Methodology for Flow and Salinity Estimates in the Sacramento-San Joaquin Delta and Suisun Marsh

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Chapter 2

Extension of DSM2 for the South Bay and California Aqueducts and Delta Mendota Canal

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2.1 Introduction

An important part of the California Department of Water Resources (DWR) Municipal Water Quality Investigation (MWQI) program is to develop short- and long-term forecasting simulation capabilities for the California Aqueduct. Similar capabilities for the Delta have been developed in order to provide forecasted quality of inflows at the Banks and Jones Pumping Plants for the California Aqueduct and Delta Mendota Canal (DMC). The short- and long-term forecast for both the Delta and California Aqueduct relies on hydrologic and water quality modeling using DWR's Delta Simulation Model 2 (Bay-Delta Office, California Department of Water Resources). The original DSM2 extension model for the California Aqueduct, South Bay Aqueduct, and Delta Mendota Canal (DSM2 Aqueduct Model) was developed by CH2MHILL in 2005 (CH2MHILL, 2005). Since then a lot of work has been done by the DWR Bay-Delta Office, Operations & Maintenance, and MWQI to verify and improve the DSM2 Aqueduct model. The report will document our work on the DSM2 Aqueduct model which includes: (1) extending the model simulation period from 3 years starting January 1, 2001 to 21 years starting from January 1, 1990; (2) modifying the ways to treat gains and losses of water as a result of seepage, evaporation, rainfall, storm water inflow, meter reading errors, etc.; (3) enhancing the model's capability of calculating water quality by adding two more constituents, dissolved organic carbon (DOC) and Bromide; and (4) incorporating inflows from ground water and storm water.

This chapter is a summary of the full Report of this project, prepared for the MWQI Program (Liu, 2013). Interested readers should refer to the full Report for complete details of the DSM2 Aqueduct Model.

2.1.1 California Aqueduct

The California Aqueduct is the primary conveyance facility for the SWP (Figure 2-1). The section of the California Aqueduct modeled with DSM2 extends over 400 miles from Banks Pumping Plant to Silverwood Lake. Along that stretch there are many canals, several siphons and tunnels, 66 check structures, and two reservoirs, O'Neill Forebay (in-line) and San Luis Reservoir (off-line). Both the South Bay Aqueduct and the West Branch of the California Aqueduct are included in the model. The South Bay Aqueduct, which begins at the South Bay Pumping Plant and ends at the Santa Clara Tank, is comprised of 7 checks, open channels, siphons, and tunnels. The West Branch simulated in the model starts from the bifurcation to the Oso Pumping Plant, and ends at Pyramid Lake. It is composed mostly of open channels and an in-line reservoir, Quail Lake. The Aqueduct is managed by four DWR Field Divisions:

- Delta Field Division, which includes Banks Pumping Plant to O'Neill Forebay and the South Bay Aqueduct;
- San Luis Field Division, which includes San Luis Reservoir, O'Neill Forebay, and the 103-mile, joint-use San Luis Canal, which extends from O'Neill Forebay to Check 21;
- San Joaquin Division, which includes Check 21 to Edmonston Pumping Plant and the Coastal Aqueduct;
- Southern Division, which includes the East Branch below Edmonston Pumping Plant and the West Branch to Los Angeles County.

Figure 2-1 California Aqueduct / State Water Project

A series of pumping plants on the Aqueduct provides incremental lifts in water head to maintain an average downstream slope of three inches per mile along the Aqueduct. These pumps include the Banks Pumping Plant, the Dos Amigos Pumping Plant, the Buena Vista Pumping Plant, the Teerink Pumping

Plant, the Chrisman Pumping Plant, and the Edmonston Pumping Plant. The Oso Pumping Plant, the Warne Powerplant, and the Castaic Powerplant are located on the West Branch. The Castaic Powerplant is below Pyramid Lake and is not included in this model. On the south side of the Tehachapi Mountains (East Branch), pumping and power generating plants include the Alamo Powerplant, the Pearblossom Pumping Plant, the Mojave Siphon Powerplant, and the Devil Canyon Powerplant. The Devil Canyon Powerplant is located below Silverwood Lake and is not included in the model.

The California Aqueduct delivers water to agricultural and municipal contractors through over 270 diversion structures. The majority of diversions are made between O'Neill Forebay and Edmonston Pumping Plant. The largest contractor south of Edmonston is the Metropolitan Water District of Southern California.

2.1.2 South Bay Aqueduct

The South Bay Aqueduct is part of the Delta Field Division of the California Aqueduct. It was the first delivery system completed under the SWP and is used to convey water from the Sacramento-San Joaquin Delta to the Alameda County and Santa Clara Valley Water Districts. The South Bay Aqueduct consists of 42.18 miles of canals and pipelines. It begins at the South Bay Pumping Plant, drawing water from Bethany Reservoir and lifting it 566 feet. The South Bay Aqueduct ends at the Santa Clara Terminal Reservoir. The Del Valle Branch Pipeline branches off of the South Bay Aqueduct 18.57 miles downstream of the pumping plant and delivers water to Lake Del Valle. The South Bay Aqueduct has a design capacity of 300 cfs.

