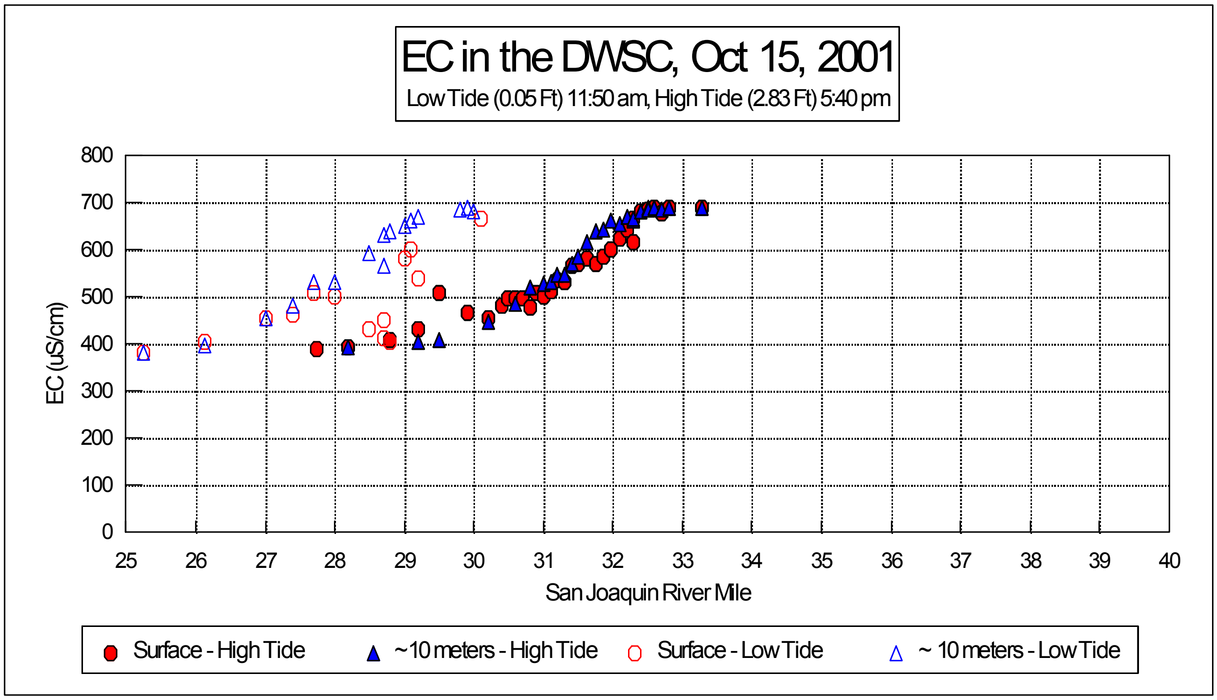
Figure 7. Electrical Conductivity Measurements at Low and High Tides on October 15 and October 26, 2001, Downstream of Turner Cut



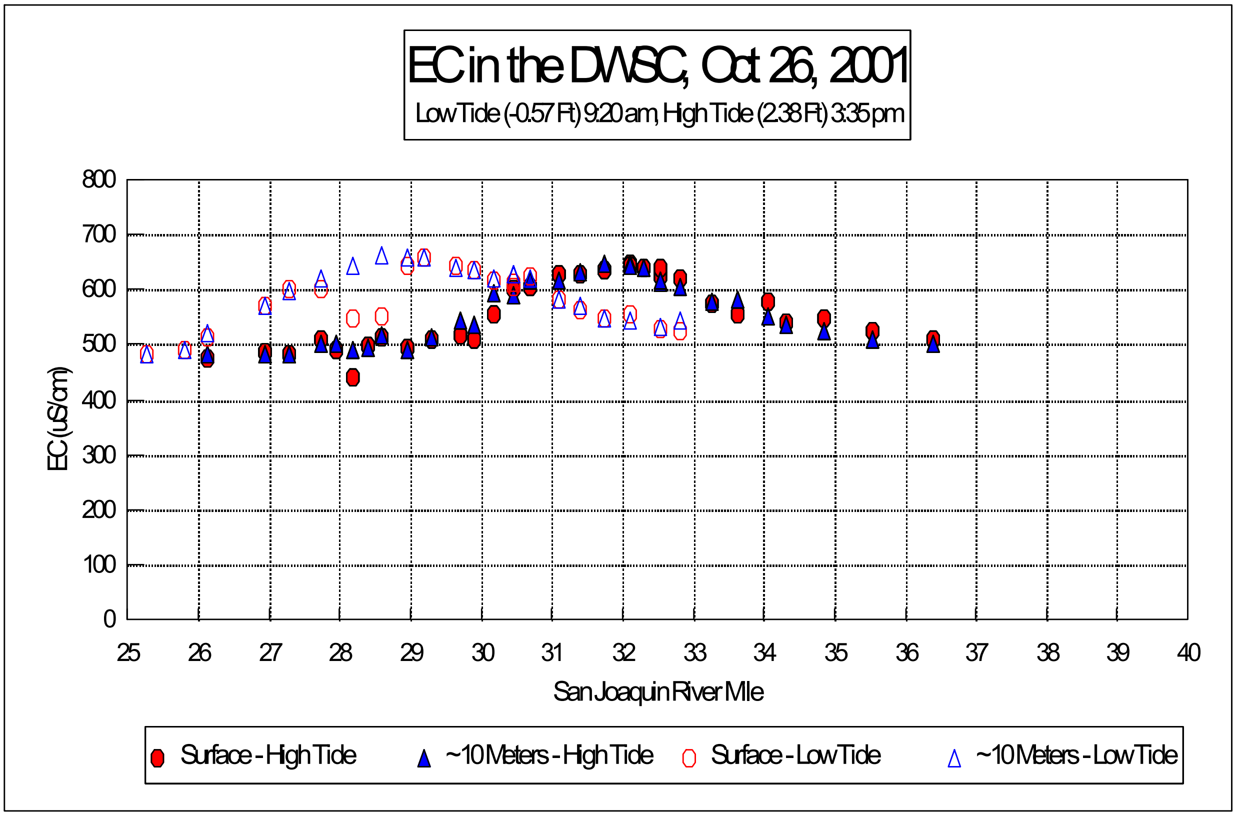


Figure 8. USGS Tidal Flow Records from the San Joaquin River Downstream of Turner Cut and from Turner Cut during May 1997

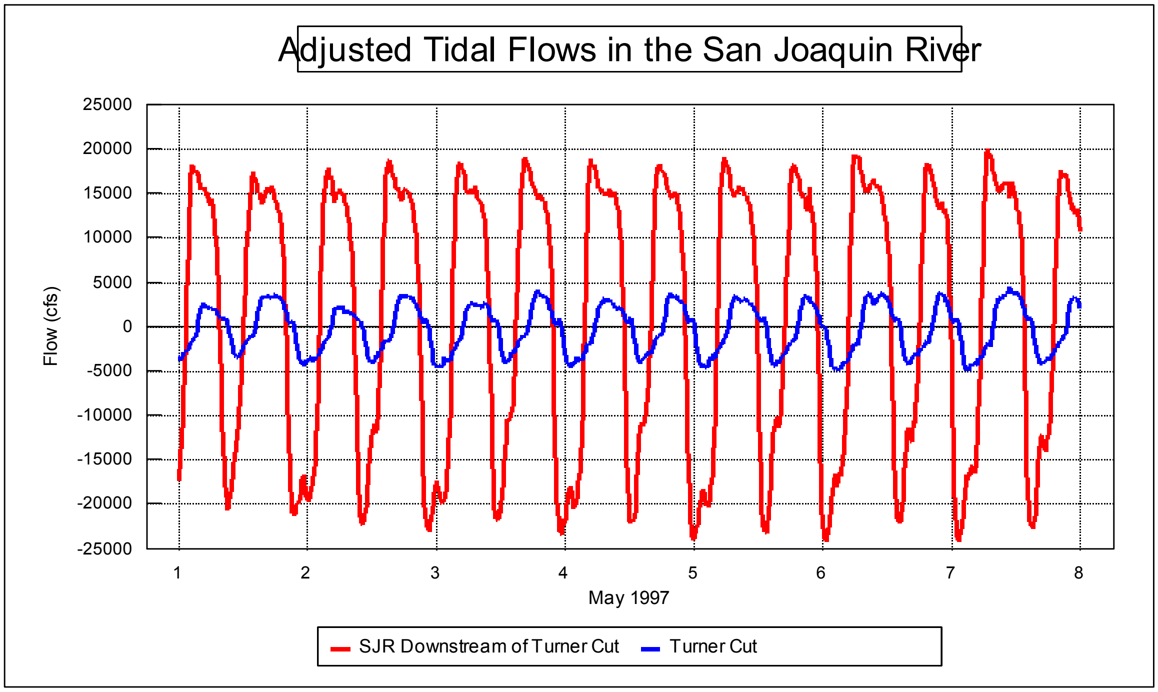


Figure 9. Simulated Net Average Flow in Turner Cut as Function of SJR Flow at Vernalis and Delta Export Pumping (Obtained from RMA Delta Hydrodynamic Model Results)

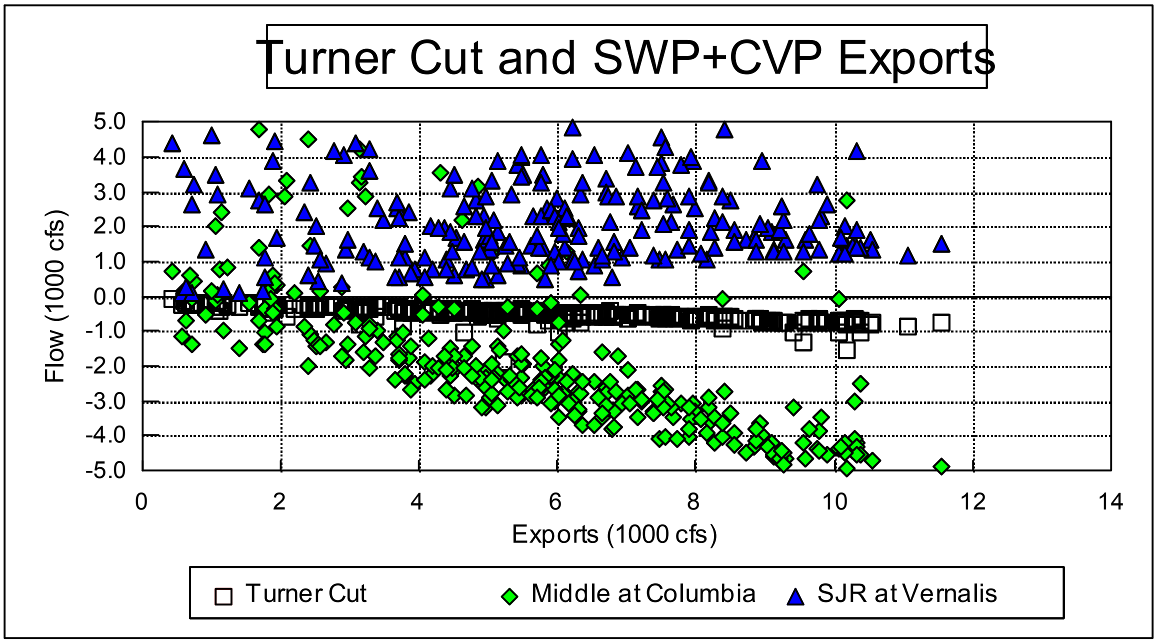
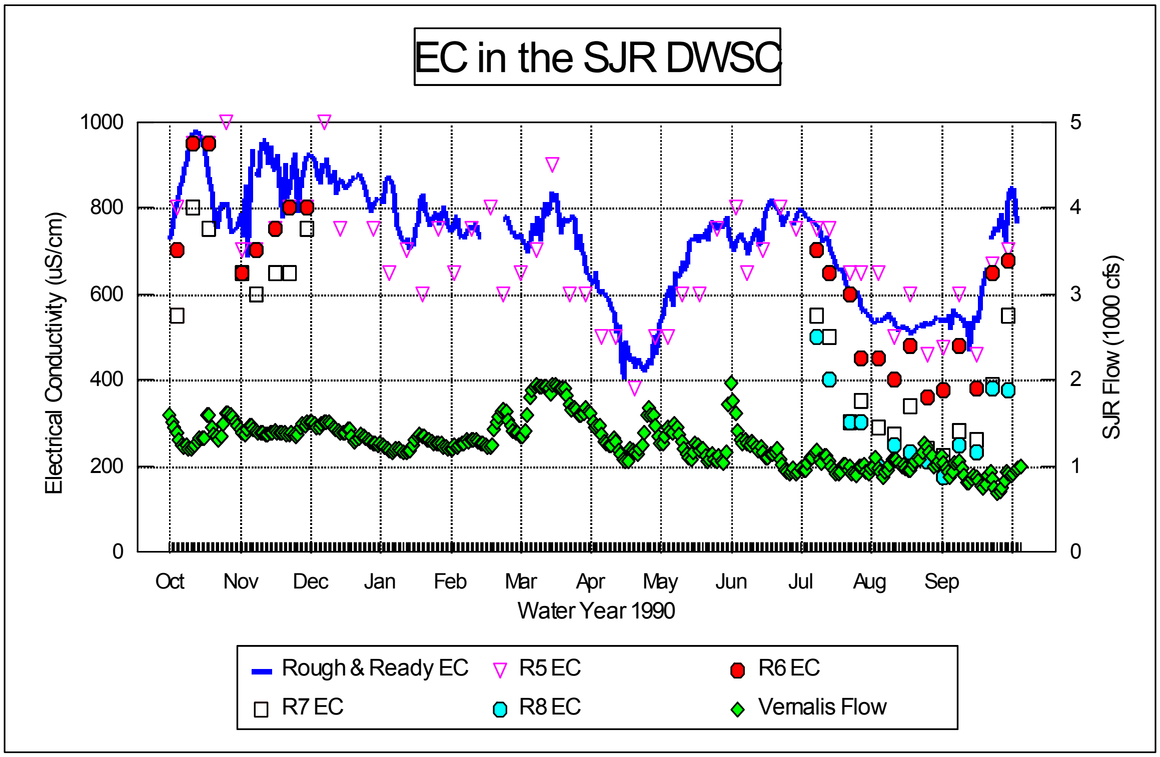


Figure 10. DWSC Measurements of EC at City of Stockton Stations R5 to R8 during 1990 and 1991



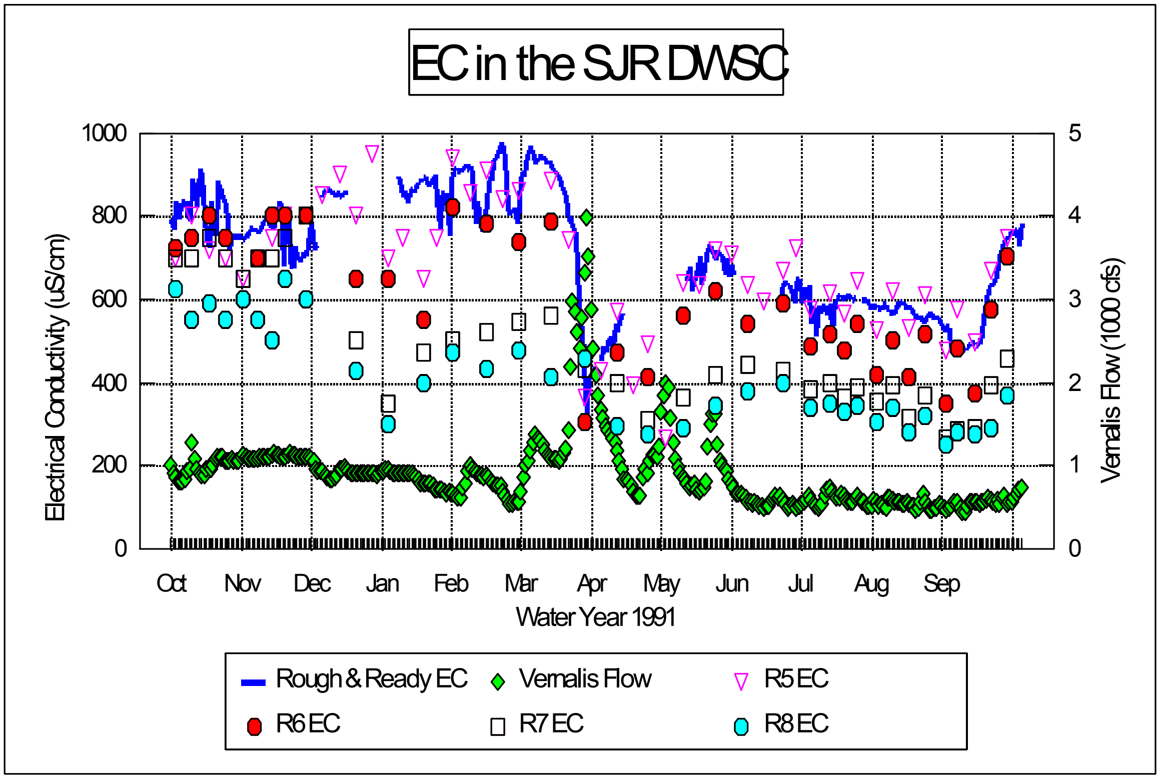
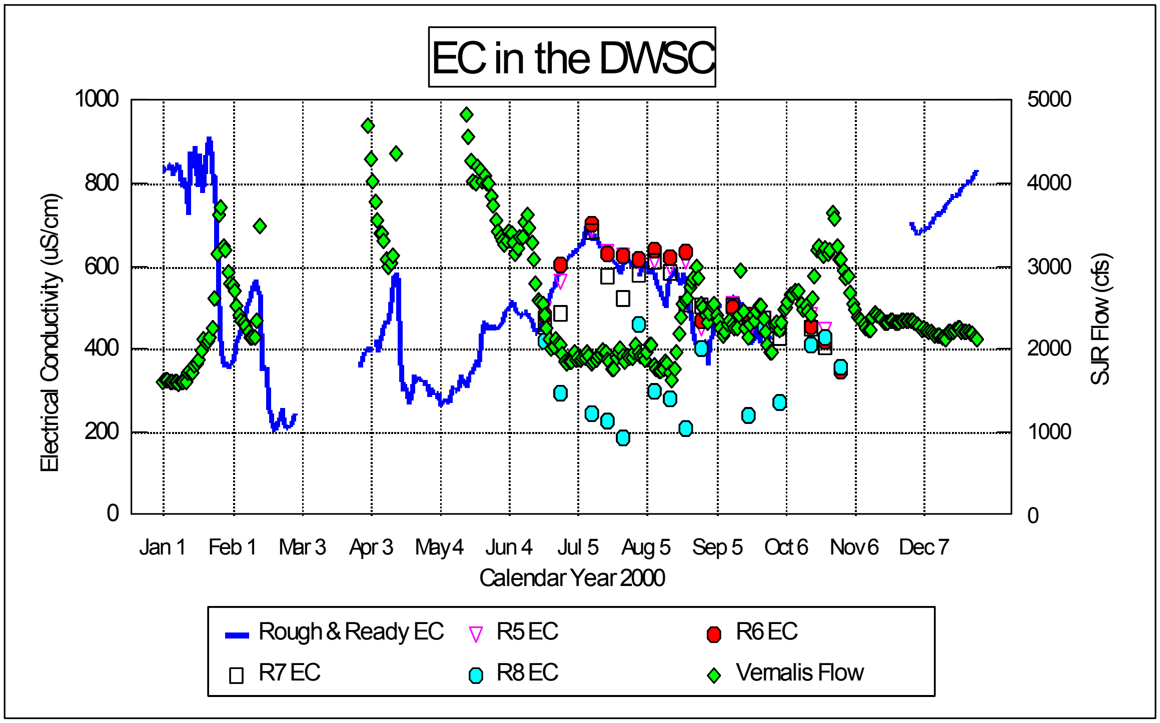


Figure 11. DWSC Measurements of EC at City of Stockton Stations R5 to R8 during 2000 and 2001