2.1.3 Delta–Mendota Canal

The Delta–Mendota Canal (DMC) is a 117 mi (188 km) aqueduct in central California. It was completed in 1951 and is operated by the United States Bureau of Reclamation (USBR) and the San Luis Delta Mendota Water Authority. The DMC is part of the USBR Central Valley Project and its purpose is to replace the water in the San Joaquin River that is diverted into Madera Canal and Friant-Kern Canal at Friant Dam. The canal begins at the C.W. Bill Jones Pumping Plant, which lifts water 197 ft (60 m) from the Sacramento-San Joaquin Delta. The canal runs south along the western edge of the San Joaquin Valley, parallel to the California Aqueduct for most of its journey, but it diverges to the east after passing San Luis Reservoir, which receives some of its water. The water is pumped from the canal and into O'Neill Forebay, and then it is pumped into San Luis Reservoir by the Gianelli Pumping-Generating Plant. Occasionally, water from O'Neill Forebay is released into the canal. The Delta–Mendota Canal ends at Mendota Pool, on the San Joaquin River near the town of Mendota, 30 mi (48 km) west of Fresno. The Delta–Mendota Canal capacity is 4,600 cu ft/s (130 m^3/s) and gradually decreases to 3,211 cu ft/s (90.9 m^3/s) at its terminus. The DMC delivers water to contractors through over 200 turn-outs. Four wasteways extend westward from the DMC toward the San Joaquin River. These include the Westley Wasteway, the Newman Wasteway, the San Luis (Volta) Wasteway, and the Firebaugh Wasteway. There are no pumping plants or generating plants on the DMC aside from the Tracy Pumping Plant.

2.2 Introduction to the DSM2 Aqueduct model

The DSM2 model has three separate components: HYDRO, which calculates water velocities and elevations; QUAL, which calculates EC and other constituents throughout the Delta; and PTM, which is a particle tracking model. HYDRO provides hydraulic inputs for QUAL and PTM. The DSM2 Aqueduct model only used HYDRO and QUAL. DSM2 HYDRO relies on an appropriate grid resolution to run with sufficient accuracy and efficiency.

For the extension model, grid nodes are located where inflows and outflows occur, or where channel geometry changes occur (usually where check structures are located). With 66 check structures, a starting node at Banks Pumping Plant, and an ending node at Silverwood Lake, the main stem of the Aqueduct contains 67 channels and 68 nodes. The DMC has 21 checks between Jones Pumping Plant and the Mendota Pool, and is modeled with 21 channels and 22 nodes. The South Bay Aqueduct begins at the South Bay Pumping Plant, contains 7 checks, and ends at the Santa Clara Tank, and is modeled with at least 8 channels and 9 nodes. The West Branch contains one check structure and an in-line reservoir, and is modeled with at least 2 channels and 3 nodes in DSM2.

South Bay Pumping Plant flow is treated as a diversion from the main stem of the Aqueduct (at Check 1) and as an inflow to the South Bay Aqueduct through a DSM2 object-to-object transfer. Likewise, pumping to the West Branch from the OSO Pumping Plant data is treated as a diversion from the main stem of the Aqueduct at DSM2 node 448 through an object-to-object transfer. O'Neill Forebay is regulated downstream by Check 13, so flow is not allowed to travel freely from O'Neill to the downstream pool in DSM2. An object-to-object transfer is used to carry water from O'Neill to the upstream node of the downstream channel (node 414, channel 415). The transfer is calculated as the flow through Dos Amigos Pumping Plant plus any diversions in pool 13 (there are no inflows to pool 13). The water exchange between O'Neill Forebay and San Luis Reservoir and between O'Neill Forebay and DMC is modeled as object-to-object transfer in the model.

The 116 mile Coastal Branch splits from the main line 11.3 mi (18.2 km) south-southeast of Kettleman City transiting Kings County, Kern County, San Luis Obispo County, and Santa Barbara County to deliver water to the coastal cities of San Luis Obispo, Santa Maria, and Santa Barbara. The Costal Branch of the SWP was not modeled directly. Instead, the pumping to the Coastal Branch from the main stem of the Aqueduct through the Las Perillas Pumping Plant is treated as a diversion from the main stem of the Aqueduct at DSM2 Node 424.

The DSM2 Aqueduct model developed by CH2MHILL was based on version 6 of DSM2. The model was calibrated by comparing model-calculated flows, stages, and EC against measured data for a three-year period beginning January 1, 2001. Model validation was not conducted using a separate input set for a time period different from the calibration time period. Many assumptions were made when the DSM2 Aqueduct model was developed, including:

(1) Gains and losses: Results of water balance calculations based on inflow and outflow data from various sources indicate gains and losses must be considered in order to maintain the measured water levels of the Aqueduct.

(2) Reservoir operations: DSM2 treats reservoirs as completely mixed, vertical-walled bodies of water (Continuously Stirred Tank Reactors).

(3) Gate operations: The check structures are modeled as broad-crested weirs, with the invert elevations fixed to control flows.

(4) Diversion data interval: The data quantifying diversions from the system are aggregated on a monthly basis. These data were used to specify the diversions in the model, and were assumed to remain constant over the month.

2.3 Verification of the DSM2 Aqueduct model

The calibration of the original DSM2 Aqueduct model covered a three-year period starting January 1, 2001. The model was not verified using a separate input set for a time period different from the calibration time period. The original model was calibrated to calculate water velocities, stages of water bodies, and EC, a surrogate for salinity. During the verification and improvement period, the model was verified using 21-year data starting January 1, 1990. The three-year calibration period was also included in the verification process since data was collected from more sources, more ground water pump-in and storm water inflows were included in the model, and the model experienced some improvement.

The completion of the verification process was a result of teamwork among three groups in DWR: the Operation Control Office (OCO), the MWQI program and the Bay Delta Office (BDO). OCO was responsible for compiling all the flow and stage data for model verification from different sources. The data includes pumping at major pumping stations which move water into or out of the Aqueduct and DMC, diversions from the California Aqueduct, DMC, or San Luis Reservoir by water contractors, groundwater pump-ins and storm water flow to the modeled system, rainfall, and evaporation. MWQI collected EC, DOC, and Bromide for the model's boundary inflows from three sources, California Data Exchange Center (CDEC), Water Data Library (WDL), and U.S. Bureau of Reclamation. More details about data compilation will be explained in the next chapter. BDO developed a tool to pre-process hydro and water quality data for the DSM2 Aqueduct model. The main tasks that the tool can accomplish include: (1) downloading data from CDEC; (2) converting monthly data to daily data required by the model; (3) conducting calculation of mass balance; (4) filling missing EC and DOC data; (5) calculating Bromide from EC and fingerprinting data; and (6) exporting data to DSS files.

2.3.1 DSM2 Version 8

DSM2 Version 8 (Bay-Delta Office, California Department of Water Resources) is an improvement on DSM2 Version 6. Several bugs found in Version 6 were fixed. Two main enhancements to DSM2 are: (1) some algorithms were changed to reduce the program's run times, and (2) operating rules were introduced in Version 8 so gates and barriers can operate according to specified operating rules. No significant differences were observed when model results from running two versions of the DSM2 model were compared. The verification for the DSM2 Aqueduct model was also done using DSM2 Version 8. Results for flows, stages, EC, Bromide and DOC from both version 6 and version 8 DSM2 Aqueduct models were compared, and no significant differences were observed. For the current version 8 of the DSM2 Aqueduct model, gate operations are treated the same way as in version 6 of the model. BDO has spent limited time on trying to use operation rules for gate operations, but without success. The problem is that the model would not converge for most of the time steps, thus the results cannot be trusted. This issue will be investigated in more detail in the future.

2.4 Hydrologic and Water Quality Data

The DSM2 extension model is driven by a lot of data, which include both hydrologic and water quality data. For the HYDRO part of the extension model, O&M compiled hydrologic data from various sources, and did analysis on gains and losses. MWQI compiled water quality data for the QUAL part of the extension model. The following several sections will cover work done by O&M and MWQI in more details.

2.4.1 Hydrologic data

For the HYDRO part of the DSM2 extension model, several types of data have to be given. Among them are: (1) pumping flows or check flows, (2) meteorological data (rainfall and evaporation) as source or sink point flows, (3) groundwater inflows as source seepage point flows, (4) storm water inflows, (5) diversion flows, and (6) storage changes of the Aqueduct. For the 21-year simulation period starting from January 1, 2010, O&M compiled data from different sources. Table 2-1 is a list of the data sources for the historical data and current data.

The pumping flows at Banks and Jones Pumping plants are treated as boundary inflows in the model. The pumping flows at South Bay Pumping Plant, Oso Pumping Plant, the Las Perillas Pumping Plant, Dos Amigos pumping Plant, and pumping/generating flow for Gianelli Generating Plant and O'Neill

Generating Plant are treated as object-to-object flow transfer. Daily delivery data for the Pacheco Tunnel is treated as a San Luis Reservoir diversion. Flows at SWP Check 21 and pumping flows at Edmonston and Pearblossom Pumping Plants were not directly used in the model; instead, they were used in mass balance calculations, which will be discussed in the next section.

Meteorological data is mainly used as inflows and outflows for San Luis Reservoir. Groundwater and storm water inflows are grouped by pool along the Aqueduct or DMC. Monthly delivery data for each diversion are grouped by pool along the Aqueduct or DMC. Because some pools are modeled with multiple channels, all diversions within a pool are aggregated and withdrawn at the node corresponding with the pool’s downstream check. Major diversions, such as wasteways on the DMC, are included as separate nodes at their actual physical location.

Table 2-1 Sources for hydrologic data

Data	Historical	Current
Evaporation / Precipitation at SWP& DMC	CIMIS http://wwwcimis.water.ca.gov/cimis/welcome.jsp	CIMIS http://wwwcimis.water.ca.gov/cimis/welcome.jsp
Evaporation / Precipitation at San Luis	Prior to 1998, SWP Monthly Operations Data Reports http://www.water.ca.gov/swp/operationscontrol/monthly.cfm	CVP Reservoir Operations Reports http://www.usbr.gov/mp/cvo/reports.html
Pumping data	MAPPER[1]	MAPPER
Pacheco Tunnel and Check 21 Flows	MAPPER	MAPPER
Diversion and Pump-in Flows for the SWP	Prior to 2000, SWP Monthly Operations Data Reports / SWP Annual Reports of Operation http://www.water.ca.gov/swp/operationscontrol/monthly.cfm http://www.water.ca.gov/swp/operationscontrol/annual.cfm	SAP[1]
Diversion and Pump-in Flows for the DMC	San Luis-Delta-Mendota Water Authority	San Luis-Delta-Mendota Water Authority

2.4.2 Gains and Losses

When the extension model was developed by CH2MHILL in 2005, it was found that gains and losses must be considered on some sections of the Aqueduct system in order for the model to run successfully.

[1] For information about MAPPER or SAP data contact the Delta Compliance and Modeling Section (dcm@water.ca.gov) or the Operations Records and Reports Section (ocoweb@water.ca.gov)

The gains and losses were the amount of water that cannot be balanced when known outflows and storage change are deducted from known inflows (Equation 2-1).

$$gain\ or\ loss\ =\ inflow - outflow - storage\ change \qquad (2\text{-}1)$$

Following the similar procedures documented in CH2MHILL's report, gains and losses were calculated using Equation 2-1 for four sections along the Aqueduct main stem (Pools 1 through 67). These four sections are defined as follows:

- Reach A runs from pool 1 through Dos Amigos Pumping Plant using Banks Pumping Plant flow as the inflow and Dos Amigos flow as the outflow.
- Reach B starts in pool 14 and runs through Check 21 using Dos Amigos flow as the inflow and Check 21 flow as the outflow.
- Reach C starts in pool 22 and runs through Edmonston Pumping Plant (Check 40), using Check 21 flow as the inflow and Edmonston flow as the outflow.
- Reach D starts in pool 41 and runs through Pearblossom Pumping Plant (Check 58), using Edmonston flow as the inflow and Pearblossom flow as the outflow.