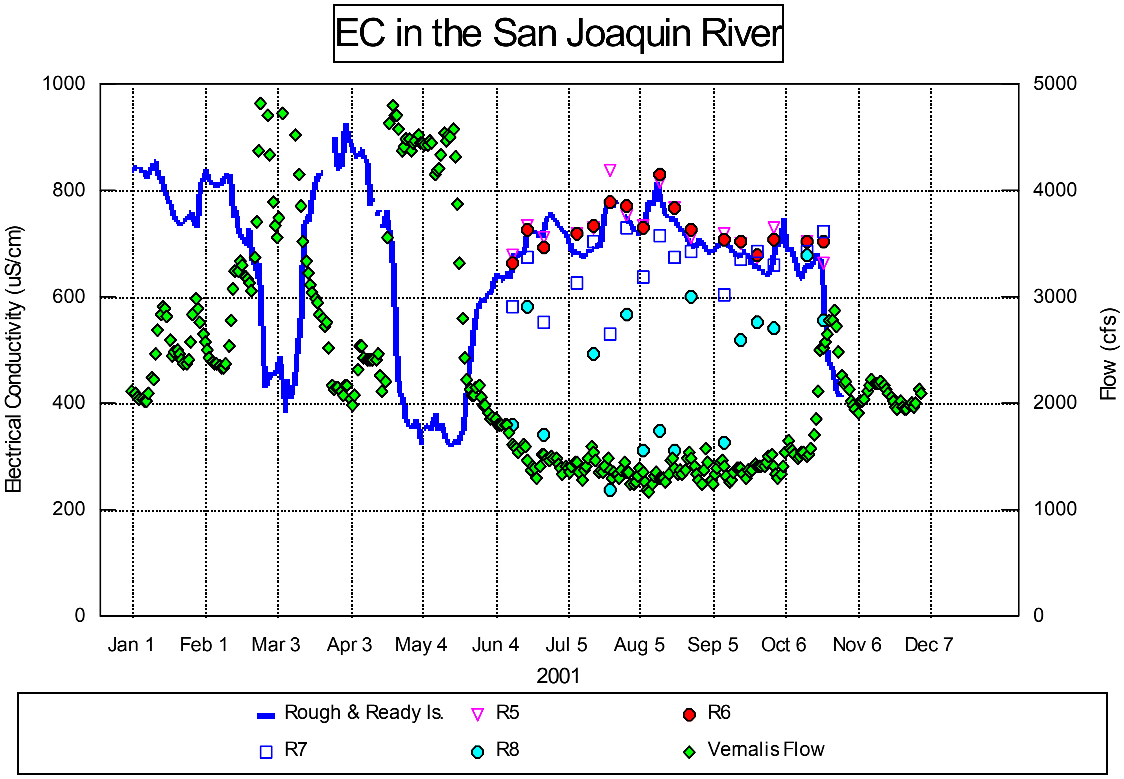


Figure 12. Longitudinal Profiles of EC Gradient Location in the DWSC during 1999

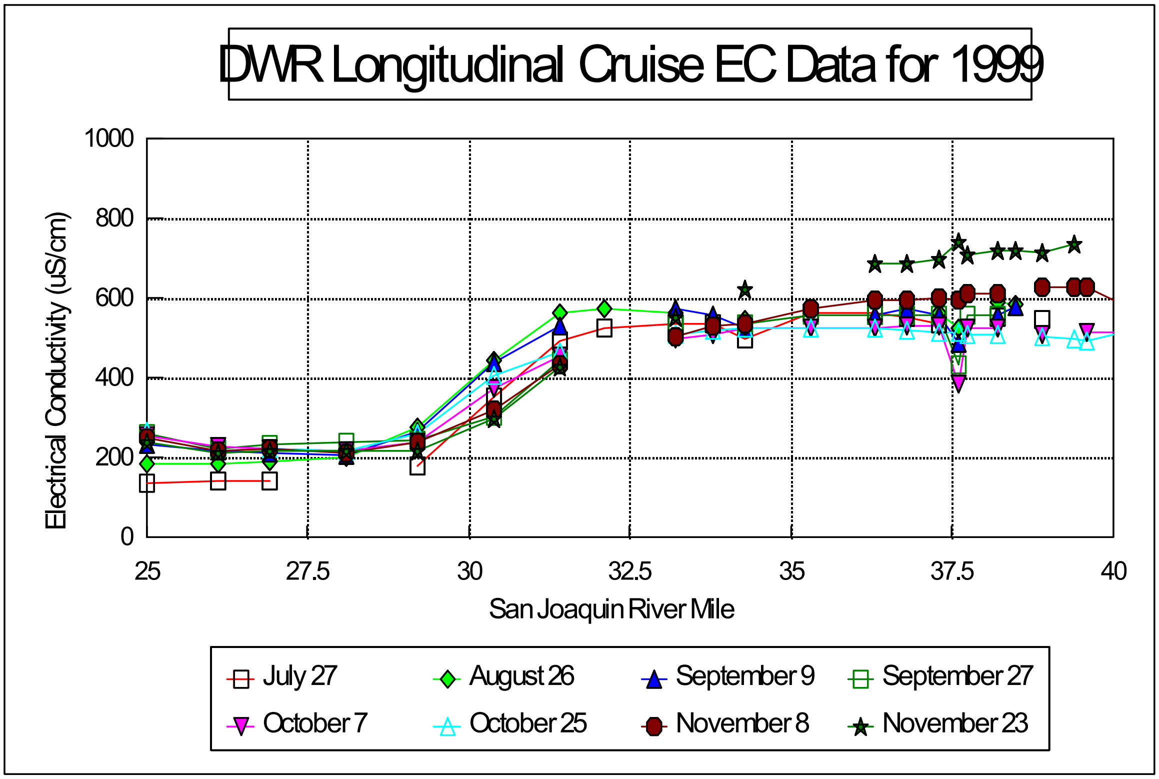
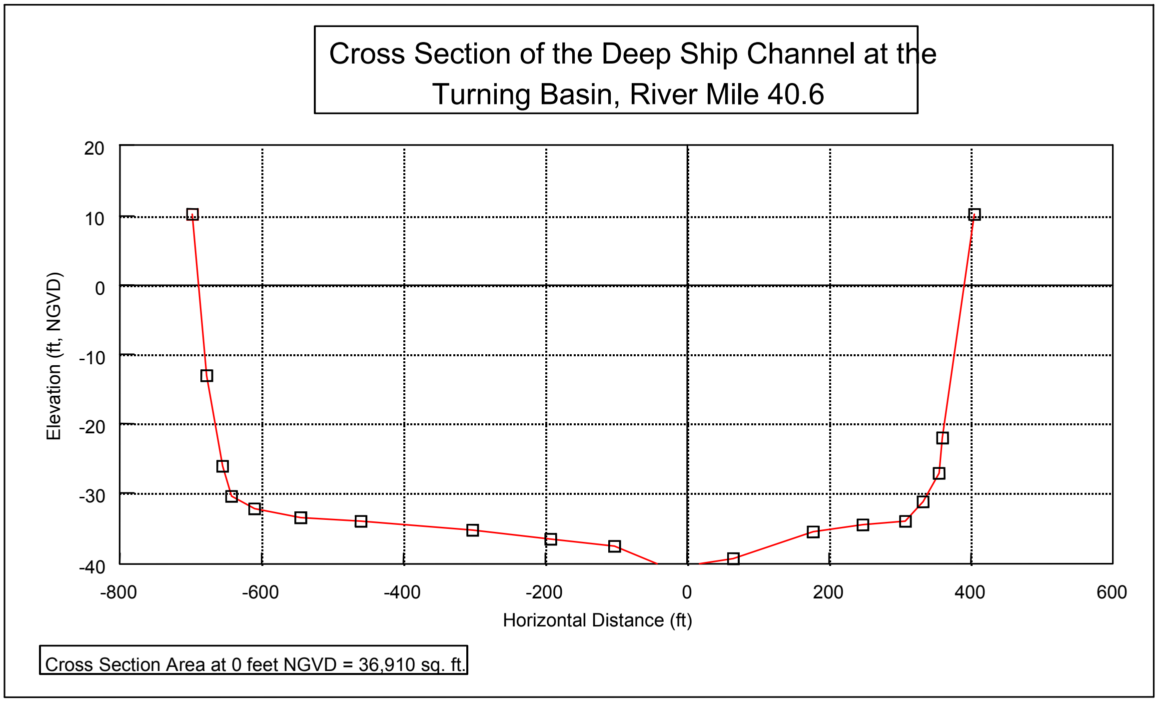
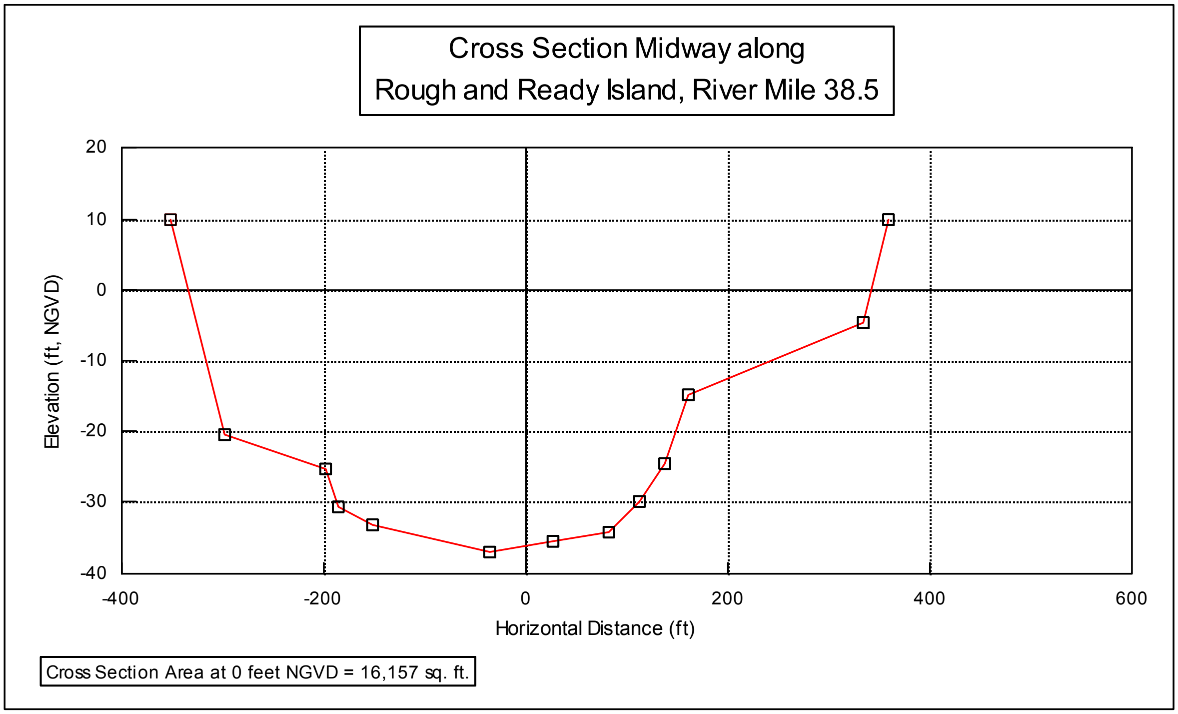


Figure 13. DWSC Cross Sections for the Turning Basin and Rough & Ready Island from the DWR Delta Cross-Section Development Program (positive horizontal distance feet are toward the right-hand bank looking downstream)

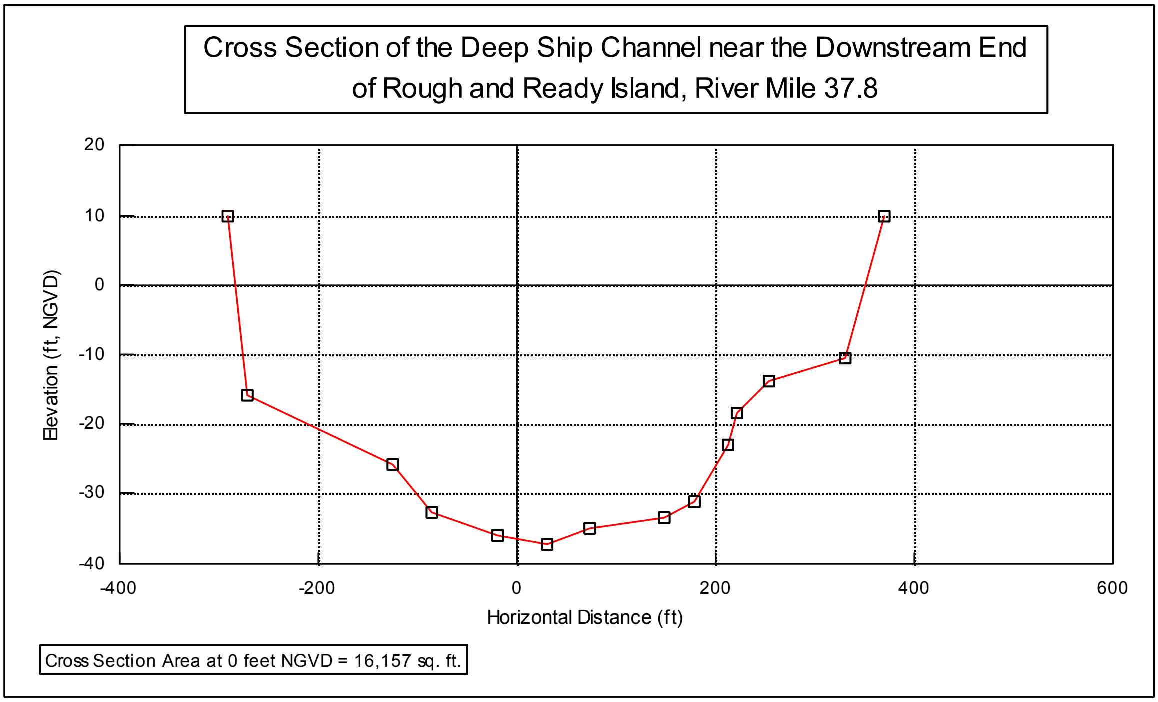

Cross Section of the Deep Ship Channel at the Turning Basin, River Mile 40.6

Cross Section Area at 0 feet NGVD = 36,910 sq. ft.

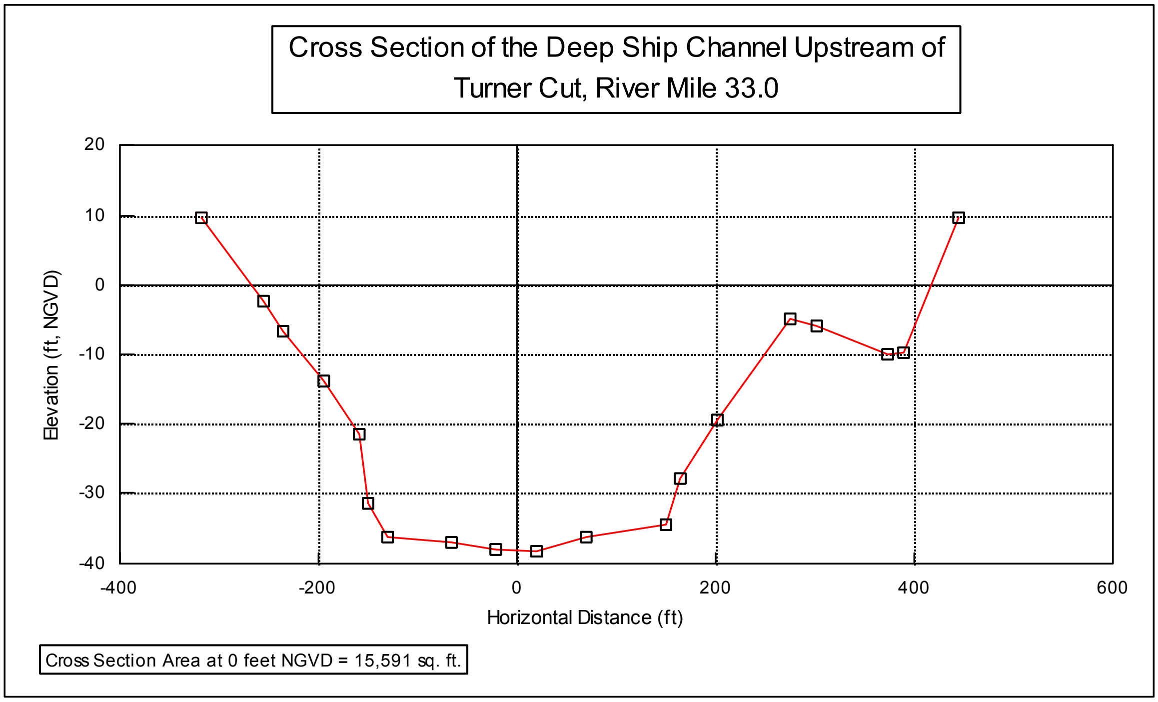

Cross Section Midway along Rough and Ready Island, River Mile 38.5

Cross Section Area at 0 feet NGVD = 16,157 sq. ft.

Figure 14. DWSC Cross Sections for Rough & Ready Island and Upstream of Turner Cut from the DWR Delta Cross-Section Development Program (positive horizontal distance feet are toward the right-hand bank looking downstream)


Cross Section of the Deep Ship Channel near the Downstream End of Rough and Ready Island, River Mile 37.8

Cross Section Area at 0 feet NGVD = 16,157 sq. ft.


Cross Section of the Deep Ship Channel Upstream of Turner Cut, River Mile 33.0

Cross Section Area at 0 feet NGVD = 15,591 sq. ft.

Figure 15. DSM2 Model Simulated Tidal Flows in the San Joaquin River near the Head of Old River (SJR 53.5). Simulated Vernalis flow of 1,000 cfs with 0 cfs Exports and Vernalis 1,000 cfs flow with 10,000 cfs Exports

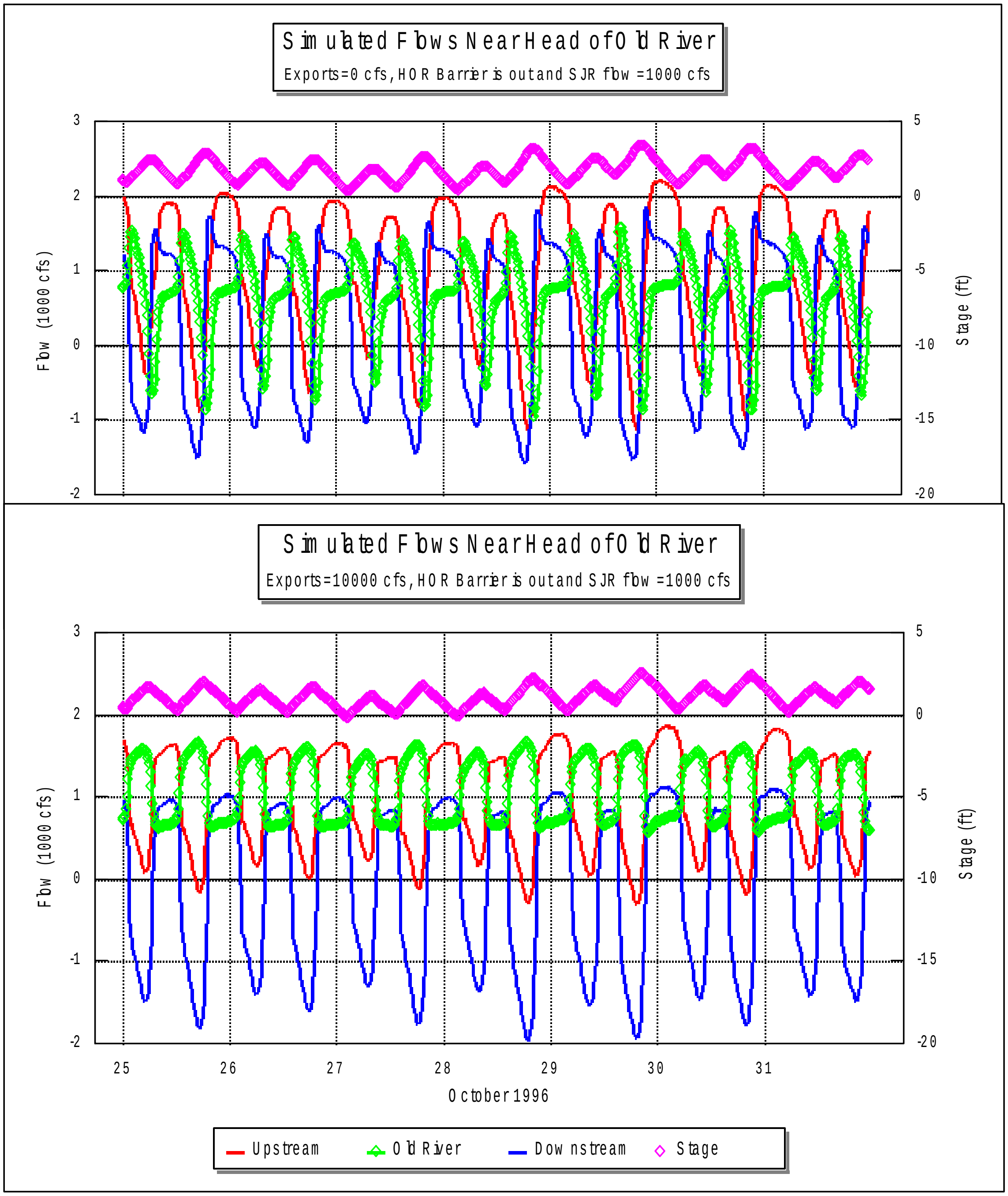
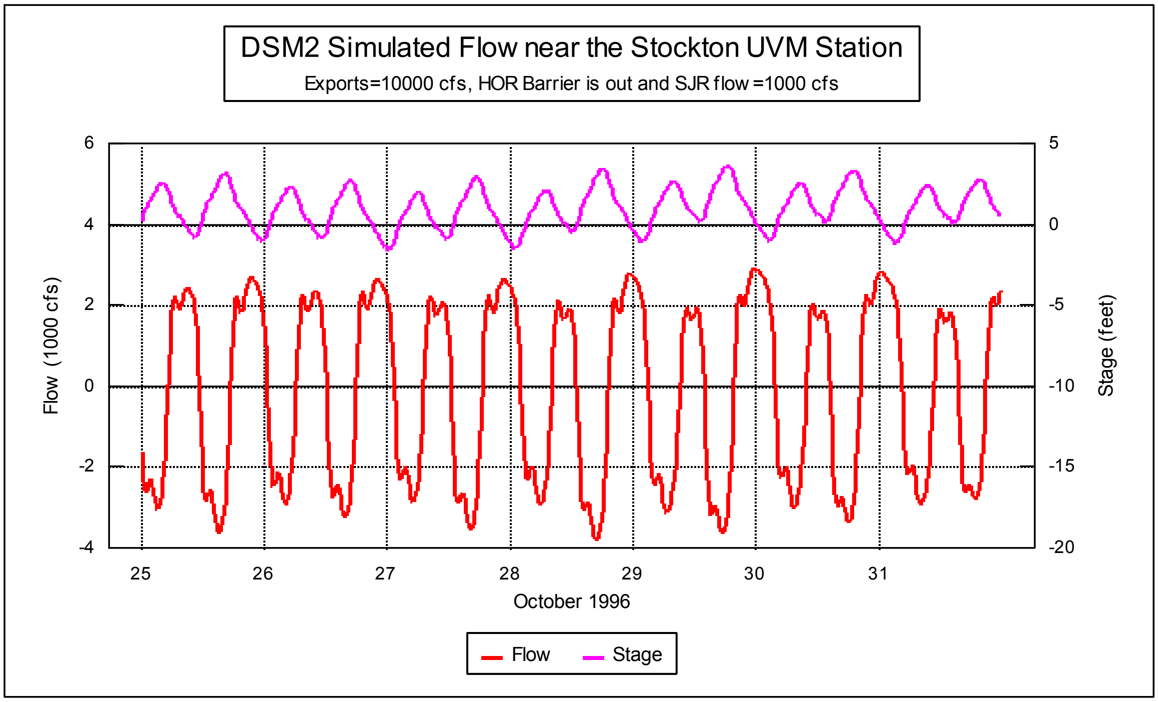