For Reach A, other major inflows include water released to O'Neill Forebay from San Luis Reservoir, water pumped to O'Neil Forebay from DMC, and groundwater pump-ins. Other major outflows include water pumped to San Luis Reservoir from O'Neill Forebay, water released to DMC from O'Neill Forebay, and water delivered to contractors between DSM2 node 401 and 415. For Reaches B and C, other major flows include groundwater pump-ins and storm water flows. Other major outflows include water delivered to contractors. There are no other major inflows for Reach D. Other major outflows include water delivered to contractors between DSM2 node 445 and 469, which include water delivered to West Branch.

A number of factors can cause gains and losses. Inaccurate measurements may result in inflows/outflows being higher or lower than actual values. Because seepage and evaporation along the canal are not explicitly measured, they are not included in outflows. At times, high flows overshoot, and excess water flows into SWP or DMC. Since the amount is not known, it is not considered in inflows. Also not considered in inflows is rainfall added to water bodies in the system. Another factor is that both daily and monthly data are used in mass balance calculations. Monthly data such as diversions, groundwater pump-ins, storm water inflows, and storage change were assumed to be a constant flow rate for the month. It is possible that there may be significant weekly or daily variation in the actual inflows/outflows that are not represented in the monthly values.

Figure 2-2 presents the results of the mass balance calculations for the four sections of the main aqueduct.

The magnitude of gains / losses in the first two reaches is higher than the magnitude of gains / losses in the last two reaches. There are no distinct seasonal patterns in the gains / losses. No single factor is solely responsible for the spatially and temporally variation of gains / losses. At first sight, the magnitude of gains / losses is significant, but in fact, it is negligible when compared with primary inflows. To further verify that the gains / losses do exist, Bryant Giorgi of O&M compared his calculation with that of Guy Masier and found that both calculations lead to very close results (Giorgi & Singh, 2011). The minor differences are results that the same data from different sources may be somewhat different.

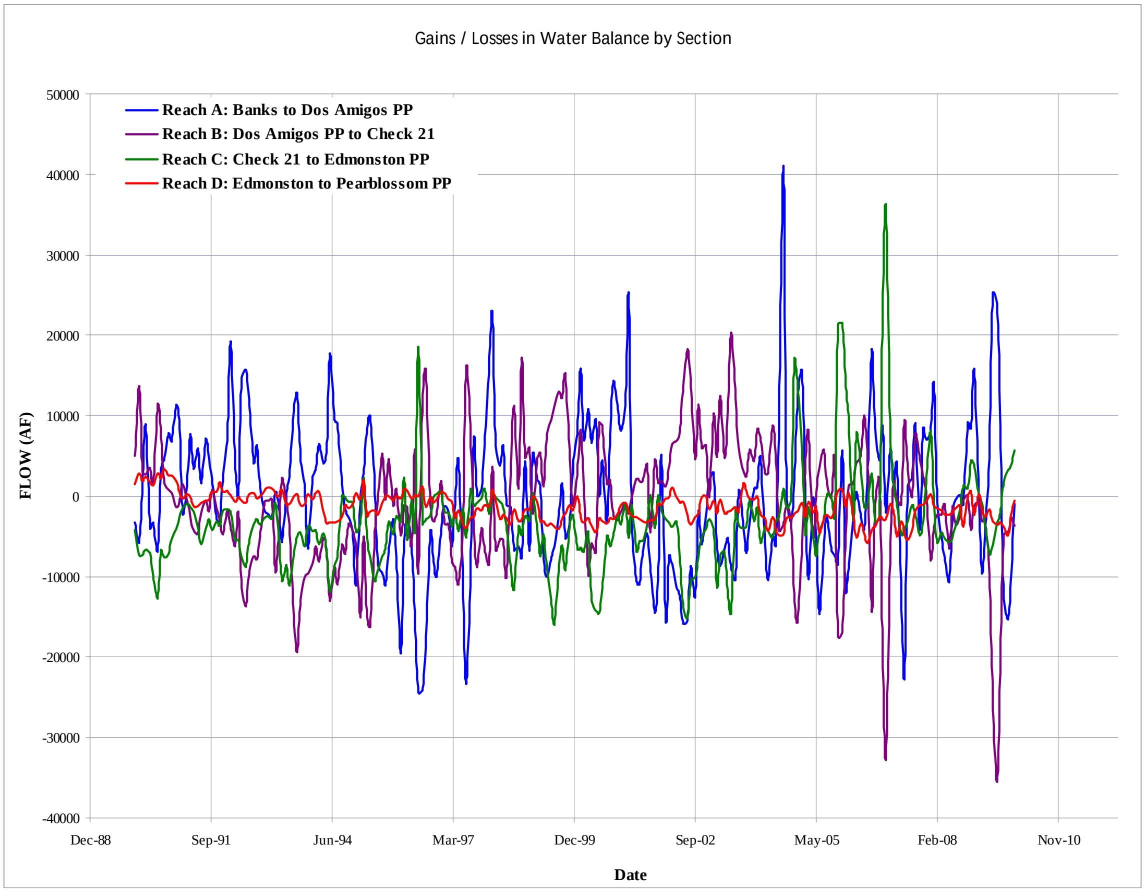


Figure 2-2 Comparison of gains / losses in Water Balance Calculations for Each Section

When CH2MHILL developed the model, closure terms to correct gains and losses were applied in the model at either the upstream or downstream node of each of the four sections. If there is a loss for a reach at any time, an additional inflow was added at the most upstream node of that reach. However, if there is a gain for a reach at any time an additional diversion was added at the farthest downstream node of the reach. Generally there is no problem with this approach except when losses are significant. For a loss, an additional inflow is added to prevent the channel from drying out. For water quality modeling, the water quality for the inflow must be given at each time step. While this is not a problem for Reach A, it is a problem for Reaches B and D, since water quality in those reaches is not known until the model is run. In our approach, when there is a loss in Reach B, C, or D, the loss is deducted proportionally from diversions in that reach to keep mass balanced, so there is no need to specify water quality for inflows used to balance losses. For a gain, it is treated the same way as in the CH2MHILL report.

2.4.3 Water quality data

In the water quality model (QUAL), all model inflows require specification of the daily water quality of the inflow. Even though the model requires daily input, for inflows such as groundwater pump-ins and storm water flows only several grab sample data is available. In this case, constant water quality values were assigned to each location using the data provided to BDO by MWQI.

MWQI worked on several tasks to compile EC, Bromide, and DOC data from different sources, conducted QA/QC for the data and filled in missing data using linear interpolation where data gaps are less than two months. Water quality data collected by MWQI consists of two parts: quality of inflows, used to run the model, and other water quality data, used to verify the model. The Metropolitan Water District of Southern California (MWD) also provided Bromide and DOC data for model verification. The following several paragraphs give more details about how data was collected and processed.

The EC data for the CA Aqueduct and DMC was analyzed using Standard Methods 2510-B (Fong & Aylesworth, 2006), (Clesceri, Greenberg, & Eaton, 1998) and EPA Method 120.1 (U. S. Environmental Protection, 2000). MWQI collected EC data for both surface water inflows and groundwater pump-ins.

Conductivity measurements were taken from 95 stations in the CA Aqueduct. When available, archived continuous-sample data from the California Data Exchange Center (CDEC) was used. When continuous-sample data was not available, grab sample data from the Water Data Library (WDL) was used.

At some stations, salts were measured as Total Dissolved Solids (TDS) instead of EC. In order to convert these measurements to EC, data from the two closest stations with complete EC and TDS datasets were identified. A Mann-Whitney test was used to determine if EC at these 2 stations were similar. If there were no statistical differences, then a regression equation between EC and TDS was derived at one station. Since EC was statistically similar between the 2 stations, it was assumed that the EC-TDS relationship would also be similar for the stations bounded by the stations with the complete datasets and that the same TDS-EC regression line could be used to calculate EC measurements from TDS data.

Conductivity measurements were taken at 59 stations in the DMC. The data for the DMC analyses came from several different sources. When available, daily and hourly data was retrieved from CDEC. Water quality, including both Central Valley Project (CVP) and non CVP data, was provided by the USBR database (U. S. Bureau of Reclamation, 2009). Data for wells pumping groundwater into the DMC between Check 13 and Check 21 data were obtained from a spreadsheet provided to us by USBR personnel.

Bromide measurements were taken at 79 stations in the CA Aqueduct. When available, real time data from the California Data Exchange Center (CDEC) was used. When real-time data was not available, grab sample data from the Water Data Library (WDL) was used. Bromide measurements were taken at 9 stations in the DMC. The data for the DMC analyses came from several different sources. When available, daily and hourly data was retrieved from CDEC. Water quality, including both Central Valley Project (CVP) and non CVP data, was provided by the USBR database (USBR 2009). Data for wells pumping groundwater into the DMC between Check 13 and Check 21 data were obtained from a spreadsheet provided by USBR.

The DOC data for the CA Aqueduct and DMC was analyzed using either the combustion method (EPA Methods 415.1) or the oxidation method (EPA Method 415.3) (U. S. Environmental Protection Agency, 1999) and (U. S. Environmental Protection, 2000). Both methods are considered equivalent by the EPA for measuring DOC. Generally, variability between the 2 methods occurs with measurements of the total organic carbon fraction, not the dissolved fraction; therefore, combining the DOC data generated by these 2 methodologies was considered acceptable for this report.

DOC measurements were taken at 91 stations in the CA Aqueduct. When available, real time data from the California Data Exchange Center (CDEC) was used. When real-time data was not available, grab sample data from the Water Data Library (WDL) was used.

At some stations, carbon was measured as Total Organic Carbon (TOC) instead of Dissolved Organic Carbon (DOC). In order to convert these measurements to DOC, data from the two closest stations with complete TOC and DOC datasets were identified. A Mann-Whitney test was used to determine if DOC at these 2 stations were similar. If there were no statistical differences, then a regression equation between DOC and TOC was calculated at one of these stations. Since DOC was statistically similar between the 2 stations, it was assumed that the DOC-TOC relationship would also be similar for the stations bounded by the stations with the complete datasets and that the same DOC-TOC regression line could be used to calculate TOC measurements from a station's DOC data.

DOC measurements were taken at 9 stations in the DMC. The data for the DMC analyses came from several different sources. Water quality, including both Central Valley Project (CVP) and non CVP data, was provided by the USBR database (USBR 2009). Data for wells pumping groundwater into the DMC between Check 13 and Check 21 data were obtained from a spreadsheet provided to us by USBR personnel.

At the DMC@McCabe Road station near Check 12 (WDL, station ID: DMC06716), carbon was measured as TOC instead of DOC for 27 of the 80 samples. Normally, in order to convert these measurements to DOC, data from the two closest stations with complete TOC and DOC datasets are identified, and a Mann-Whitney test is used to determine if DOC at these 2 stations were similar. However, only the Delta Mendota Canal station at mi 67.15 has enough DOC and TOC measurements to be compared. Therefore, a regression equation between DOC and TOC was calculated for the station Delta Mendota Canal at mi 67.15 without a Mann-Whitney test. The linear correlation coefficient for DOC and TOC was 0.963.