Figure 16. DSM2 Model Simulated Tidal Flows at Stockton UVM Station (near Stockton RWCF) for Vernalis flow of 1,000 cfs and Export Pumping of 10,000 cfs



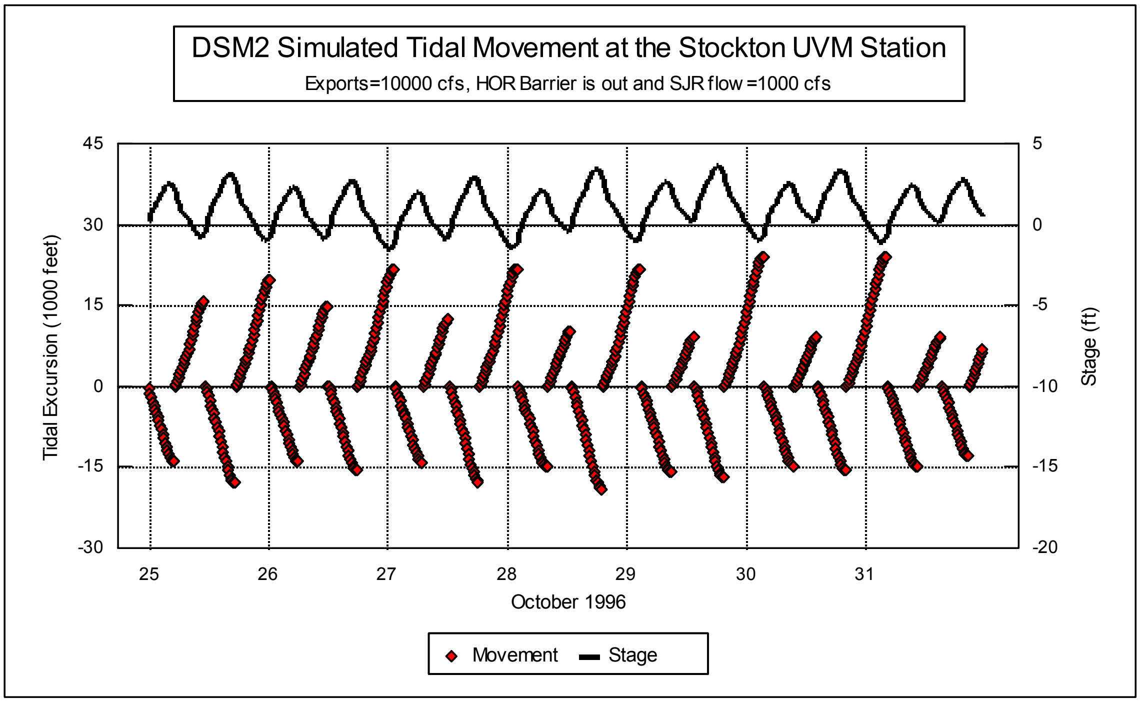
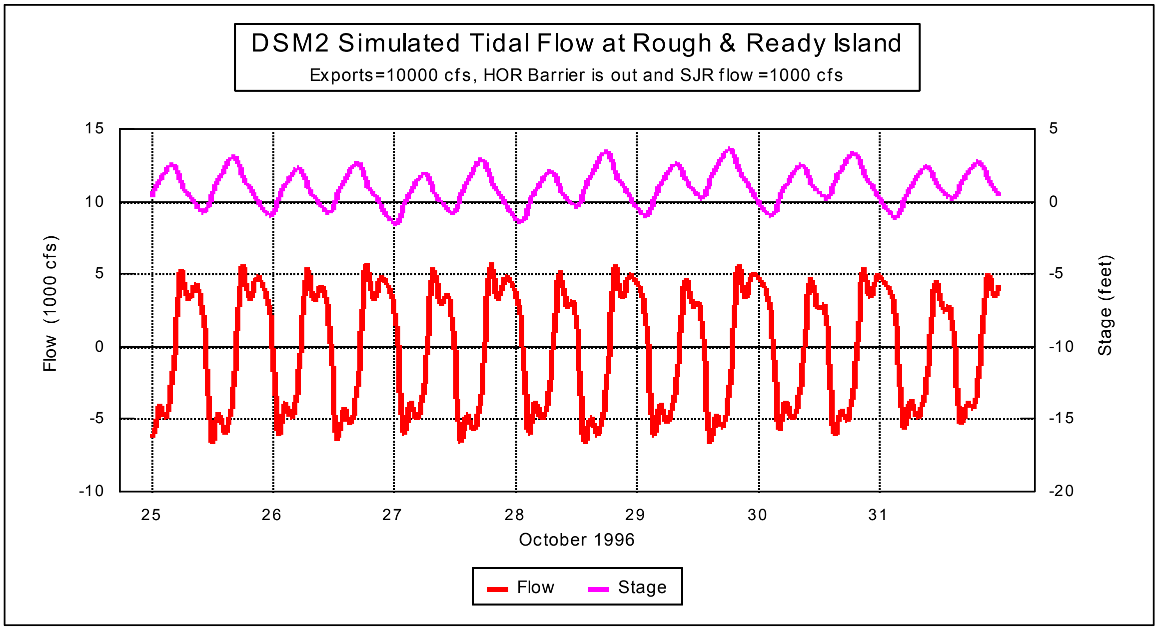


Figure 17. DSM2 Simulated Tidal Flows at Rough & Ready Island Tidal Flow Station with Vernalis flow of 1,000 cfs and Export Pumping of 10,000 cfs; net flow of -72 cfs (reversed upstream)



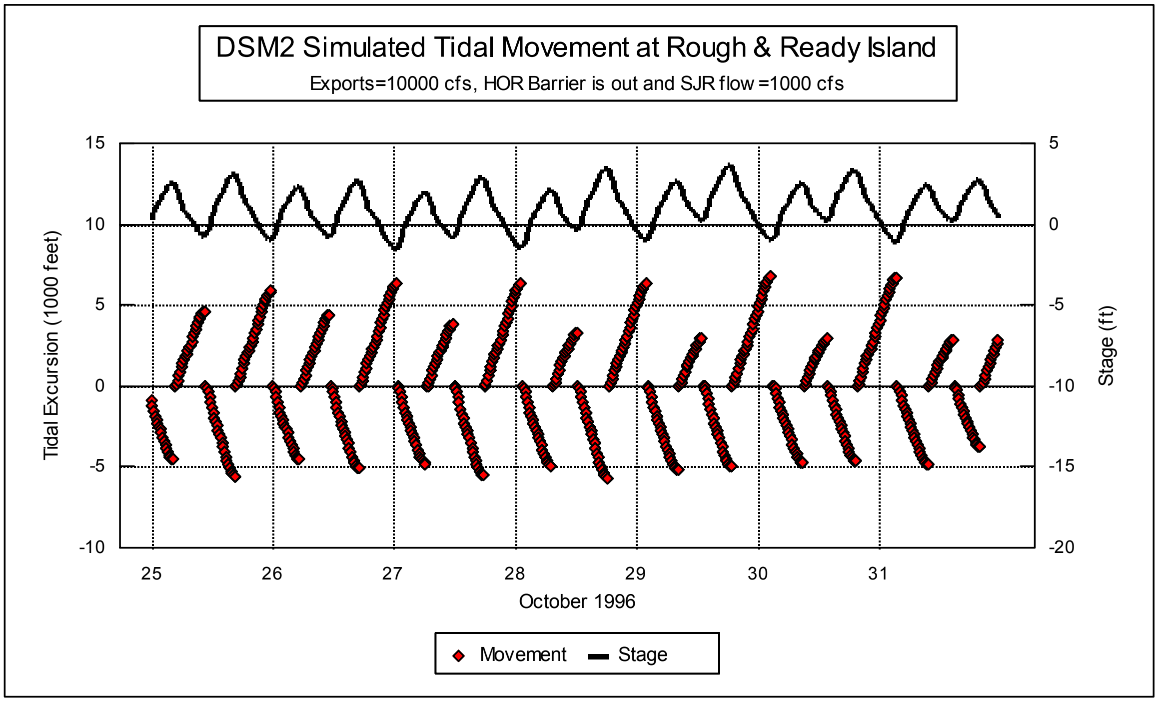
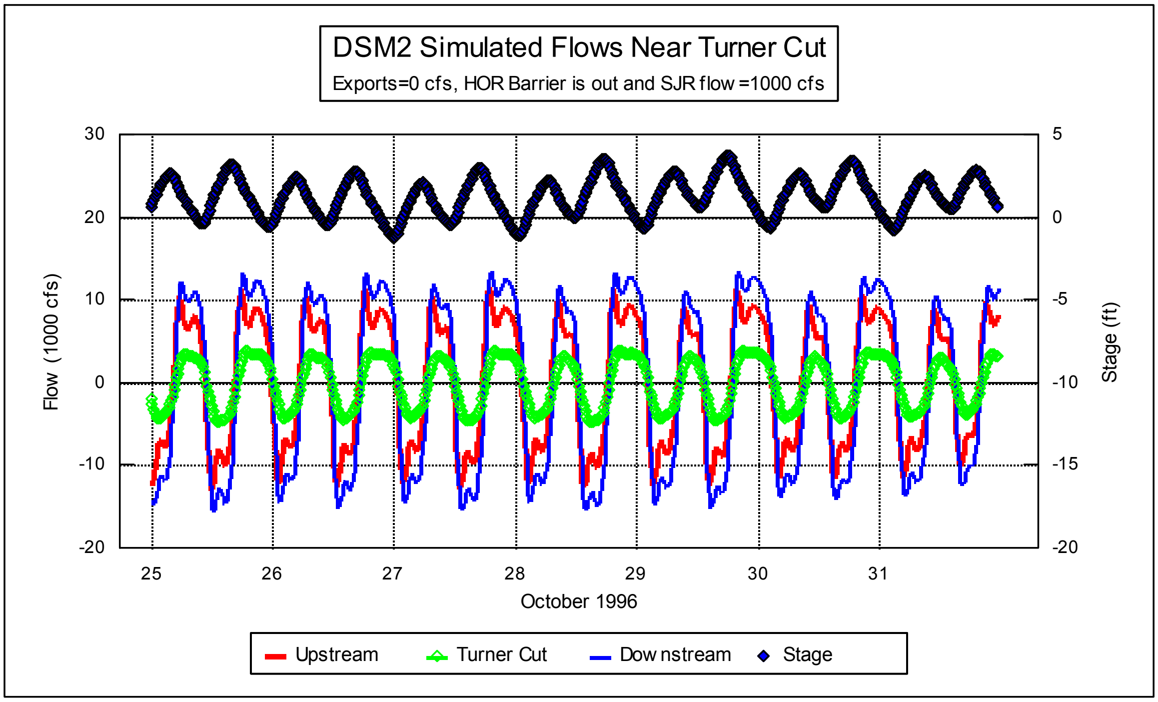


Figure 18. DSM2 Simulated Tidal Flows in DWSC at Turner Cut for October 1996



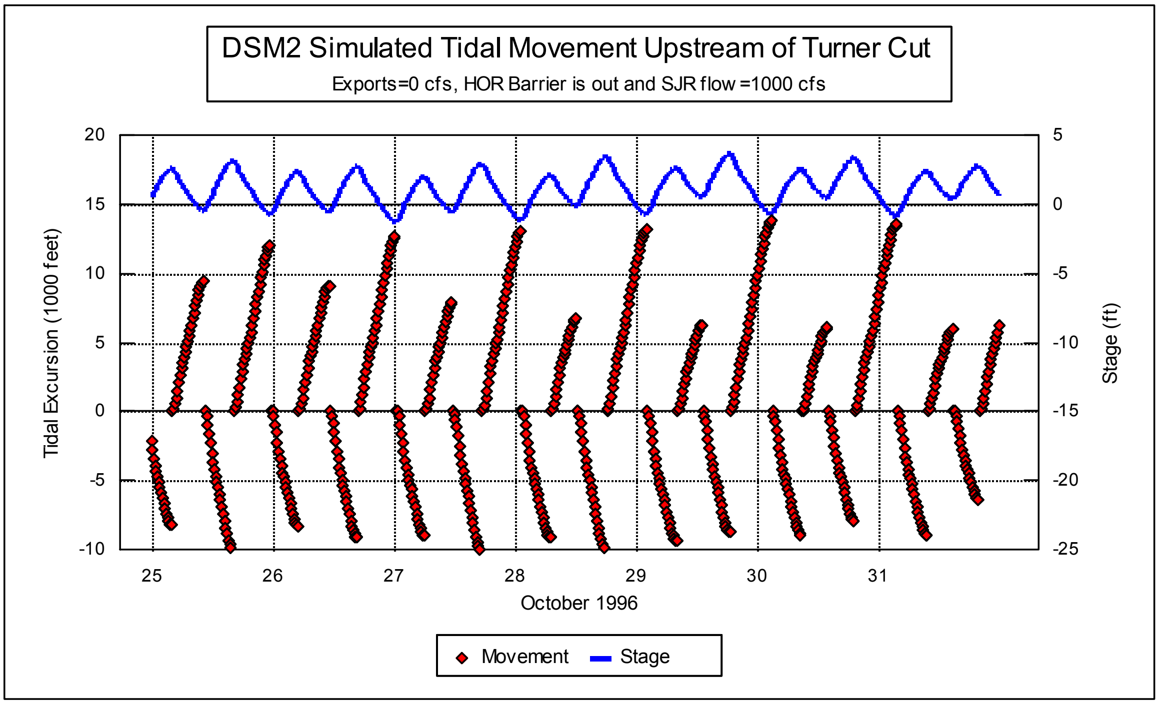
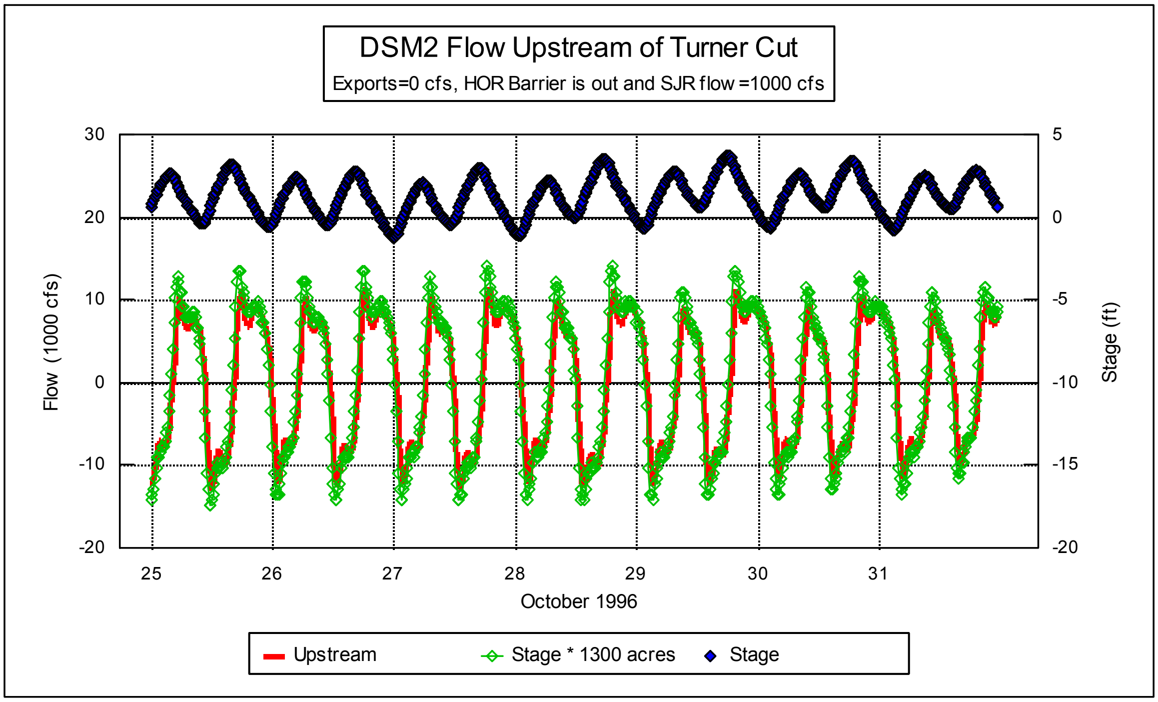


Figure 19. Comparison of DSM2 simulated tidal flow and tidal flow calculated as the stage change times the upstream tidal area at Tuner Cut and Rough & Ready Island.



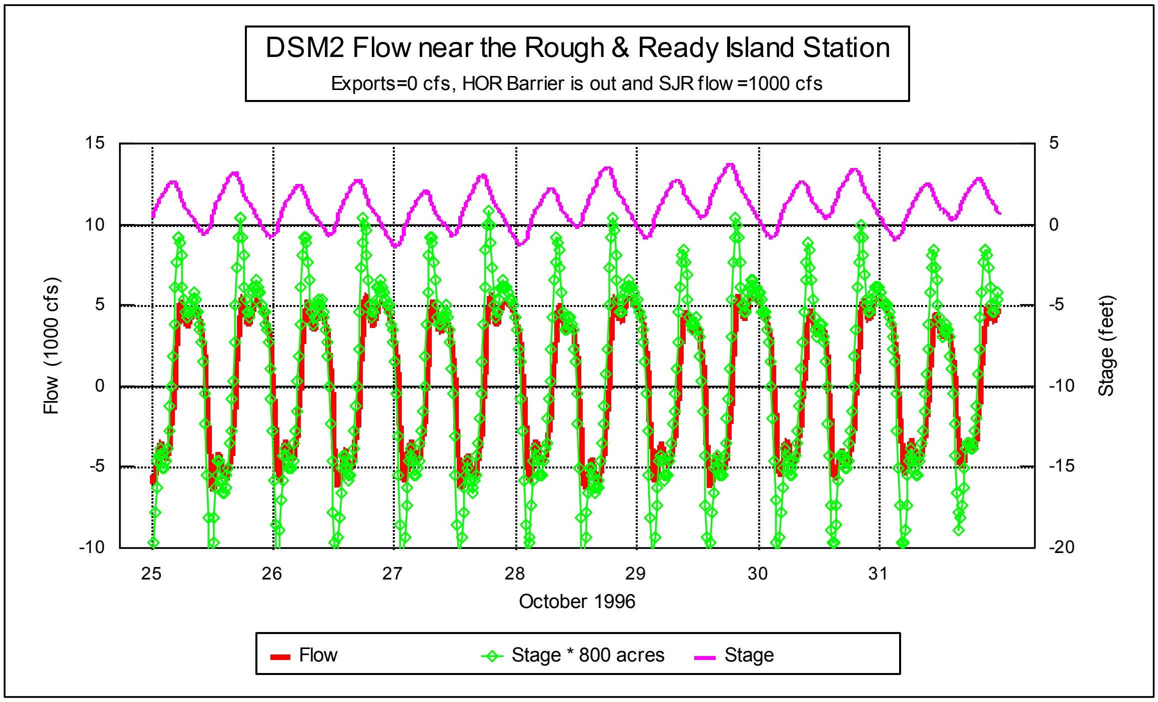


Figure 20. DSM2 Simulated EC Gradients in DWSC with SJR Inflow of 1,000 cfs with EC of 1,000 uS/cm; HOR is open and Exports are 0 cfs; simulated DWSC Flow is 320 cfs and Turner Cut Flow is 113 cfs

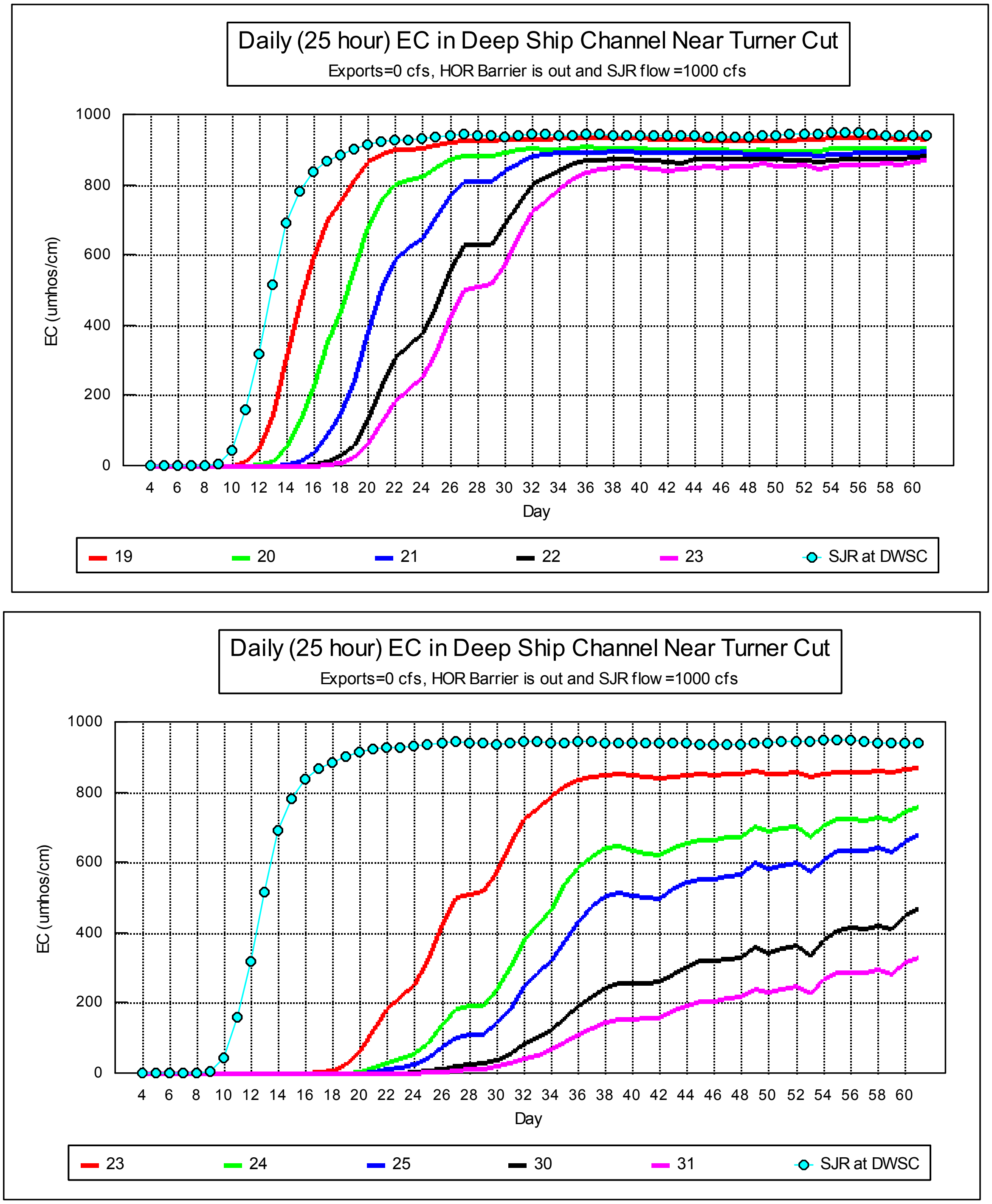
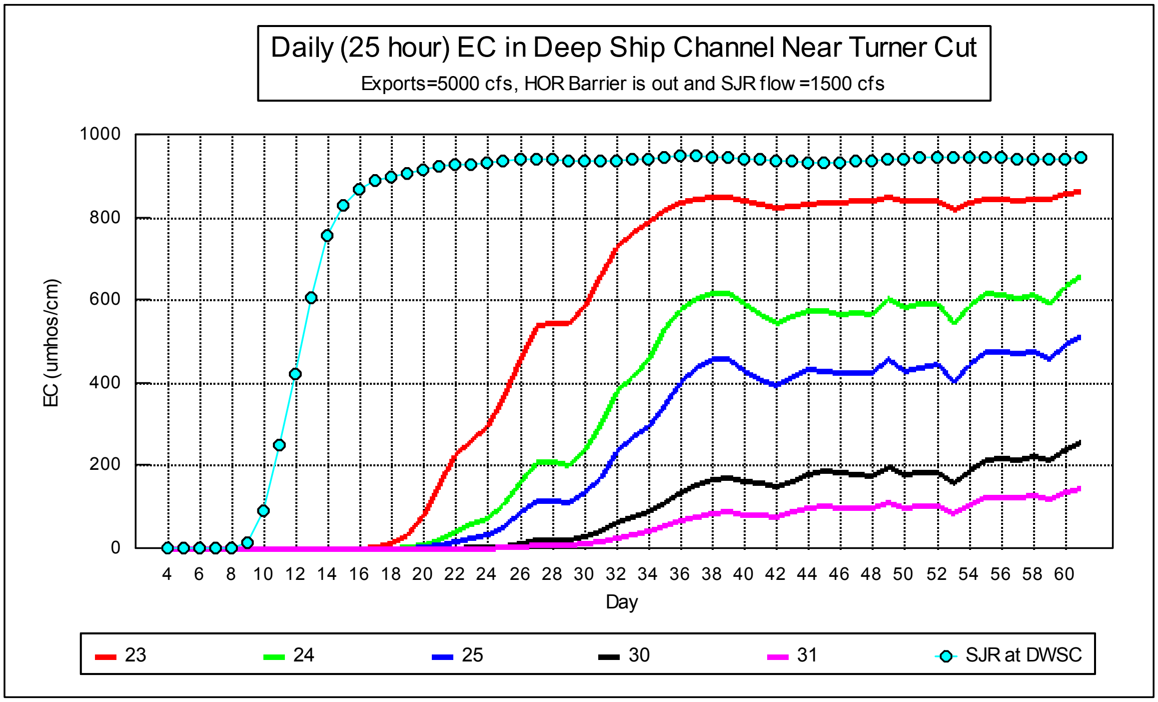
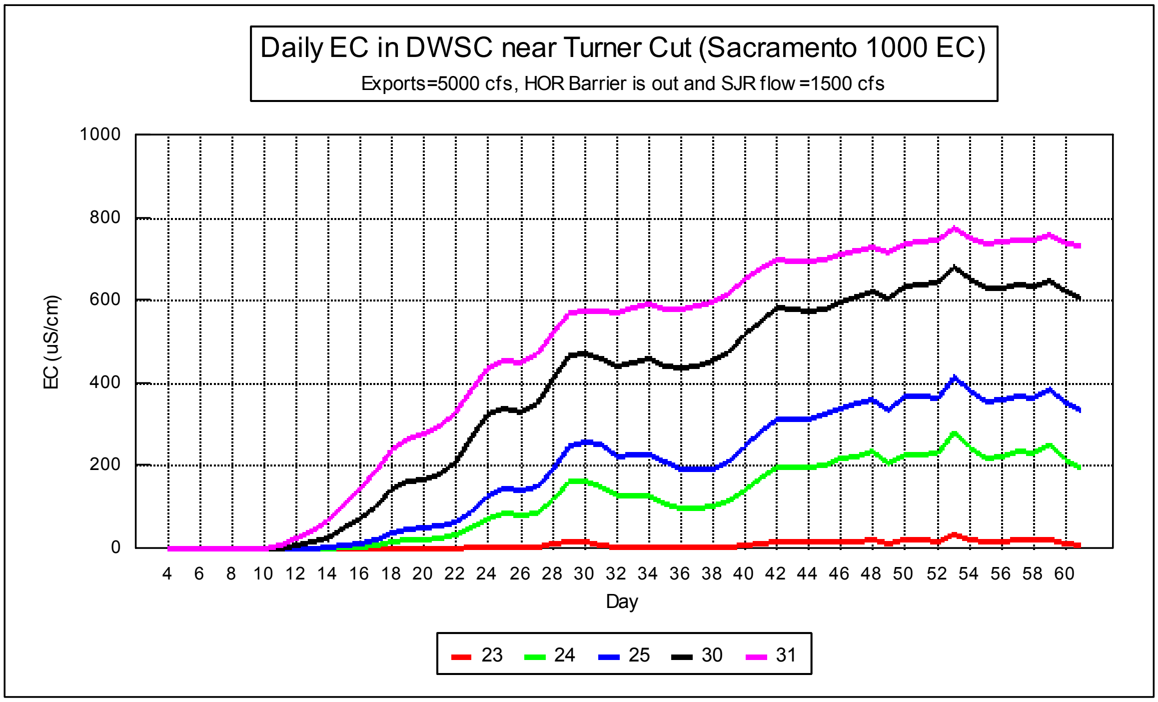


Figure 21. DWSC Simulated EC Gradients in DWSC with SJR inflow of 1,500 cfs, HOR open, and exports of 5,000 cfs. Simulated DWSC flow of 335 cfs and Turner Cut Flow of 461 cfs. SJR flow downstream of Turner Cut is -129 cfs (reversed). Top panel tracks SJR and bottom panel tracks Sacramento River with EC = 1,000 uS/cm.





Evaluation of Stockton Deep Water Ship Channel Water Quality Model Simulation of 2001 Conditions: Loading Estimates and Model Sensitivity

Prepared for:

San Joaquin River Dissolved Oxygen TMDL
Technical Advisory Committee

and

CALFED Water Quality Program

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September 2002

Jones & Stokes. 2002. Evaluation of Stockton Deep Water Ship Channel Water Quality Model Simulation of 2001 Conditions: Loading Estimates and Model Sensitivity. September. (J&S 01-417.) Prepared for CALFED Bay-Delta Program. Sacramento, CA.

Contents

Page

Figures

All figures follow the report text

Acronyms and Abbreviations

BOD	biochemical oxygen demand
CBOD	carbonaceous biochemical oxygen demand
cfs	cubic feet per second
DO	dissolved oxygen
DWR	Department of Water Resources
DWSC	Deep Water Ship Channel
EC	electrical conductivity
HOR	Head of Old River
R&R	Rough & Ready Island
RWCF	Regional Wastewater Control Facility
SJR	San Joaquin River
TAC	Technical Advisory Committee
TKN	total kjeldahl nitrogen
TOC	total organic carbon
USGS	U.S. Geological Survey
VAMP	Vernalis Adaptive Management Program
VSS	volatile suspended solids
WQCP	Bay-Delta Water Quality Control Plan
µS/cm	microSiemens per centimeter

Appendix A

Evaluation of Stockton Deep Water Ship Channel Water Quality Model Simulation of 2001 Conditions: Loading Estimates and Model Sensitivity

Introduction

The San Joaquin River (SJR) Dissolved Oxygen TMDL Technical Advisory Committee (TAC) directed some of the money in CALFED Directed Action Task 01-N61-06 “Downstream Tidal Exchange” (awarded to Jones & Stokes) to be used for preliminary data analysis and simulation of 2001 water quality conditions in the Deep Water Ship Channel (DWSC). The modeling was accomplished by Systech Engineering using the improved San Joaquin River water quality model developed under the CALFED 2000 Grant. The results from the 2001 simulations are described in this short technical report. This modeling work was accomplished in February 2002 by Systech Engineering to support the preliminary analysis of 2001 data that was requested by the TAC.

Modeling Task Description

The improved version (CALFED 2000 Grant) of the Stockton Water Quality Model, originally developed by Systech in 1993 for the City of Stockton, was used to simulate calendar year 2001 dissolved oxygen (DO) and other water quality conditions. The results show the validation of the water quality model for 2001 flows and concentrations, using the previously calibrated model coefficients. Additional simulations demonstrate the sensitivity of the DO concentrations to slightly different coefficient values and inflow concentrations during 2001. The simulated cases are:

1. Validation results for 2001 using the best estimates of river and Stockton Regional Wastewater Control Facility (RWCF) effluent flows, river and RWCF concentrations, and calibrated coefficients. Comparisons with DO, volatile suspended solids (VSS), ammonia, chlorophyll and phaeophytin are emphasized.

2. Sensitivity of DO to river flow are demonstrated by comparison with two runs with slightly higher (150%) and slightly lower (50%) net river flows. The summer low-flow period are emphasized in the flow evaluation. Simulations with a constant steady flow of 250 cubic feet per second (cfs), 500 cfs, and 1,000 cfs are shown to indicate the flow sensitivity throughout the year.
3. Sensitivity of DO to light and resulting algae growth in the DWSC are evaluated with two runs with slightly higher (150%) and lower (50%) euphotic depths (depth with 1% surface light). The effects of higher and lower algal growth rates also are compared.
4. Sensitivity of DO to the RWCF effluent concentrations (loads) are simulated. The carbonaceous biochemical oxygen demand (CBOD) load and the ammonia load are reduced to 50% and increased to 150% to accomplish this comparison.
5. Sensitivity of DO to the SJR loads of CBOD, VSS, and algae biomass (chlorophyll) are evaluated with a series of comparisons that include increasing the concentrations to 150% and reducing the concentrations to 50%.
6. The sensitivity of DO to the settling rate coefficients for particulate organic materials (VSS and chlorophyll) are shown with increased settling rates (150%) and decreased settling rates (50%).

Review of Model Assumptions and Coefficient Values

The Stockton Water Quality model is fully documented in the final report for the CALFED 2000 Grant (Chen and Tsai 2002). The model extends about 20 miles from the Head of Old River (HOR) to the City of Stockton River Station 8 (Navigation Light 17/18) near Columbia Cut. The model calculates tidal flows between segments (approximately 0.5 to 1.0 mile long) and uses mass balance equations to simulate the concentrations of several water quality variables, including DO. The model includes several tidal sloughs (Fourteen Mile, Mormon, French Camp) and side channels that join the SJR in the vicinity of Stockton.

The water quality variables that are simulated include the following: temperature, DO, CBOD, chlorophyll (live algae) and phaeophytin (dead algae), VSS (detritus), TSS, ammonia, nitrate, total phosphorus, and salinity measured as electrical conductivity (EC). The original purpose of the model was to simulate the effects of RWCF effluent on DO concentrations in the DWSC. Some water quality variables that are not currently included in the model are pH, organic nitrogen, and total organic carbon (TOC). The model processes that produce or consume oxygen include: atmospheric reaeration, sediment oxygen demand, detritus decay, algae growth, algae respiration/decay, nitrification (ammonia to nitrate), and CBOD decay. The model also can simulate artificial aeration from bubble columns or waterfall devices; the model properly simulates the amount of DO added as a function of the DO deficit from saturation at the location of the aeration device.

The model has been improved and calibrated as part of the CALFED 2000 Grant (DO modeling project). Several years have been simulated (1991, 1996, 1999, and 2000), and a generally reasonable match to the measured water quality concentrations (temperatures, DO, nutrients, and TSS) has been obtained with the model. Several additional parameters were measured in the special field studies during the summer of 1999, 2000, and 2001 that allow more of the model variables (biochemical oxygen demand [BOD], chlorophyll, phaeophytin) to be calibrated and validated. The calibrated coefficients are described in the final modeling report (Chen and Tsai 2002).

Estimating Daily River and Regional Wastewater Control Facility Flows and Concentrations

Daily SJR flows passing the HOR and entering the DWSC are generally provided by the U.S. Geological Survey (USGS) tidal flow meter (UVM) located near the Stockton RWCF. However, the UVM tidal flow device was not operational for a large portion of the summer in 2001, and estimates of DWSC daily flow were obtained using flow regression equations developed from Vernalis flow and Delta Export pumping (Jones & Stokes 2001).

Figure 1 shows the measured and estimated DWSC flows during 2001. The Vernalis USGS flows are shown for reference. The measured UVM data generally follow the estimated range of Stockton flows at the beginning and ending of the summer period with missing records. The June–September Stockton flows are estimated to have ranged between 750 cfs and 1,000 cfs. The combination of measured UVM flow and estimated flow on days without UVM measurements was used in the modeling. The flows are very important in the water quality modeling because they control the dilution of the RWCF discharge, the travel time between Mossdale and the DWSC, and the residence time within the DWSC.

Figure 2 shows the Stockton RWCF daily discharge flows for 2001. Although the discharge is sometimes shut off on weekends and holidays, the monthly average discharge rate during the summer and fall was between 31 cfs and 47 cfs. The RWCF flow is important because it directly controls the effluent loads (e.g., ammonia and CBOD) discharged to the river. The river or discharge load can be calculated from the concentration and flow as:

Daily load (lbs/day) = 5.4 $*$ concentration (mg/l) $*$ flow (cfs)

Daily River Concentrations

A large amount of field data is needed to provide daily estimates of the model inflow concentrations for the river and the RWCF discharge. The Department of Water Resources (DWR) Mossdale water quality monitoring station provides hourly temperature, pH, conductivity, and DO measurements. These were used for estimating daily river concentrations. Weekly water quality measurements were available from Mossdale and Vernalis during the summer and fall TMDL sampling period (Jones & Stokes 2002). Concentrations for the winter period were only roughly estimated from assumed general seasonal patterns.

Figure 3 shows the daily average EC measured at Vernalis, Mossdale, and Rough & Ready Island (R&R). The Vernalis EC was relatively constant at about 600–650 microSiemens per centimeter (µS/cm)] during the summer period, as required by the SWRCB 1995 Bay-Delta Water Quality Control Plan (WQCP) Vernalis salinity objective of less than 700 µS/cm from April through August. The EC at Mossdale is slightly higher than at Vernalis during the summer period, suggesting the influence of agricultural drainage. The EC at R&R is not very much higher than at Mossdale, although the RWCF discharge EC is about 1,200 µS/cm. The expected increase in river EC at R&R would be about 25 µS/cm with a dilution of 20 (river flow of 760 cfs and RWCF discharge of 40 cfs). The water quality model is expected to match the observed EC changes in downstream segments. For example, the delayed reduction in EC at R&R following the October pulse flow event at Vernalis would be reasonably well simulated by the model. This simulated EC pattern was not evaluated, however, because the emphasis of this study was on the 2001 DO concentrations.

Figure 4 shows the temperatures in the SJR at Vernalis, Mossdale, and R&R. Temperatures were greater than 20˚C from May through September, and were greater than 25˚C for portions of June, July, and August. Temperatures of less than 10˚C were measured only in January, early February, and December. Nitrification is greatly reduced at temperatures of less than 10˚C. The saturated DO concentration declines from about 11.5 mg/l at 10˚C to about 8.5 at 25˚C. All of the model decay rates are assumed to be temperature-dependent, so BOD and algae decay will have a stronger effect on DO in the summer.

Figure 5 shows the Mossdale minimum and maximum DO and the daily average value used in the model. The Mossdale average DO was greater than saturation and the diurnal range was greater than 2 mg/l from June through September, indicating significant algae concentrations because algae photosynthesis is the only process that can create this diurnal variation in DO. Mossdale DO was slightly less than saturation (1–2 mg/l) and the diurnal range was less than 1 mg/l during the remainder of the year.

Figure 6 shows the minimum and maximum pH recorded at Mossdale. Although pH is not included in the water quality model, the pH data confirm the diurnal DO measurements and indicate a substantial algae concentration in the river from June through September. The Mossdale pH is greater than 8 from late May through September. The pH is generally lower at R&R (7.5–8.0), suggesting that algae growth is still present but less active. The RWCF effluent pH is usually about 6.5.

Figure 7 shows the measured and estimated turbidity values for Mossdale in 2001. The assumed seasonal pattern is somewhat arbitrary. A mathematical "sine-squared" shape has been assumed for the seasonal pattern. Summer concentrations of TSS and turbidity are higher than winter values, unless a large storm produces surface runoff to the river. The model uses the turbidity values to represent inorganic suspended solids (TSS) that may settle in the DWSC. The model estimates the light extinction coefficient and depth of algae growth (euphotic depth, 1% of surface light) from the TSS, as well as algae and VSS concentrations. TSS is settling and is resuspended in the DWSC by the tidal velocity. Because the observed downstream decrease in turbidity is only moderate, there must be substantial resuspension of the clay particles, or else the settling rate is very slow.

Figure 8 shows the measured and estimated VSS (organic particles including algae and detritus) concentrations for 2001. The strong seasonal pattern follows the Mossdale diurnal DO and pH measurements that are strongly peaked (i.e., sine-squared shape) during the summer. The VSS measurements at Mossdale and Vernalis are very similar, declining rapidly in September at both stations. The seasonal estimate of river VSS concentration uses a minimum of 2 mg/l and a maximum of 12 mg/l. VSS is the simplest and most basic measurement of organic material entering the DWSC. However, the model will separately track the DO decay from algae respiration and decay, so the algae contribution to the VSS must be separated from the VSS estimate. This separation requires an important assumption about the pigment content of algae.

The primary algae measurements are the pigments, chlorophyll and phaeophytin, assumed to represent the live and decaying algae. To estimate algae biomass, the fraction of algae that is pigment molecules must be assumed. The water quality model assumes a constant pigment content of 1.25% of the biomass. With this assumption, 1 mg/l of algae biomass (VSS) would be equivalent to 12.5 μg/l of pigment (chlorophyll or phaeophytin). This basic assumption can be confirmed by comparing the total pigment concentration with the VSS measurements. The VSS (μg/l) concentration should always be greater than 80 times the total pigment (μg/l) concentration. The measured algae pigment at Mossdale and Vernalis has been converted to equivalent biomass with the assumed 1.25% pigment content. Figure 8 indicates that this ratio is a reasonable guess and that the algae biomass may represent a majority of the river VSS concentrations. The detritus variable in the model represents the non-algae organic particles that decay and settle. The estimated river detritus concentrations for 2001 obtained by subtracting the algae biomass from the VSS concentrations are relatively constant at between 2 mg/l and 4 mg/l.

Figure 9 shows the measured and estimated Mossdale chlorophyll concentrations used for the model input. The chlorophyll concentrations decreased rapidly in September.

The weekly measurements at Mossdale and Vernalis were used to fit an assumed seasonal curve with a very strong peak (sine-cubed shape). Although both temperatures and light have seasonal sinusoidal shapes, the reason for this extremely peaked shape is not obvious. The maximum chlorophyll is assumed to be 80 μg/l (equivalent to 6.4 mg/l VSS) and the winter minimum is 0 μg/l.

Figure 10 shows the measured and estimated Mossdale phaeophytin concentrations that were assumed to be 50% of chlorophyll, based on the summer TMDL measurements. The maximum of 40 μg/l corresponds to a VSS concentration of 3.2 mg/l. The total algae biomass (live and dead) is the majority of the 10–12 mg/l VSS measured in June and July.

Figure 11 shows the estimates of ultimate dissolved CBOD at Mossdale. The 5-day total BOD measurement was used to estimate the dissolved CBOD values. Because the model tracks the CBOD separately from ammonia oxidation, algae decay, phaeophytin decay, and detritus decay, only the dissolved CBOD fraction of total BOD is simulated with the CBOD variable in the model. The model assumes that 1 mg/l of detritus or algae biomass will produce 1.6 mg/l of BOD during decay. The model assumes that ultimate CBOD is 2.5 times the 5-day CBOD. The 2.5 factor is derived from long-term BOD measurements that indicate the 5-day BOD is about 40% of the ultimate (30-day) BOD. This ratio suggests that the daily BOD decay rate is about 0.10 day^{-1}. After accounting for the BOD equivalent of the measured VSS (detritus and algae), the data suggest that only about 1 mg/l is dissolved 5-day CBOD. The model therefore assumes the ultimate CBOD is about 2.5 mg/l throughout the year.