Compared to other inflows, pumping from Banks and Jones PP has more influence on the water quality downstream the Aqueduct. From Table 2-6 it can be seen that water quality data at Banks and Jones PP may have gaps for a long period. A tool, described in the next section, was developed to fill in those gaps in a most reasonable way. For example, there exists no DOC data at Banks PP before October 23, 2003 and at Jones PP before February 25, 2009, and no EC data at Jones PP before August 24, 1999. In this case, EC and DOC outputs from Delta DSM2 Model were used to fill in the gaps. For other EC and DOC gaps that last more than a week, EC and DOC outputs from Delta DSM2 model were not directly used, instead EC and DOC output were adjusted so that the first data just before a gap and the first data just after a gap are the same as measured data of the same day. Data gaps for Bromide were filled in a similar way. The only difference is that at present the Delta-only DSM2 Model does not simulate Bromide, so there is no existing direct output for Bromide. The tool used an expression to calculate Bromide from EC (measured or DSM2 calculated) and Martinez fingerprinting at Banks or Jones PP.

Table 2-2 Available EC, DOC and Bromide Data from CDEC

Station	Constituent	Duration	Data Available
Banks PP	EC	daily	01/01/1986 to present
	DOC	daily	10/23/2003 to present.
	Bromide	daily	01/29/2009 to 02/07/2011
	Bromide	event	10/25/2007 to present
Jones PP	EC	daily	08/24/1999 to present
	EC	hourly	03/31/1988 to present
	DOC	daily	02/25/2009 to present
	Bromide	event	03/05/2011 to present

2.5 Preparing DSM2 for Historical Simulation

It's a very time consuming process to pre-process all input data for the extension model. A tool based on Microsoft Excel VBA was developed to save time and reduce possible mistakes when many raw data are processed for use in the DSM2 Aqueduct model. The tool consists of an interface (Figure 2-3) and related Excel worksheets. On the interface are Excel cells for data input, tabs for worksheets for storing raw and processed data, buttons for executing the 8 steps for pre-processing input data, running the DSM2 Aqueduct model, and post-processing model results.

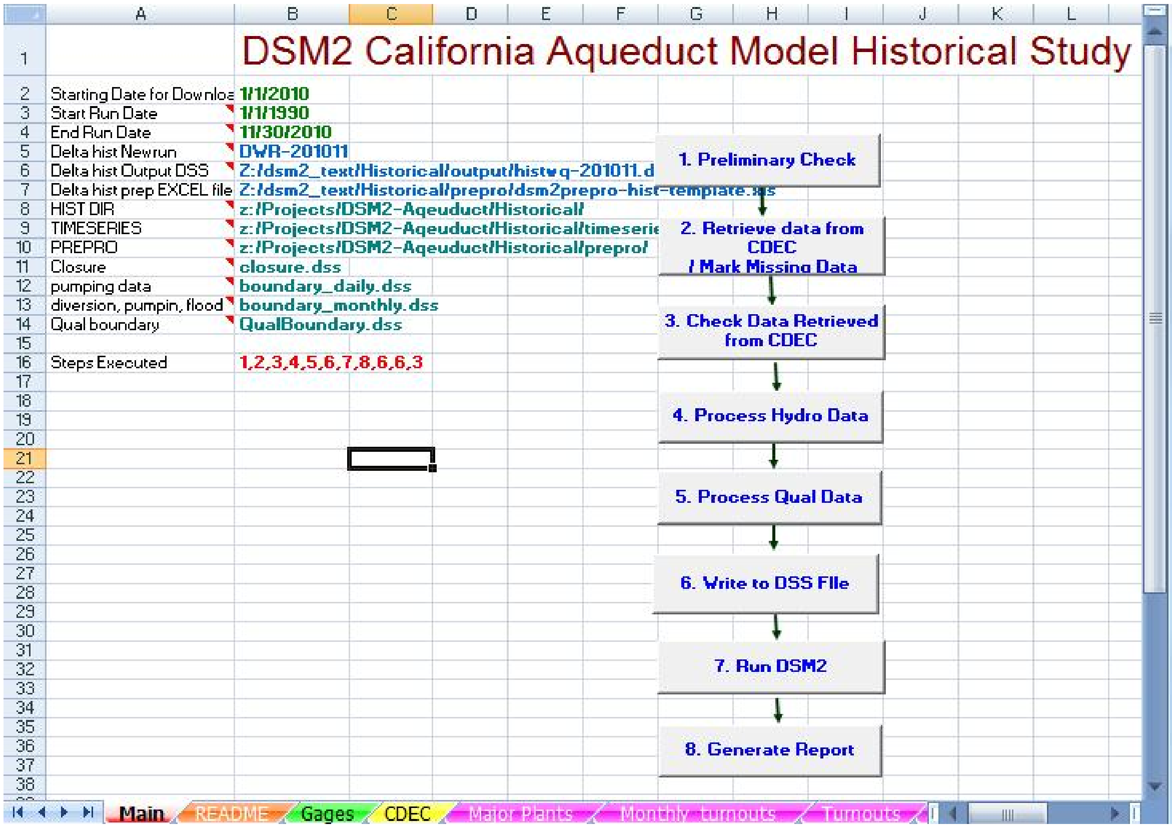


Figure 2-3 Interface of the tool for pre-processing raw data for use in the DSM2 Aqueduct model

Tasks that can be completed by using the tools include: (1) downloading water quality data from CDEC; (2) pre-processing hydraulic and water quality data; (3) calculating water gains and losses for the Aqueduct system; (4) exporting data to DSS file for use by the DSM2extension model; (5) executing the DSM2 Aqueduct model; and (6) post-processing model results. More detailed descriptions of each task are available in the full Report (Liu, 2013).