The model requires estimates of river ammonia, nitrate, and phosphate concentrations. The ammonia at Mossdale varied from 0 to 1.0 mg/l and was simulated as a constant 0.5 mg/l, which will have an ultimate BOD equivalent of about 2.5 mg/l. The SJR nitrate concentrations are very high at Mossdale and were simulated as a constant of 2.0 mg/l. The SJR phosphorus concentrations (assumed dissolved and available for algae growth) were assumed to be a constant of 0.15 mg/l.

There may be substantial variations in the daily river concentrations that are not included in these seasonal model estimates, which are based on weekly summer and fall grab samples. The daily changes in river concentrations caused by variations in river flows or variations in algae growth conditions were not simulated by the model for 2001.

Daily Stockton Regional Wastewater Control Facility Effluent Concentrations

Daily (24-hour composite) measurements of CBOD, VSS, and ammonia-N in the RWCF effluent are routinely collected. These measurements provide very accurate RWCF load estimates for the model (Jones & Stokes 2002).

Figure 12 shows the daily measurements of 5-day CBOD and the corresponding estimates of ultimate CBOD in the RWCF effluent. The first estimate of ultimate CBOD is assumed to be 2.5 times the 5-day CBOD measurements. The second estimate of ultimate CBOD is based on the assumption that each 1 mg/l of VSS will produce 1.6 mg/l of ultimate CBOD during decay. The two estimates of ultimate CBOD are similar throughout the summer and fall. Because the oxidation ponds and tertiary dissolved air flotation and sand filters are most effective in the summer, the CBOD concentrations are actually lowest in the spring and summer periods.

The data suggest that the ultimate CBOD estimated from VSS (particulate) is often slightly greater than the ultimate CBOD estimated from 5-day CBOD. Therefore, very little RWCF effluent CBOD is dissolved. The total ultimate RWCF effluent CBOD (detritus and algae and dissolved) varies from about 5 mg/l to 25 mg/l during the summer and fall months, with the estimates from VSS being about 5 mg/l higher than the estimates from 5-day CBOD. The assumed 2.5 factor for 5-day CBOD or the 1.6 factor for VSS must be adjusted slightly to produce the same estimate of ultimate CBOD.

Figure 13 shows the daily ammonia-N concentrations for the RWCF effluent. The maximum ammonia-N concentrations of 25 mg/l during the winter are similar to the inflow concentrations to the RWCF, and indicate that very little removal of ammonia occurs during the winter. The majority of the ammonia is removed by algae uptake and growth during the spring and summer months. The RWCF performance during 2001 was not as good as in most years, when ammonia has consistently been less than 2 mg/l from May through August (Jones & Stokes 1998). The total kjeldahl nitrogen (TKN), which includes ammonia and organic nitrogen, is measured weekly and is shown in Figure 13. The majority of the TKN concentration was ammonia-N.

Figure 14 shows the ultimate BOD equivalent for the TKN, assuming that 4.7 mg/l of oxygen are required to oxidize (nitrify) each 1 mg/l of ammonia-N. The maximum ultimate NBOD concentrations are about 150 mg/l during the winter, when the TKN concentration is 30 mg/l. However, the nitrification rate is less during the winter and may cease altogether at temperatures of less than 10°C. The ultimate NBOD dominates the ultimate CBOD, which was generally less than 25 mg/l. These high ultimate BOD concentrations from the RWCF effluent are, however, diluted by the SJR flow before entering the DWSC.

Combined San Joaquin River and Regional Wastewater Control Facility Biochemical Oxygen Demand Loads to the Deep Water Ship Channel

A simple way to visualize the two sources of BOD loading (i.e., river and RWCF) is to consider the total ultimate BOD concentrations entering the DWSC each day. The river load at Mossdale will change (decay) as it flows to the DWSC. The RWCF load will be diluted by the river flow before entering the DWSC. The model simulates the decay of BOD and decline of algae biomass during the travel time from Mossdale to the DWSC. At a flow of 500 cfs the travel time is about 2.5 days, and at a flow of 1,000 cfs the travel time is only 1.2 days. Field measurements of VSS and chlorophyll indicate that the R3 concentrations are generally less than 50% of the Mossdale concentrations. A considerable reduction in the Mossdale load of particulate organics (i.e., ultimate BOD) apparently occurs in the river between Mossdale and the DWSC, although the travel time was generally only 1–2 days during 2001.

The ultimate BOD concentration that enters the DWSC from Mossdale was assumed to be 50% of the Mossdale ultimate BOD. The ultimate BOD concentration entering the DWSC from Mossdale follows a seasonal pattern that is a minimum of 5 mg/l in the winter and a maximum of 12 mg/l in the summer. The ultimate BOD concentration entering the DWSC will be increased by the RWCF effluent BOD concentration after dilution by the river flow. The fraction of the effluent concentration of ultimate BOD that will enter the DWSC in the river flow can be estimated from the ratio of the combined river flow and effluent discharge to the effluent discharge:

Dilution Factor = (River flow + RWCF Discharge) / RWCF Discharge

A higher river flow will provide a greater dilution of the RWCF discharge. The river and diluted effluent water will move through the DWSC more quickly and exert less of the ultimate BOD within the DWSC volume when the river flow is higher. A 5-day moving average of the river flow and discharge has been assumed to account for tidal mixing in the SJR.

Figure 15 shows the resulting dilution factor pattern for 2001. The model assumed the higher flow estimate shown in Figure 1. The dilution factor was generally greater than 20 throughout the summer. During December the dilution factor declined to less than 10 for several days.

The ultimate BOD concentrations from the RWCF effluent were high when ammonia-N concentrations were greater than 10 mg/l (i.e., 50 mg/l ultimate NBOD). However, because the dilution of effluent by the river flow was generally greater than 20, the contribution of ultimate BOD from the RWCF discharge to the DWSC was almost always less than 5 mg/l. Only in January and December were the ultimate BOD concentrations entering the DWSC from the diluted RWCF effluent higher than 5 mg/l. The contribution of ultimate BOD from the RWCF discharge to the DWSC was therefore almost always less than the contribution of ultimate BOD from the river.

Figure 16 shows the measured daily DO deficit (saturated DO – average DO) at the R&R monitoring station operated by DWR. The DO deficit pattern already accounts for the change in DO saturation that depends directly on the water temperature. The DO deficit reflects the total BOD decay that was exerted in the river downstream of Mossdale or in the DWSC during the travel time of the water to the R & R station. The longer the travel time, the more of the ultimate BOD will actually decay within the DWSC and cause the DO concentrations at R&R to decline. The total ultimate BOD entering the DWSC, assuming 50% of the Mossdale BOD and the diluted RWCF BOD, is also shown in Figure 16. The two patterns show a strong similarity and suggest that the seasonal ultimate BOD concentration entering the DWSC accounts for the majority of the observed DO deficits at the R&R station.

The DO deficit indicates that the ultimate BOD loads exceeded the ability of reaeration and algae production to add DO to the DWSC. Reaeration of the DWSC is increased as the DO deficit increases and as the residence time of the BOD loads increases, but the net effects of reaeration on the effective BOD loads are difficult to evaluate without a model to perform the calculations. A model is also needed to track the net effects of algae growth in the DWSC. Algae photosynthesis is assumed to produce as much DO as algae respiration and decay will subsequently consume, but the net effects on DO in the DWSC do not appear to be balanced. These more complicated and involved calculations can be performed only with a water quality model.

Validation of Model Results for 2001 Dissolved Oxygen Conditions

The Stockton DWSC water quality model was used to simulate 2001 conditions without any changes in model coefficients. The inflow concentrations were specified as described in this report, and the field data collected at the City of Stockton river sampling stations in the DWSC were compared with the model predictions. Because the river concentration estimates do not include daily variations, only the basic seasonal patterns of river water quality can be simulated with the model. The daily changes in river flow and the daily changes in RWCF effluent concentrations and flows will produce some daily variations in simulated water quality in the DWSC. Daily fluctuations in water temperatures also will slightly change BOD decay rates in the DWSC. Figure 4 indicates that temperatures between Mossdale and R&R are very similar. The model is able to reproduce the short-term temperature fluctuations caused by meteorology, but the seasonal effects of temperature on DO saturation and BOD decay processes are the dominant effects of temperature on the simulated DO concentrations.

Figure 17 shows the simulation of ammonia concentrations at R3 and R5 compared with Mossdale. Mossdale ammonia was assumed to be 0.5 mg/l, although the data indicate considerable variation in ammonia. The highest summer ammonia concentration of about 1.0 mg/l was measured at R3 during August. The concentrations had decreased to about 0.75 mg/l at R5. The model concentrations were a little less than measured at R3, and the simulated decline at R5 was smaller, suggesting that the simulated decay rate may be slightly too fast. The green line represents the expected ammonia concentration entering the DWSC without any ammonia oxidation (dilution only). The DWSC ammonia values would have been about 1.5 to 2.0 mg/l during the summer. The model appears to be simulating about the right amount of nitrification, although reducing the rate slightly from 0.05 day^{-1} to 0.04 day^{-1} might improve the match with field data. The model also could be modified to include organic nitrogen, which would allow the TKN measurements to be used and allow the complete nitrogen cycle to be simulated. The TKN concentrations at Mossdale were about 1.0 to 1.5 mg/l during the summer, and this additional organic nitrogen will decay to ammonia and then nitrify, thereby increasing the oxygen demand.

Figure 18 shows the measured and simulated VSS concentrations at Mossdale, R3 and R5 for 2001. The water quality model had a re-suspension term added that is a function of the river velocity that includes a strong tidal component within the DWSC. The resuspension term for VSS is unlimited (i.e., total VSS is not tracked) and therefore acts as a net source of VSS. The model is simulating too much resuspension of VSS in the river and the DWSC, with model R3 concentrations of 5 to 15 mg/l. The measured VSS at R3 is about 5 mg/l. The simulated decrease of about 1 mg/l VSS between R3 and R5 is properly simulated. But the simulated tidal signal (i.e., spring-neap tidal energy) in VSS is much greater than indicated by the VSS data. Field measurements suggest a more constant resuspension source of VSS within the DWSC that counteracts the settling of VSS (Litton 2002). The VSS simulation for 2001 is not adequate because the average VSS is too high (from the simulated resuspension source of VSS) and the tidal variation within each month is too strong.

Figure 19 shows the measured and simulated chlorophyll concentrations at Mossdale, R3 and R5 for 2001. The simulated net decline in chlorophyll (i.e., algae) between Mossdale and R3 is apparently too slow in the model because the simulated chlorophyll at R3 is about 3 times higher than measured. As Figure 19 indicates, the model simulates the R3 chlorophyll to decline to about 75% of the Mossdale chlorophyll, but the data indicate that the R3 chlorophyll is only about 25% of the Mossdale value. The algae simulations at R5 are also too high compared with the data. The model does simulate a 50% decline in chlorophyll between R3 and R5, which is similar to the observed decline. The chlorophyll simulation for 2001 is not adequate because the net decline in chlorophyll between Mossdale and the DWSC is not enough to match the R3 algae data. The modeled algae growth rate may be too high, or the decay rate might be too slow.

Figure 20 shows the measured and simulated phaeophytin concentrations at Mossdale, R3 and R5 for 2001. The net decline in phaeophytin (i.e., dead algae) between Mossdale and R3 is apparently too slow in the model because the simulated phaeophytin at R3 is higher than measured in June, July, and August. The data indicate that phaeophytin at R3 and R5 was higher than at Mossdale in September and October. The model decay rates for both chlorophyll and phaeophytin may be too low. Some special algae decay rate experiments suggest that the dark decay of chlorophyll was about 0.5 day^{-1} and the dark decay of phaeophytin was about 0.25 day^{-1} (Litton 2002). The model is currently using a chlorophyll decay rate of 0.13 day^{-1} and a phaeophytin decay rate of 0.10 day^{-1}. Increasing these coefficient values may improve the match with field data. The simulated growth rate of algae in the light conditions typical of the river below Mossdale (i.e., 10–15 feet depth) and in the DWSC (i.e., 25–35 feet depth) should also be verified with field measurements.

Figure 21 shows the simulated and measured DO concentrations at R3 and R5. The minimum daily DO concentration from the DWR R&R monitoring station are also shown. The saturation DO concentration for the R&R station temperature is shown for comparison. The seasonal decline in DO at R3 and R5 is simulated. The simulated DO at R5 is about 1 mg/l below the measured R5 data and below the R&R minimum DO concentrations during the spring and summer. The measured DO was nearly saturated during April and May when the flows were at least 3,000 cfs during the Vernalis Adaptive Management Program (VAMP) period for outmigration of juvenile chinook salmon. The simulated DO at R5 was about 2 mg/l lower than the R&R data during this event.

The general magnitude of the simulated DO deficit at R5 matches the field data quite well during the summer and fall period of June through October 2001. However, the simulated DO at R3 was considerably less than the measured DO data at R3, suggesting that the model is simulating too much BOD decline in the river between Mossdale and the DWSC. The model therefore simulates too little

BOD remaining at R3 to lower the DO between R3 and R5. The simulated settling and decay processes between Mossdale and R3 should be better balanced with the simulated settling and decay processes within the DWSC from R3 to R5.

Figure 22 shows the cumulative travel time between Mossdale and R3 and then to R5. The DO deficit measured at R5 appears to be generally related to this pattern. As described in Figure 16, the highest concentrations of CBOD and NBOD from the river and the RWCF effluent occurred during the June–September period. The travel time to the DWSC was about 3 days, and the cumulative travel time to R5 was about 10 days, with a corresponding dilution factor of about 20 for the RWCF effluent. The model is not able to track the short-term fluctuations in the measured DO at the R&R station that were observed during this summer period. Some of the suggested changes in the VSS, ammonia, and algae simulations will also likely improve the DO simulations.

Sensitivity Results

The model was also used to demonstrate sensitivity of simulated DO concentrations in the DWSC to changes in RWCF effluent and river concentrations, as well as to changes in river flow and some important model coefficients. These sensitivity results will increase confidence in the model if the sensitivity simulations bracket the measured data. The sensitivity results also emphasize the importance of the measured river and RWCF concentrations of the ultimate BOD components (i.e., algae, TKN, detritus, and dissolved CBOD).

Sensitivity of Dissolved Oxygen to Flow in 2001

Figure 23 shows the simulated daily average DO concentrations at R3 for the base case with actual flows in 2001 compared with a reduced (50%) flow case and an increased (150%) flow case. The base simulation used the high flow estimate shown in Figure 1. The same seasonal Mossdale river concentrations and the same RWCF effluent flows and concentrations were used in each simulation. The higher flow case gave shorter travel times (67% of base) and greater dilution of the RWCF effluent so the effective BOD concentrations entering the DWSC were less than the base. The reduced flow case gave longer travel times (2 times base) and less dilution (50% of base) for the RWCF effluent. The simulated changes in DO concentrations at R3 were greater for the reduced flow case than for the increased flow case. A large difference (i.e., 2–3 mg/l) in the simulated DO concentrations at R3 was predicted during the summer period, indicating that flow is a very important variable for accurately simulating DO concentrations. The measured DO data at R3 appear to be better matched with the increased flow (150%) case.

Figure 24 shows the simulated daily average DO concentrations at R5 (R&R) for the base case with actual flows in 2001 compared with a reduced (50%) flow case and an increased (150%) flow case. The simulated changes in DO concentrations at R5 were greater for the reduced flow case than for the increased flow case. A difference of 1–2 mg/l in the simulated DO concentrations at R5 was predicted during the summer period, indicating that flow is a very important variable for accurately simulating DO concentrations. The measured DO data at the R&R monitoring station appears to be better matched with the increased flow (150%) simulation case. This does not mean that the flows should be increased, because the flows are measured accurately. Rather, the model coefficients need to be further adjusted to match the DO data with the measured base flows.

Sensitivity of Dissolved Oxygen to Volatile Suspended Sediment and Algae Settling Rates in 2001

Figure 25 shows the simulated daily average DO concentrations at R3 for the base case compared with reduced settling rates (50%) and with increased settling rates (150%) for algae and VSS. The same seasonal Mossdale river concentrations of algae and VSS and the same RWCF effluent flows and concentrations of VSS were used in each simulation. The reduced settling produced lower DO concentrations (i.e., 1 mg/l less during the summer period), presumably because of greater concentrations of VSS and algae remaining in the flow entering the DWSC. Figure 26 shows the simulated results at R5 (R&R). The effects of the increased settling rates (150% base) were not as great at either R3 or R5. These results suggest that VSS settling is a very important coefficient for simulating DO in the DWSC. The settling rates should not be reduced, however, because the simulated DO concentrations with the reduced settling rates were much lower than the measured DO data at R3 and R5. The increased-settling-rates case gave a better match with the measured DO, but the settling rates should be adjusted only if comparison with the measured VSS and algae (i.e., chlorophyll and phaeophytin) concentrations suggests a change is necessary. The model VSS settling and resuspension formulations might need to be revised to track to total VSS and limit the mass of VSS that is available to be resuspended from the bottom.

Sensitivity of Dissolved Oxygen to Algae Growth Rates in 2001

Figure 27 shows the simulated daily average DO concentrations at R3 for the base case compared with reduced algae growth rate (50%) and increased algae growth rate (150%) cases. The reduced algae growth rate produced slightly higher DO concentrations at R3. The reduced algae growth rate only slightly reduced the algae biomass, suggesting that the majority of the algae originated from Mossdale, rather than growing in the river between Mossdale and the DWSC. The increased algae growth rate had a dramatic effect on the simulated DO at R3, reducing the DO concentrations by 2 mg/l during the summer period. This indicates that the simulated growth rate should not be raised. Any additional algae biomass grown in the river will enter the DWSC and reduce the DO as the algae decays. Figure 28 shows the simulated results at R5 (R&R).

The effects of the increased algae growth rate (150% base) on DO at R5 was very strong, causing a decrease of 2 mg/l during the summer period. Because this is the same effect as simulated at R3, the mechanism appears to be growth of algae in the river between Mossdale and the DWSC.

Conclusions

The Stockton DWCS water quality model is our most useful existing tool for data integration and systematic analysis and evaluation of alternative management actions. The existing model should continue to be used to increase our understanding of the DWSC water quality processes. The model equations and coefficient values have been improved from the original model developed in 1993 for the City of Stockton. However, additional simulations and integration of results from recent experiments performed by the CALFED–funded projects (e.g., Litton 2002 and Lehman 2002) should be made. The recent peer review panel wondered why the existing model was not being used to provide integration of field data and analysis of potential management actions. The existing water quality model should be used until a more comprehensive alternative model are available.

The sensitivity results suggest that the model needs additional calibration of the algae growth, decay, and settling processes that occur between Mossdale and the DWSC. Similarly, the VSS settling and resuspension processes that occur between Mossdale and the DWSC need additional calibration. Model simulations of the moderate decline in algae, VSS, and DO concentrations between R3 and R5 appear to be much closer to the measured data.