2.6 Model Verification

The original DSM2 Aqueduct model was calibrated using 3 years of data starting January 1, 2001. There was no verification based on independent data. The original model was calibrated to calculate water velocities, stages of water bodies, and EC. After the model was improved, the model was verified using 21 years of data starting from January 1, 1990. Model verification includes comparisons between model predictions and known system data for not only flow, stage, and salinity (EC), but also two other constituents, Bromide and DOC. The model was run using a warm-start file, which provides the initial conditions for all DSM2 nodes and reservoirs. This is especially important for the San Luis Reservoir, since water residence time for San Luis Reservoir is much longer when compared with the California Aqueduct.

To estimate the predictive power of the model, the Nash–Sutcliffe (N-S) model efficiency coefficient is used. It is defined as:

$$E = 1 - \frac{\sum_{t=1}^{T}\left(Q_o^t - Q_m^t\right)^2}{\sum_{t=1}^{T}\left(Q_o^t - \overline{Q_o}\right)^2}$$

where Q_o is observed values, and Q_m is modeled values. Q_o^t is observed value at time t.

Nash–Sutcliffe efficiencies can range from −∞ to 1. An efficiency of 1 ($E = 1$) corresponds to a perfect match of modeled discharge to the observed data. An efficiency of 0 ($E = 0$) indicates that the model predictions are as accurate as the mean of the observed data, whereas an efficiency less than zero ($E < 0$) occurs when the observed mean is a better predictor than the model. Essentially, the closer the model efficiency is to 1, the more accurate the model is.

2.6.1 Verification of Flow and Storage

The DSM2 Aqueduct model can produce flow rates and stages for reservoirs and each node of a channel. Since water balance was conducted for the main section of the California Aqueduct, and gains and losses were enforced to maintain water level of each pool, the verification was conducted only for flows in the Aqueduct and DMC. For the San Luis Reservoir, all inflows and outflows were specified, and no gains/losses were enforced, so the verification was conducted for stages.

Comparison of measured and observed flow are presented for Check 21, the Buena Vista Pumping Plant (Check 30 on the California Aqueduct), the Teerink Pumping Plant (Check 35 on the California Aqueduct), the Edmonston Pumping Plant (Check 40 on the California Aqueduct), and the Pearblossom Pumping Plant (Check 58 on the East Branch of the California Aqueduct) in the full Report (Liu, 2013). These locations were chosen because of the readily available flow data at the pumping plants. To reduce the length of this summary chapter, only figures for Check 40 and San Luis Reservoir are shown.

The N-S efficiency for each location is listed in Table 2-3. The high N-S model efficiency for each location indicates that the model did well in estimating flows at Checks 21, 30, 35, 40 and 58, and storage at San Luis Reservoir.

Table 2-3 Nash–Sutcliffe (N-S) model efficiency for check flows and reservoir storage

Location	SWP Check 21	SWP Check 30	SWP Check 35	SWP Check 40	SWP Check 58	San Luis Reservoir
variable	Flow	Flow	Flow	Flow	Flow	Storage
N-S	0.94	0.82	0.81	0.78	0.86	0.85

Figure 2-4 shows measured and modeled flow at Check 40, and Figure 2-5 shows the comparison of measured and modeled storage of San Luis Reservoir. Figure 2-7 is a scatter plot with box charts for both measured and modeled flows at Check 40. To examine the difference between measured and modeled flows at different flow ranges, we created Exceedance curves (Figure 2-6) based on flow data for the period between 1990 and 2010. Overall as the Exceedance percentage decreases, the difference between measured and modeled flows also increases. Shown on Figure 2-6 are box-whisker plots for measured and modeled flow. For a box-whisker plot, the bottom and top of the box are flows of the 25th and 75th percentile; the band near the middle of the box is the 50th percentile (median). The ends of the whiskers represent the lowest datum still within 1.5 interquartile range (IQR) of the lower quartile, and the highest datum still within 1.5 IQR of the upper quartile. From the box-whisker plots, we can find that for Checks 21 and 58, August is the month that modeled flows deviate the most from measured flows; for Checks 30, 35 and 40, modeled flows are closer to measured flows for the period between October and December.

Water is pumped uphill into the San Luis reservoir from the O'Neill Forebay when there is surplus water, and is released back into the Forebay to continue downstream along the aqueduct as needed for farm irrigation and municipal uses. Considering the amount of water that is pumped into or released from San Luis reservoir, water quality in the reservoir is important for modeling water quality in the Aqueduct. The verification effort included comparing the model predictions with the reported storage in San Luis Reservoir. Figure 2-5 presents the measured and modeled storage at San Luis Reservoir. In DSM2, the reservoirs are represented as vertical walled vessels, and thus the storage is calculated using a constant surface area. In reality, San Luis Reservoir undergoes a considerable change in surface area throughout the year as the reservoir is drained in the summer months to provide water for deliveries downstream. Considering this limitation, the model provides a reasonable representation of the storage in the reservoir.

2.6.2 Verification of EC

As in the calibration period, salinity or EC was also investigated in the verification period. Comparison between modeled EC and measured EC is presented for Aqueduct Checks 12, 13, 18, 21, 29, 41, 66, San Luis Reservoir, DMC Checks 13, 20, and 21, and South Bay Aqueduct Check 7 in the Full report (Liu, 2013). The source of measured EC data at SWP Checks 12, 13, 18, 21, 29, 41, 66, DMC Checks 13, 20, and 21, South Bay Aqueduct Check 7, and San Luis Reservoir was CDEC. Table 2-4 lists the N-S efficiency for each location. Except for DMC Check 20, N-S efficiency for other locations is high enough to prove that model can calculate EC satisfactorily. The low N-S for DMC Check 20 was the result that the model did not do well for two periods. By removing data during the two periods, the N-S coefficient will be increased to 0.53.