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Figure 1. Measured and Estimated SJR Flows Entering the Stockton Deep Water Ship Channel in 2001

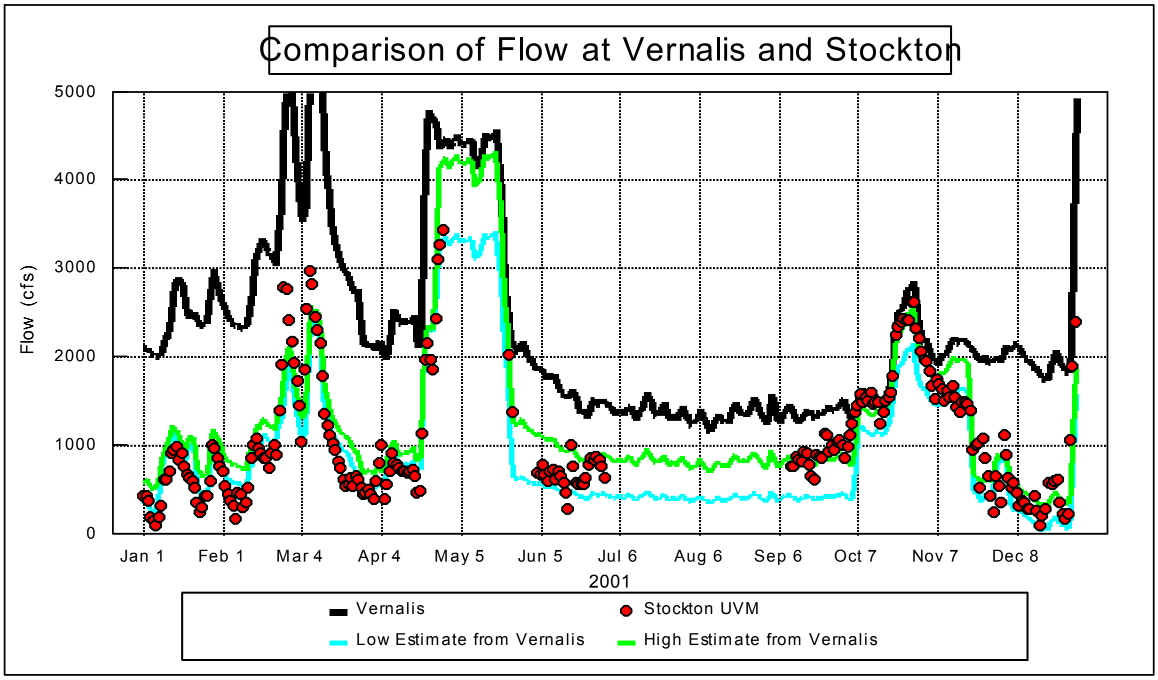

Figure 2. Stockton RWCF Daily Discharge during 2001

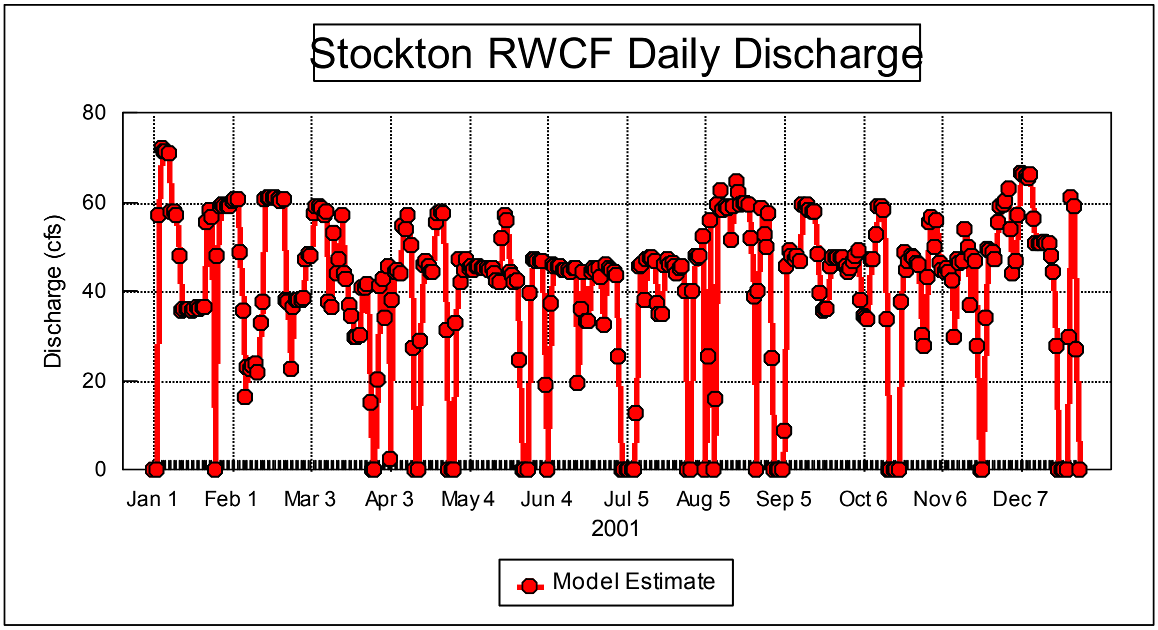

Figure 3. San Joaquin River Mean Daily EC Measurements for 2001

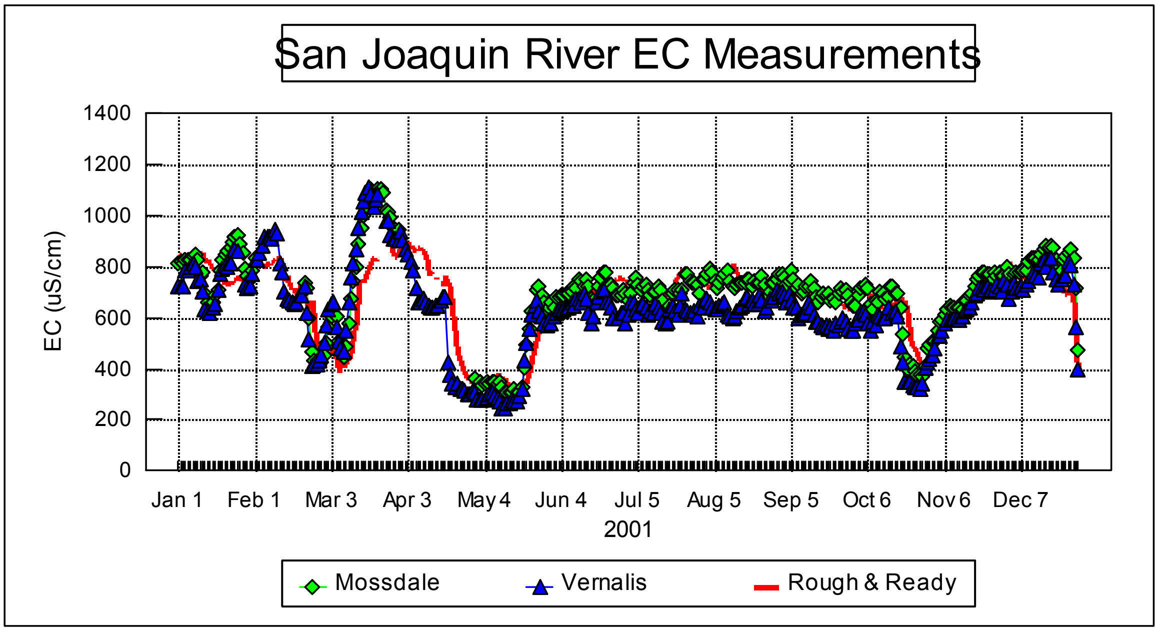

Figure 4. San Joaquin River Mean Daily Temperature Measurements for 2001

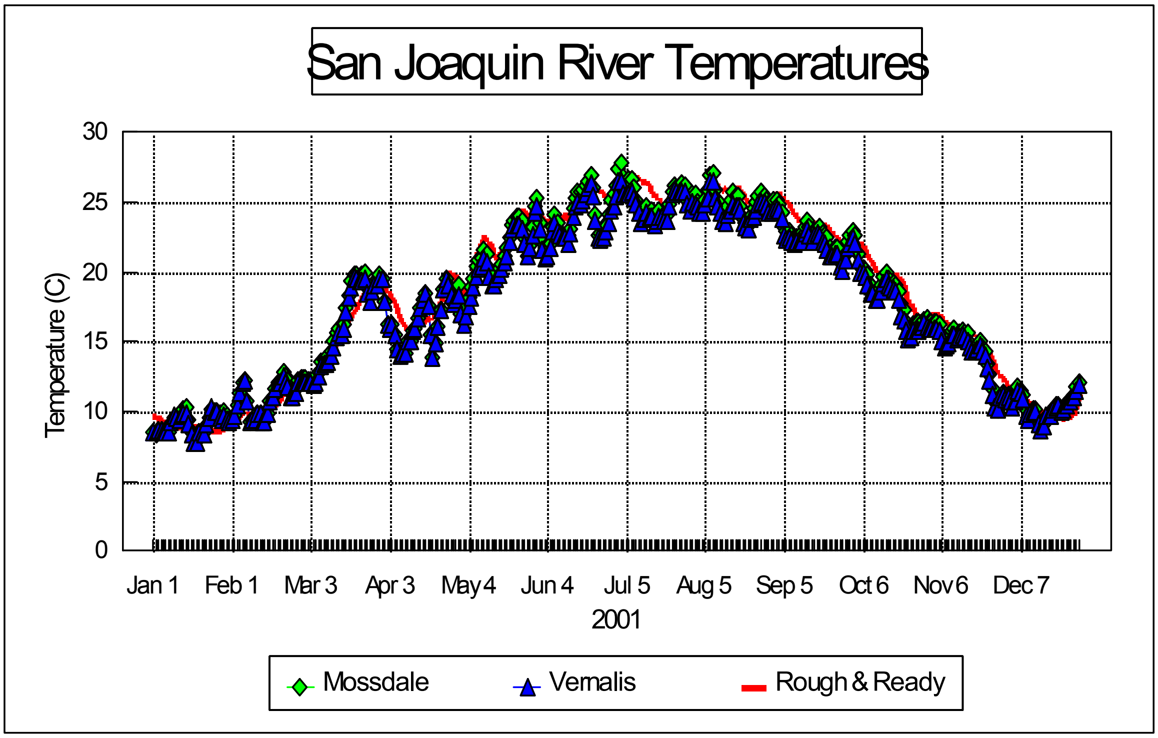

Figure 5. Mossdale Daily Average DO Compared to Saturated DO and Minimum and Maximum DO Measurements for 2001

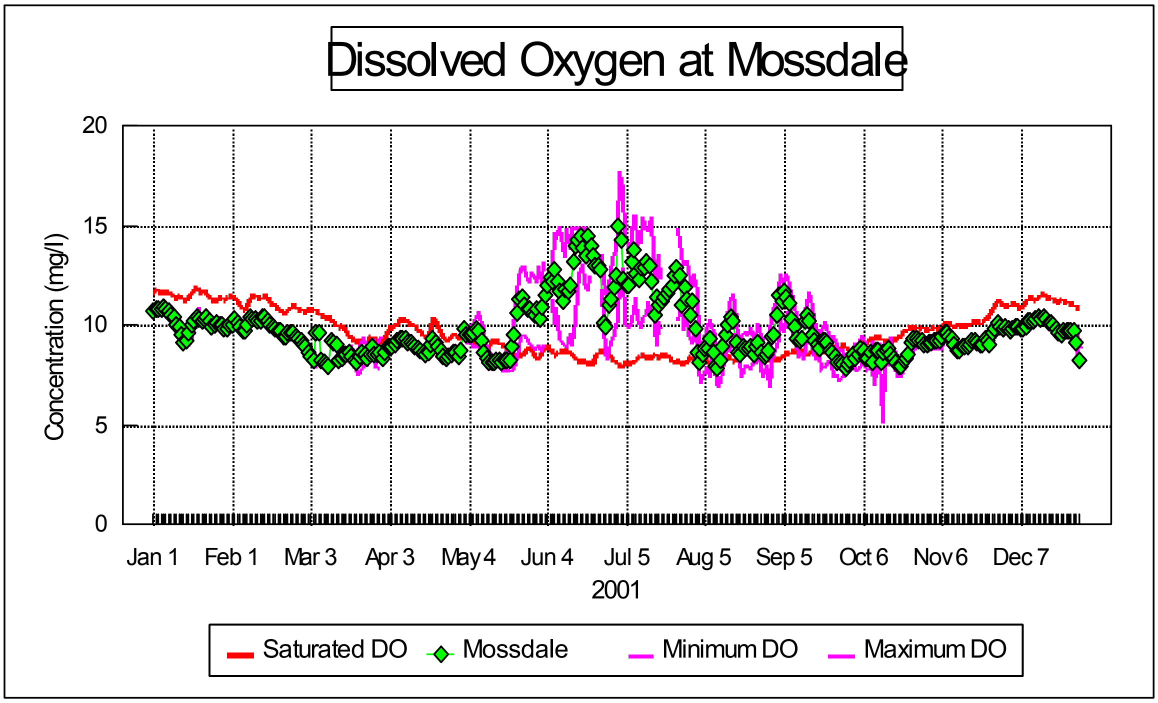

Figure 6. Daily Minimum and Maximum pH at Mossdale and Rough & Ready Island

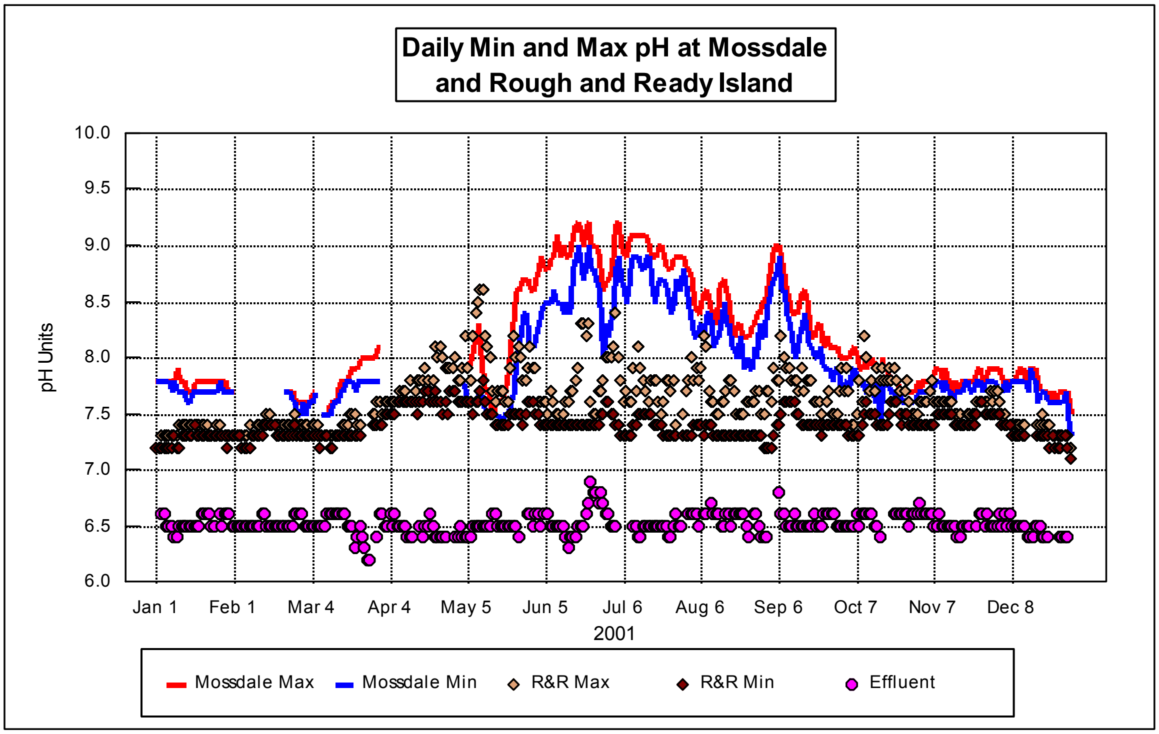

Figure 7. Measured and Estimated Turbidity (TSS) Values at Mossdale in 2001

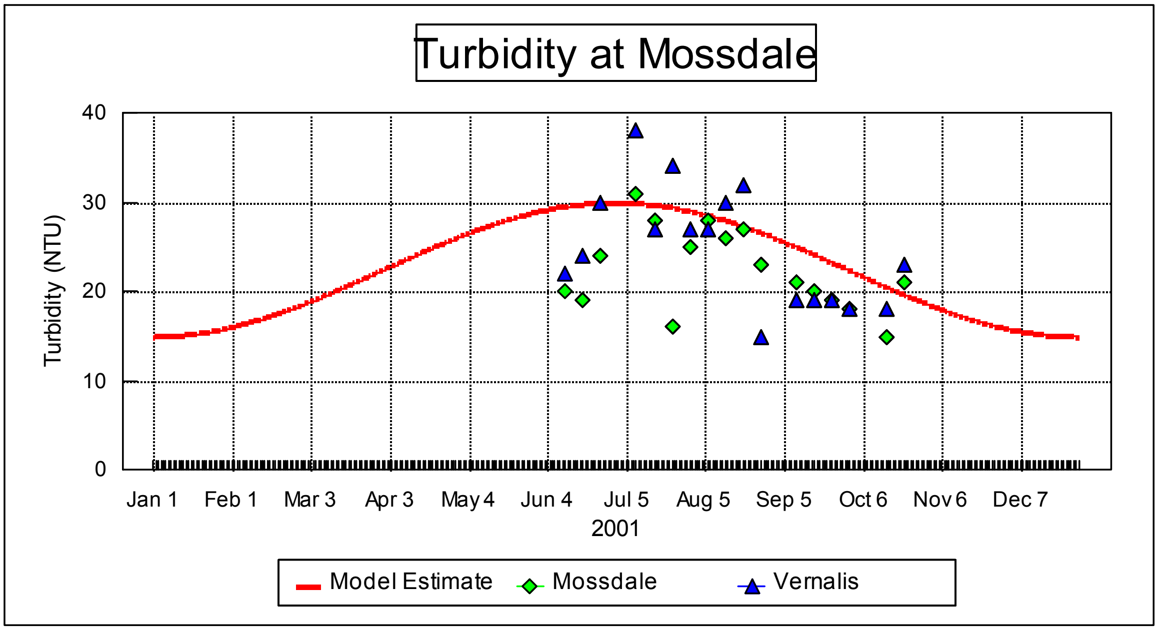

Figure 8. Measured VSS and Estimated Detritus and Algae Concentrations for 2001

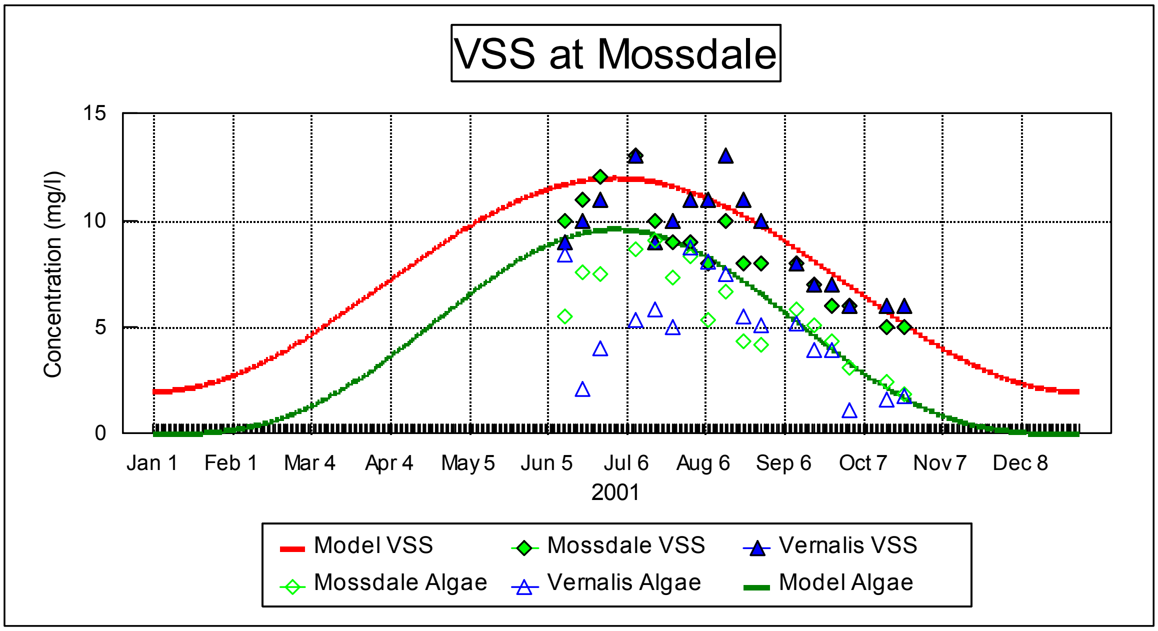

Figure 9. Measured and Estimated Chlorophyll Concentrations for 2001

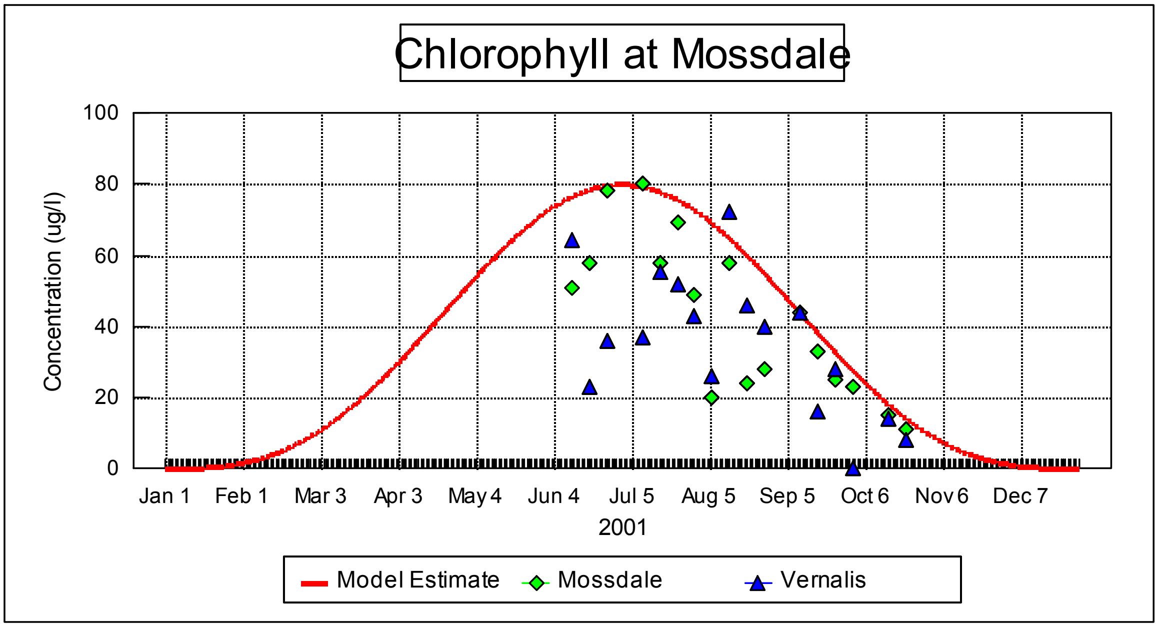

Figure 10. Measured and Estimated Phaeophytin Concentrations for 2001

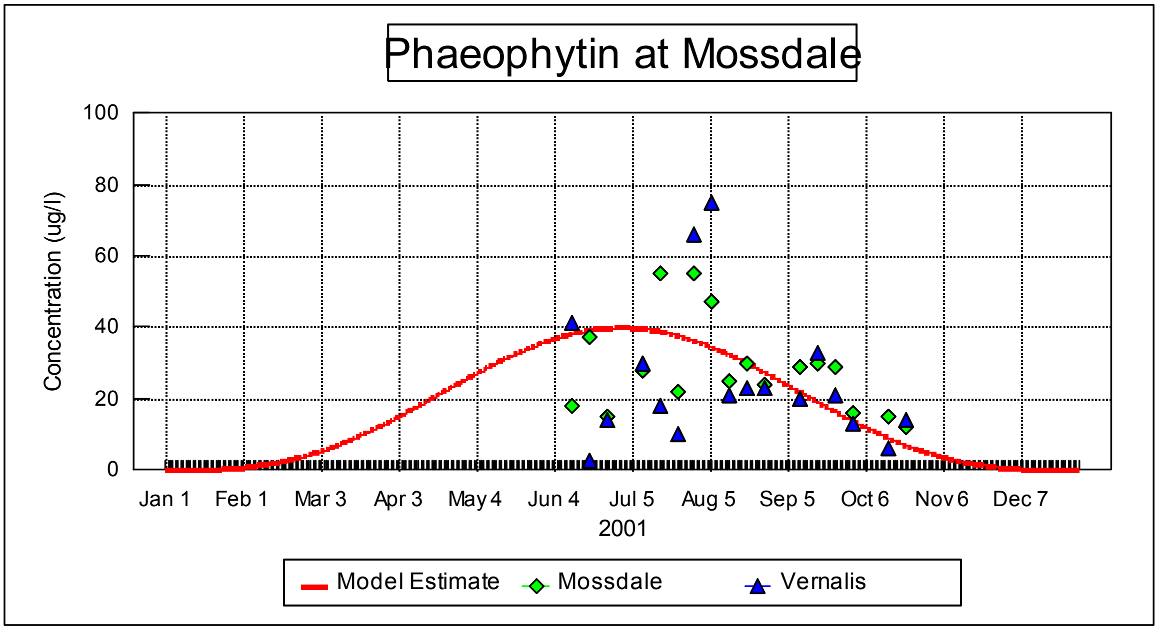

Figure 11. Measured and Estimated 5-Day BOD and 5-Day CBOD Estimates for 2001

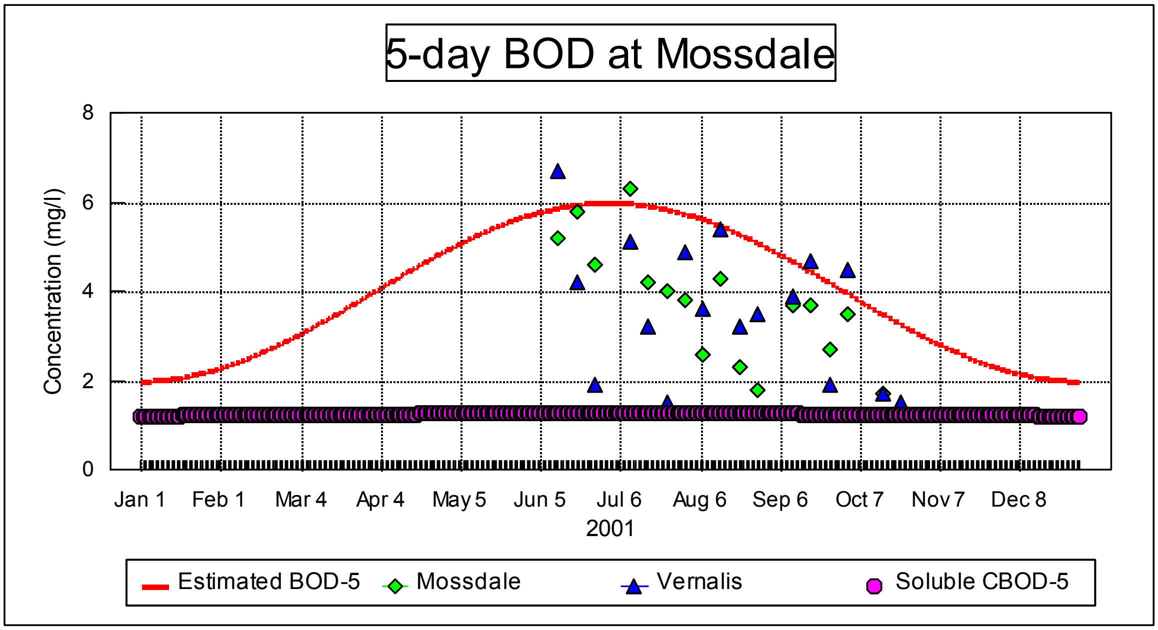

Figure 12. Estimated Stockton RWCF Ultimate CBOD from 5-day CBOD and VSS Data

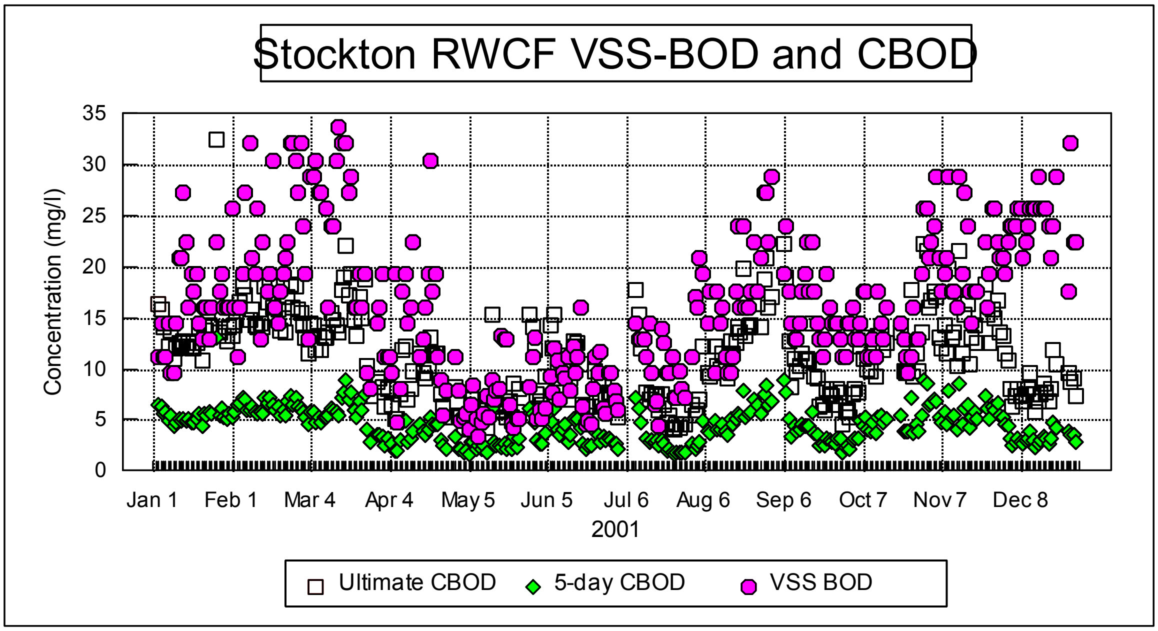

Figure 13. Daily Measurements of RWCF Ammonia-N and TKN Concentrations for 2001

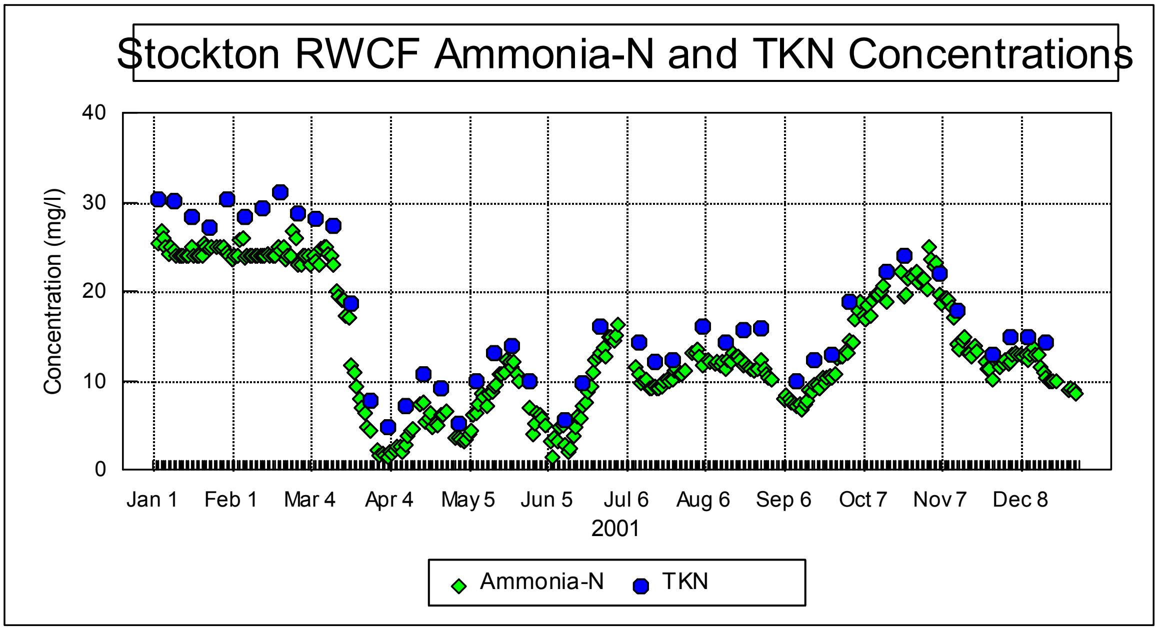

Figure 14. Comparison of Ultimate CBOD and Ultimate NBOD from RWCF

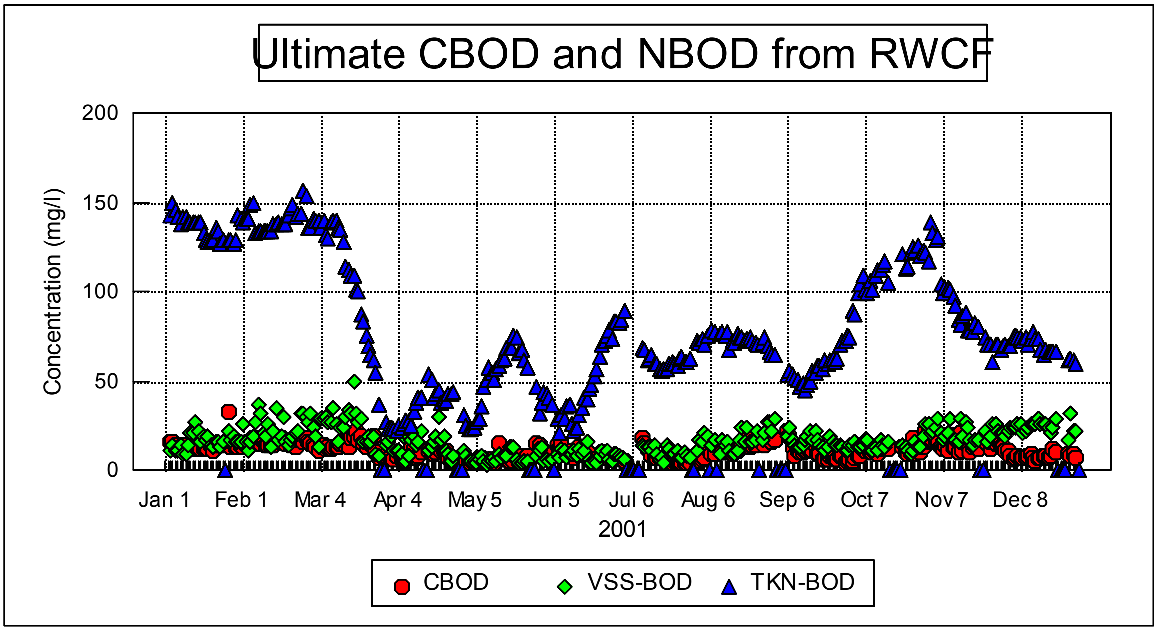

Figure 15. Estimates of Total Ultimate BOD Concentrations Entering DWSC from RWCF Discharge

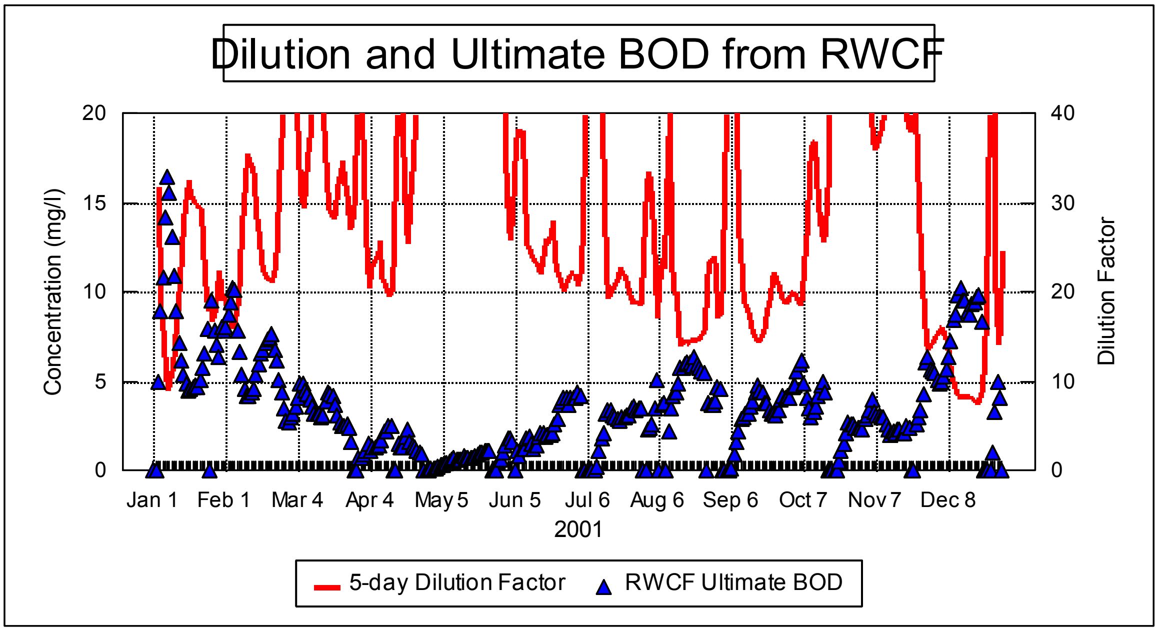

Figure 16. Daily DO Deficit at Rough & Ready Island in 2001 Compared to Ultimate BOD Entering the DWSC from Mossdale and RWCF

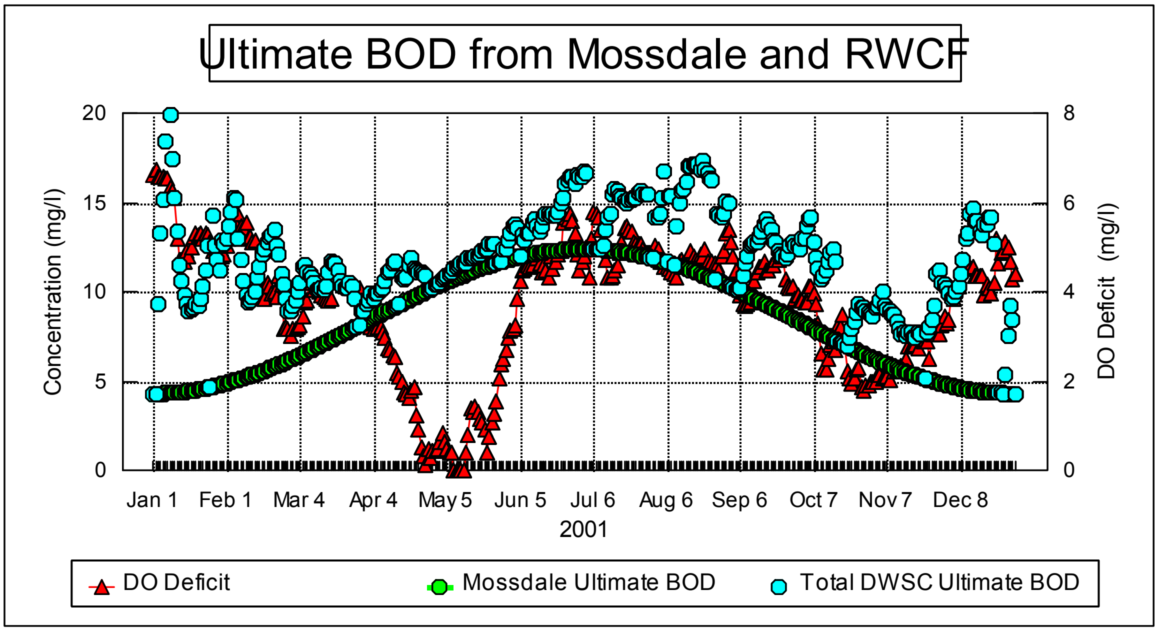

Figure 17. Model Simulated Ammonia-N Concentrations Compared with Ammonia-N Measurements in the DWSC at R3 and R5 in 2001

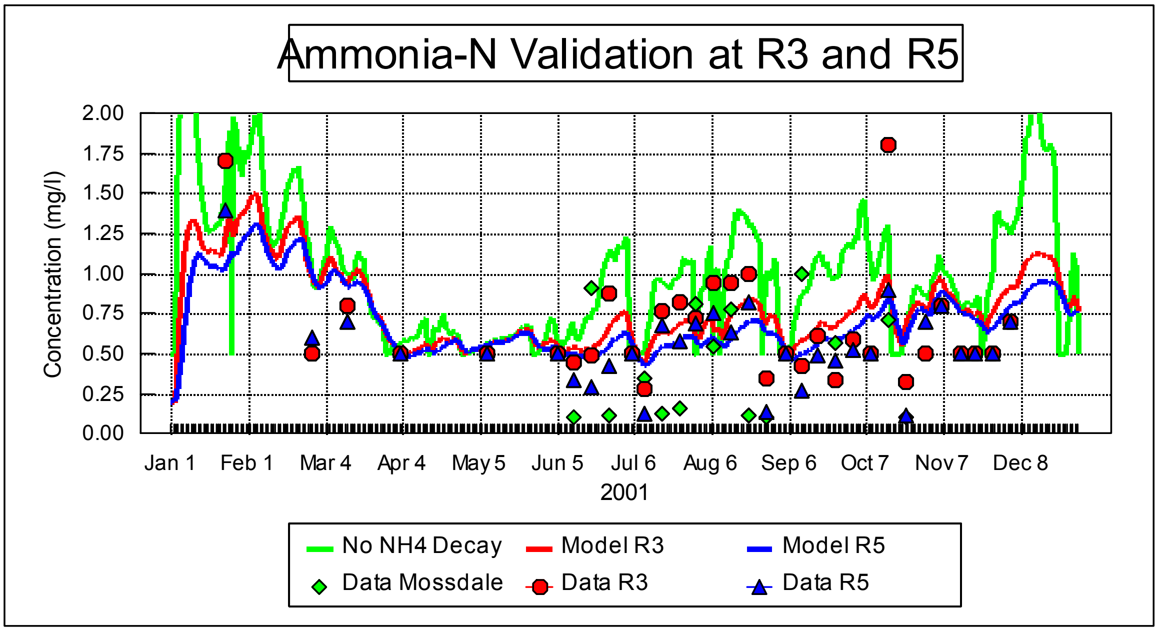

Figure 18. Model Simulated VSS Concentrations Compared with VSS Measurements in the DWSC at R3 and R5 in 2001

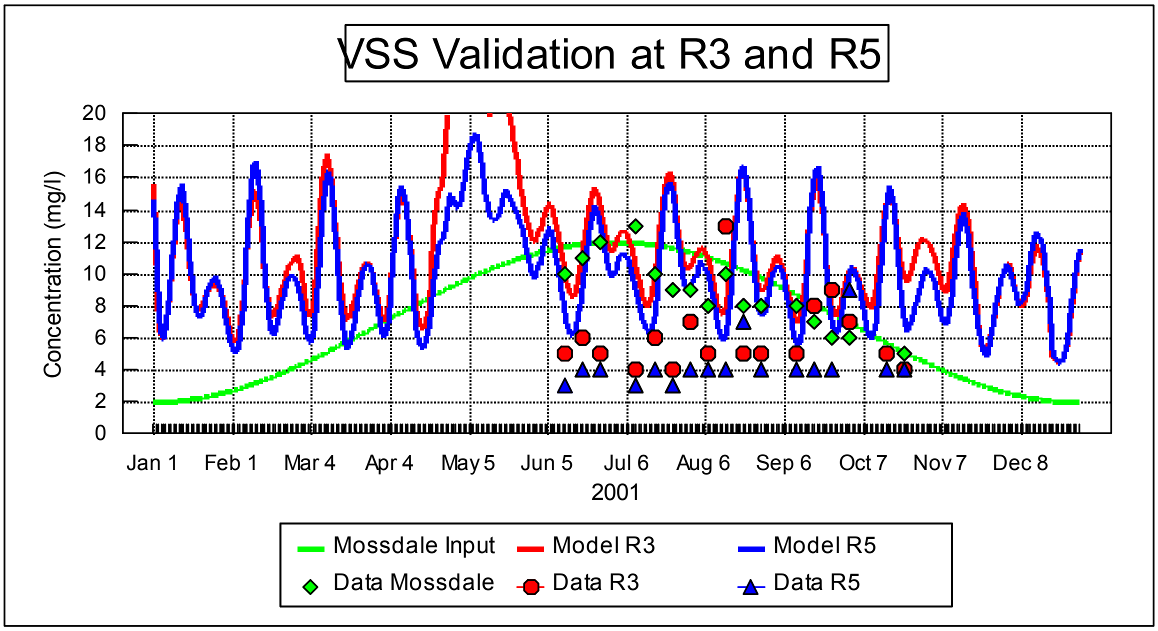

Figure 19. Model Simulated Chlorophyll Concentrations Compared with Chlorophyll Measurements in the DWSC at R3 and R5 in 2001

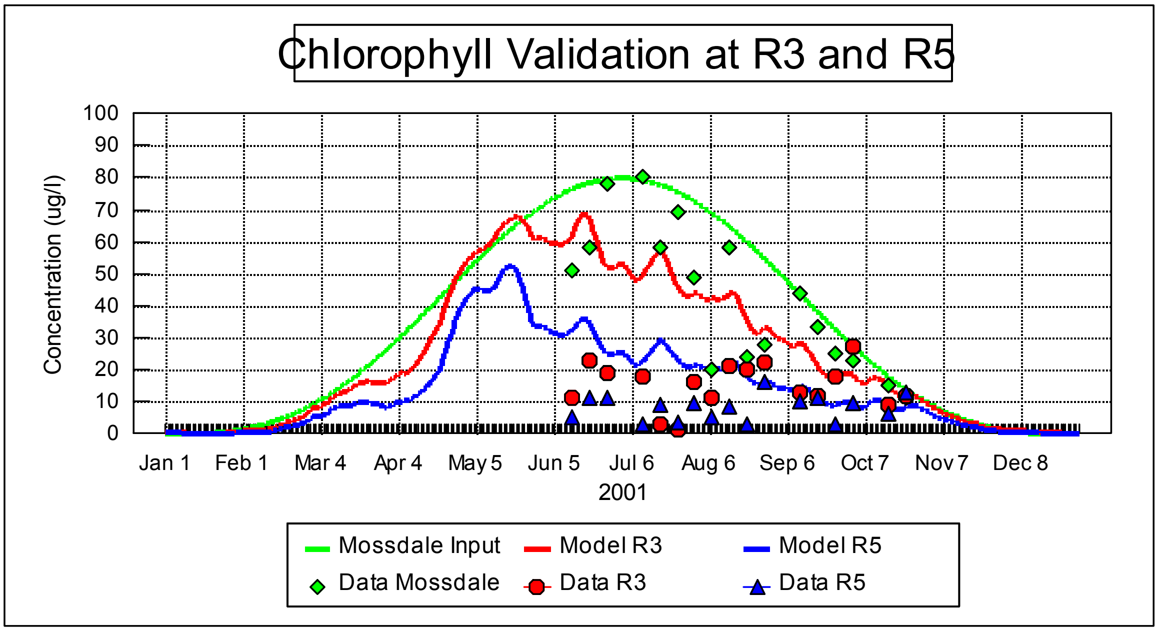

Figure 20. Model Simulated Phaeophytin Concentrations Compared with Phaeophytin Measurements in the DWSC at R3 and R5 in 2001

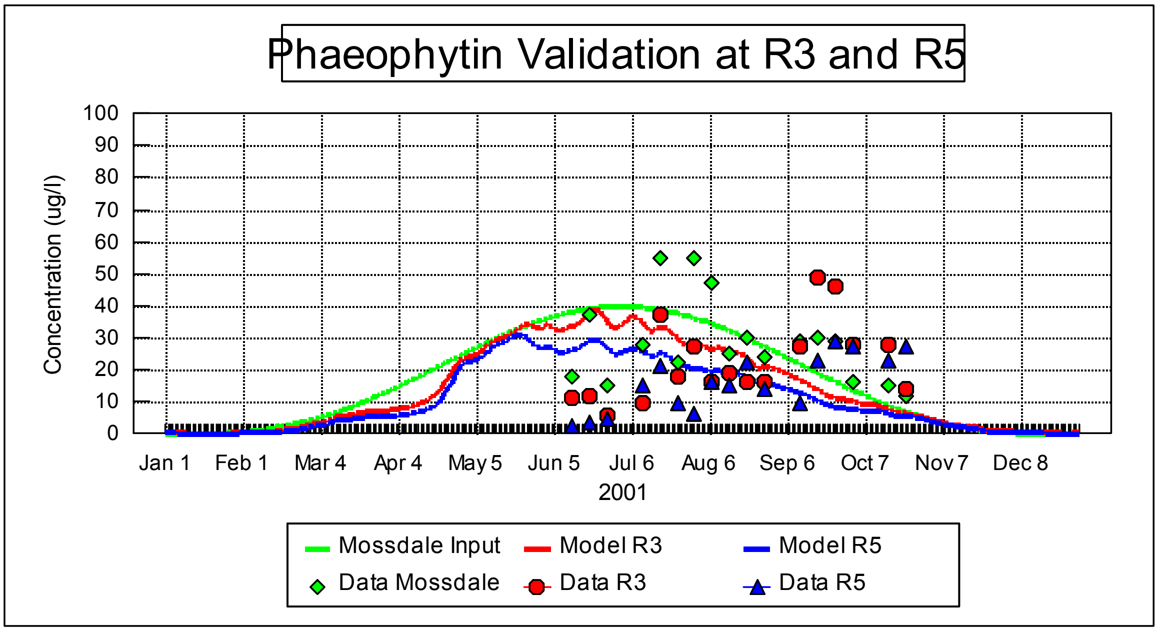

Figure 21. Model Simulated DO Concentrations Compared with DO Measurements in the DWSC at R3 and R5 (Rough & Ready Island) in 2001

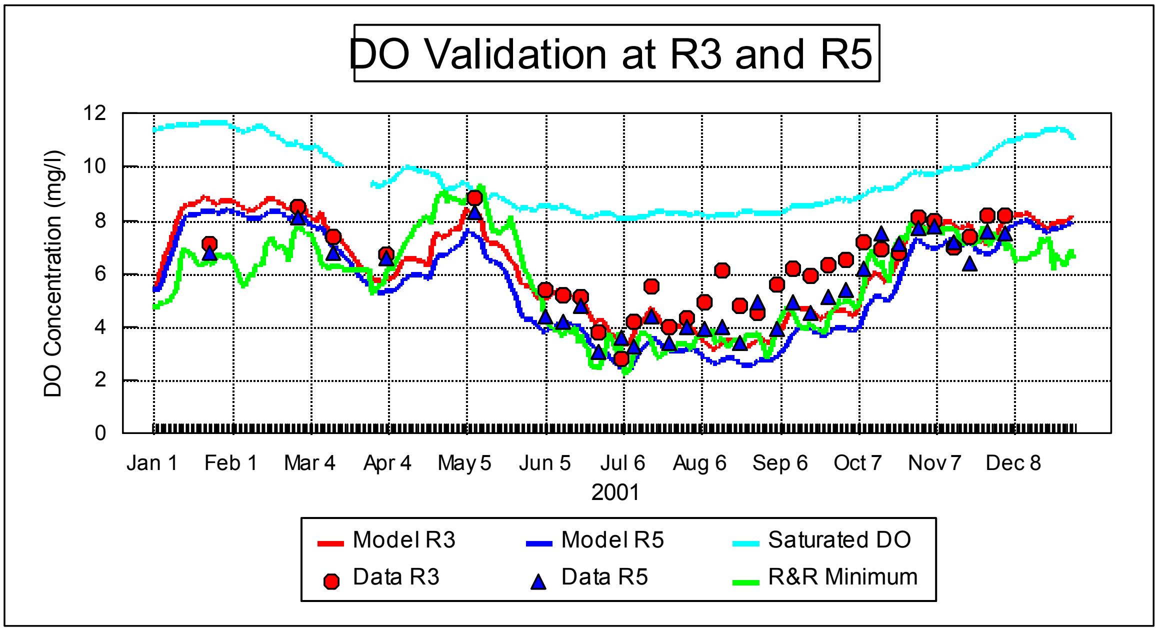

Figure 22. Simulated Travel Time between Mossdale and the DWSC at R3 and R5

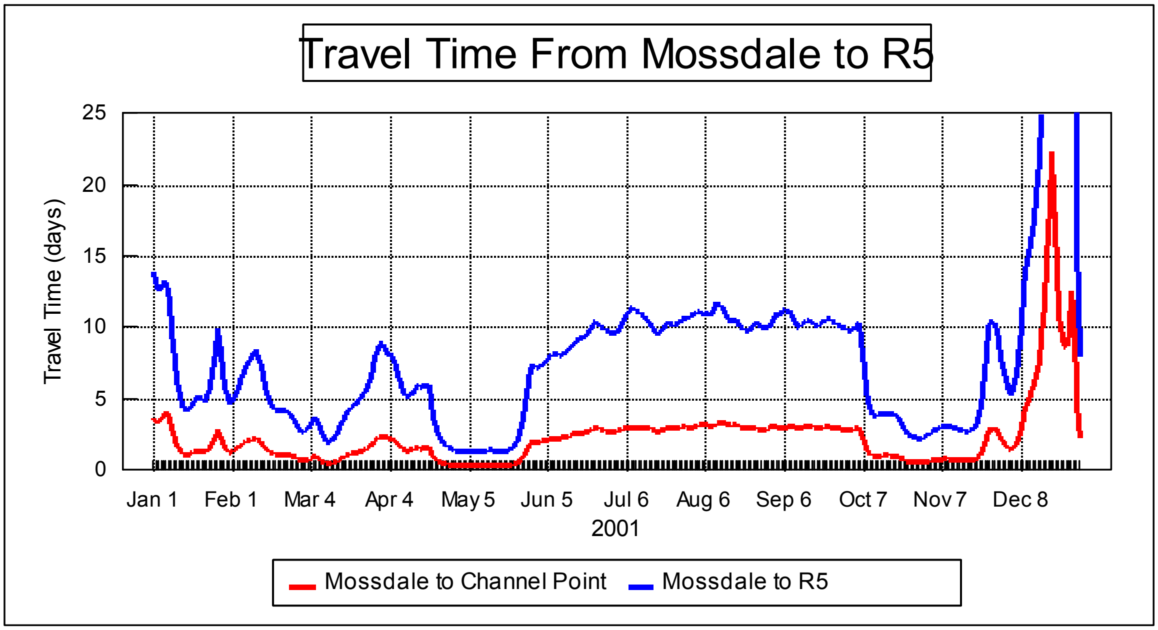

Figure 23. Sensitivity of Simulated DO at R3 to DWSC Flows

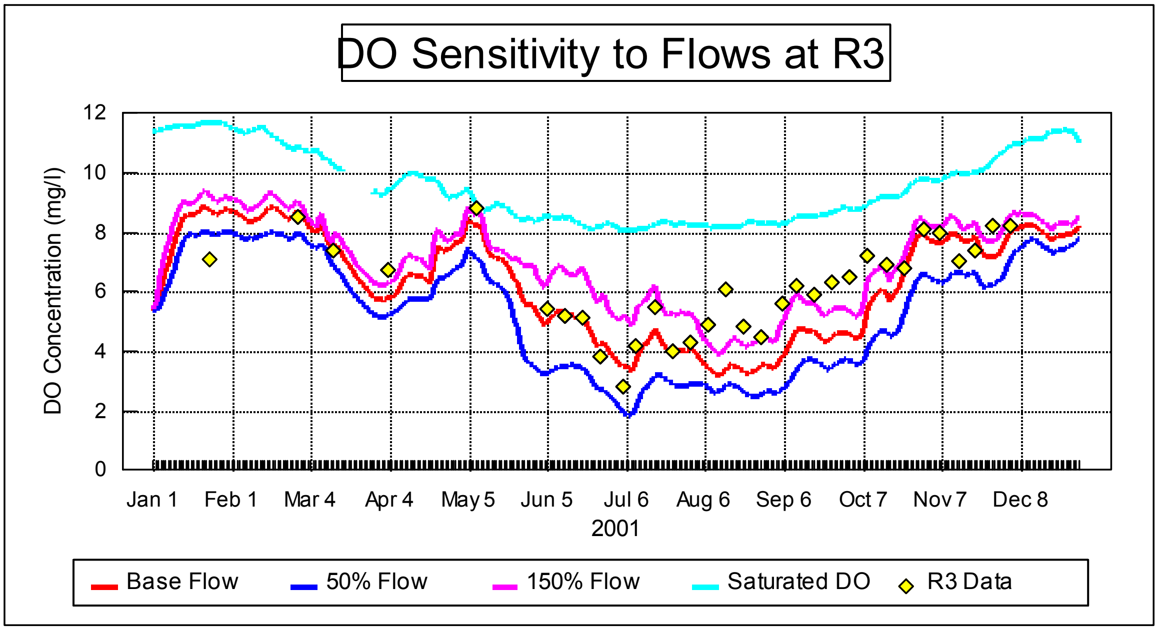

Figure 24. Sensitivity of Simulated DO at R5 (Rough & Ready) to DWSC Flows

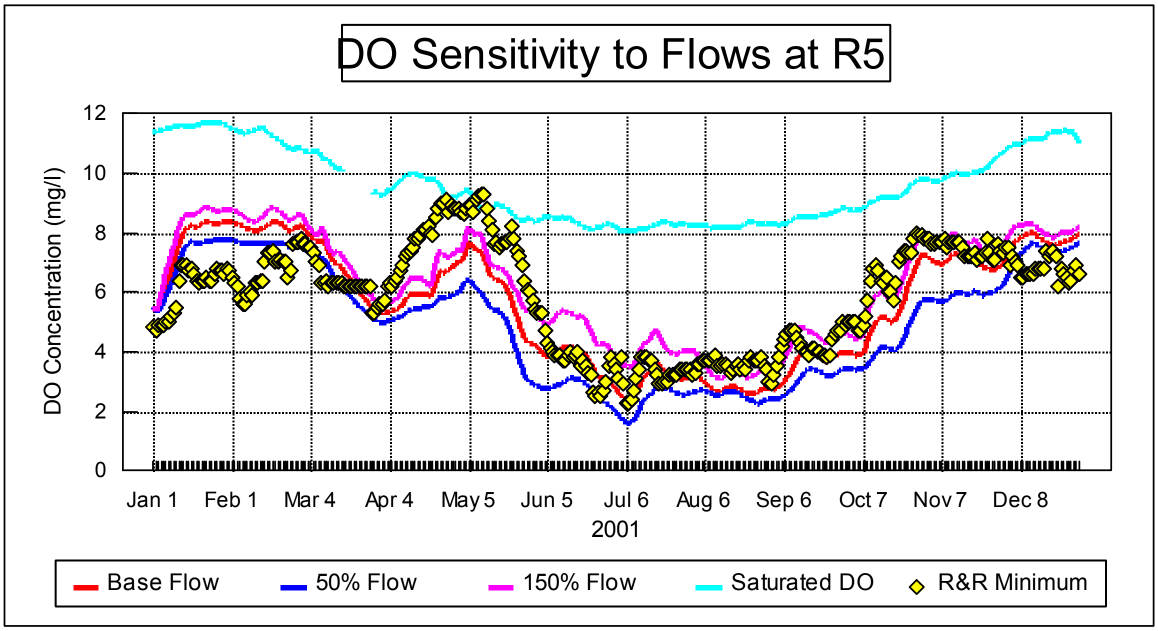

Figure 25. Sensitivity of DO at R3 to VSS and Algae Settling Rates

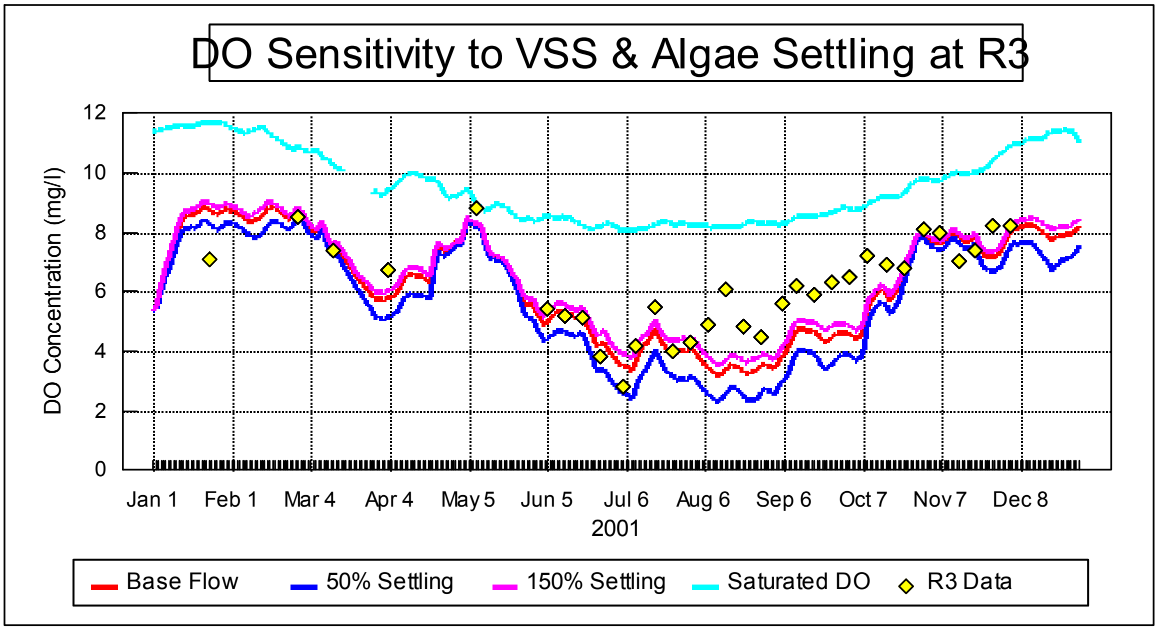

Figure 26. Sensitivity of Simulated DO at R5 to VSS and Algae Settling Rates

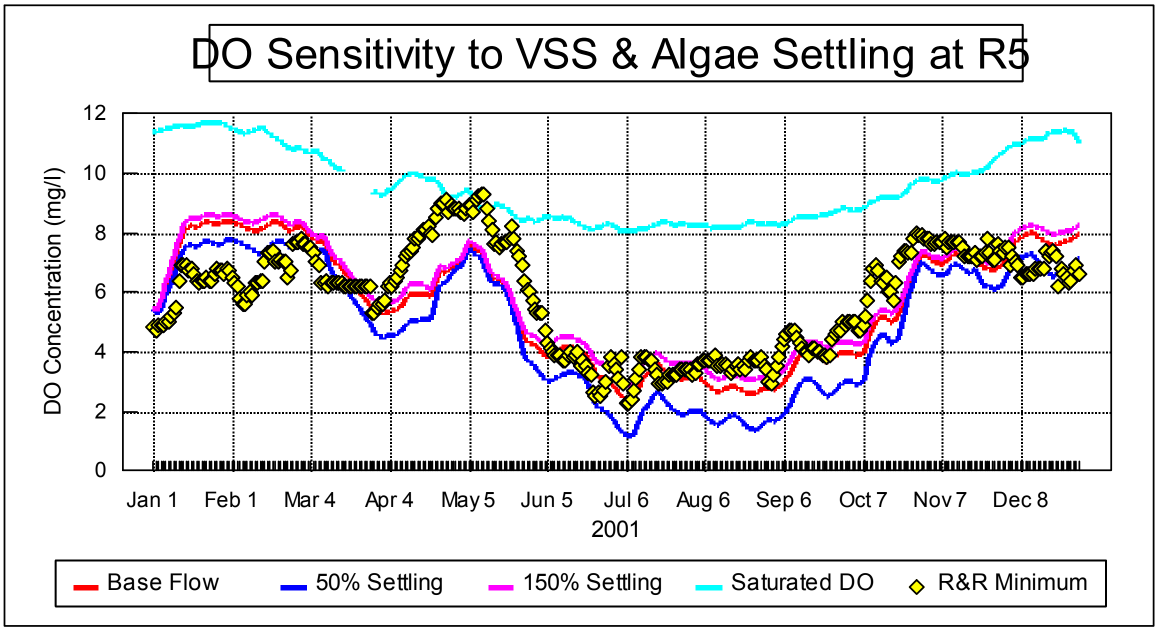

Figure 27. Sensitivity of Simulated DO at R3 to Algae Growth Rate

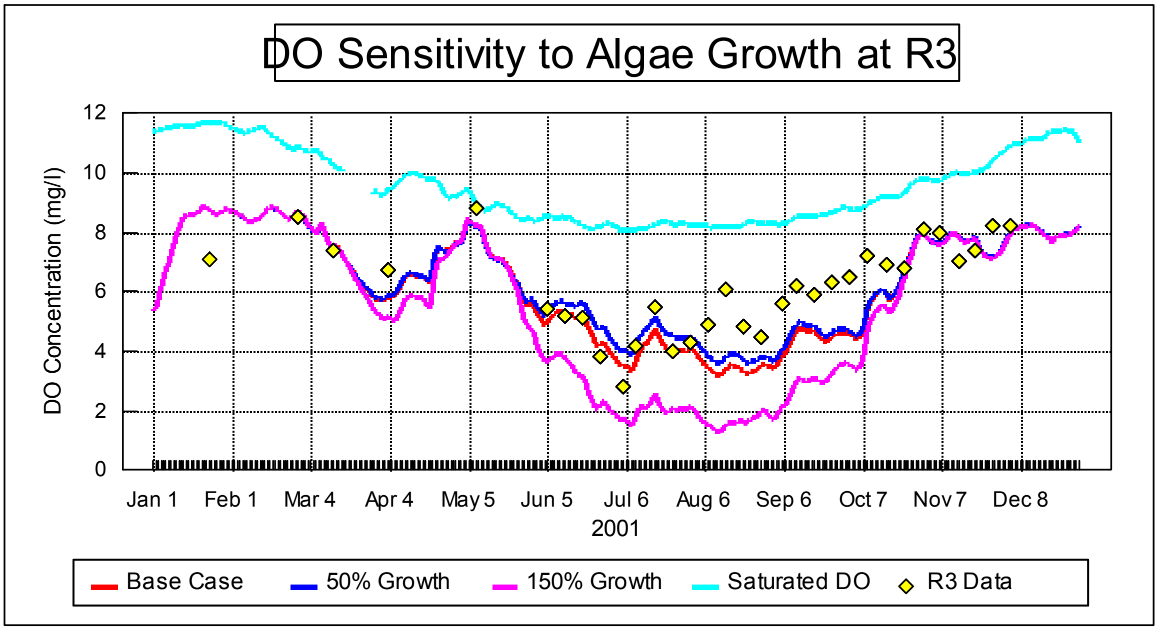

Figure 28. Sensitivity of Simulated DO at R5 to Algae Growth Rate