Table 2-4 Nash–Sutcliffe (N-S) model efficiency for EC calculation

Location	SWP CK 12	SWP CK 13	SWP CK 18	SWP CK 21	SWP CK 29	SWP CK 41	SWP CK 66	DMC CK 13	DMC CK 20	DMC CK 21	South Bay CK 7	San Luis Reservoir
N-S	0.81	0.89	0.93	0.92	0.56	0.49	0.70	0.88	0.14	0.38	0.87	0.67

Plots are presented in this Chapter in both time series format (Figure 2-9 and Figure 2-13) and scatter format (Figure 2-12 and Figure 2-11) for San Luis Reservoir and Check 41.

Exceedance curves for EC (Figure 2-13 and Figure 2-14) are used to compare modeled and measured EC at Check 41 and San Luis Reservoir, from another perspective. For San Luis Reservoir, the simulated EC values are lower than the observed EC values for the same Exceedance percentage that is above 20%. The simulated EC values are generally greater than the observed EC values for Exceedance percentage below 20%, except for Exceedance percentage below 5%.

The Box-Whisker plots in Figure 2-15 and Figure 2-16 show the comparison of the lower quartile (Q1), median (Q2), upper quartile (Q3) of modeled and observed EC. Overall, the monthly medians of modeled and observed EC at each location are close. However, monthly ranges of box and whisker can sometimes be quite different. For San Luis Reservoir, the monthly mean of modeled EC is equal or less than that of observed EC.

2.6.3 Verification of Bromide

In the calibration period, only salinity or EC was investigated. In the verification period, besides EC, Bromide was also investigated. The model setup for Bromide simulation was exactly the same for EC simulation. The only difference was that the boundary conditions for Bromide simulation were changed. Measured Bromide data is available for Aqueduct Checks 13, 21, 29, 41, 66, DMC Check 12, South Bay Aqueduct Check 7, and San Luis Reservoir. Measured Bromide data is scarce for those locations except for SWP Checks 13, 41, and 66. The sources for measured Bromide include, WDL and MWD ((Liu, 2013) contains more details). Table 2-5 lists the N-S efficiency for each location. Overall the model did well in estimating Bromide at all locations.

Table 2-5 Nash–Sutcliffe (N-S) model efficiency for Bromide calculation

Location	SWP CK 13	SWP CK 21	SWP CK 29	SWP CK 41	SWP CK 66	DMC CK 12	South Bay CK 7	San Luis Reservoir
N-S	0.85	0.79	0.46	0.61	0.78	0.60	0.95	0.83

Much more information about Bromide performance of the DSM2 Aqueduct Model is in (Liu, 2013).

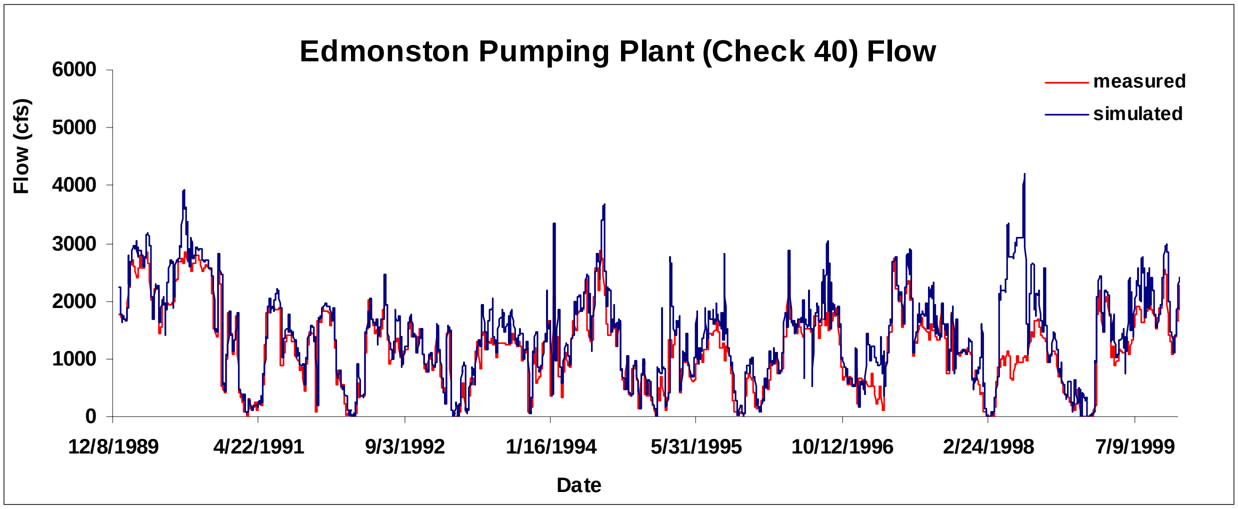
2.6.4 Verification of DOC

In the verification period, the DOC simulation was also investigated. The model setup for DOC simulation was similar to that for EC and Bromide simulation, with the difference that the boundary conditions for DOC simulation were changed. Measured DOC data is available for Aqueduct Checks 12, 13, 21, 29, 41, 66, DMC Check 12, South Bay Aqueduct Check 7, and San Luis Reservoir. Measured DOC data is scarce for those locations except for SWP Checks 13, 41 and 66. The sources for measured DOC include CDEC, WDL, and MWD. Table 2-6 lists the N-S efficiency for each location. Overall the model did a reasonably good job in calculating DOC, but not as good as its calculations for EC and Bromide. It may be that DOC is more subjected to decay during travel.

Table 2-6 Nash–Sutcliffe (N-S) model efficiency for DOC calculation

Location	SWP CK 12	SWP CK 13	SWP CK 21	SWP CK 29	SWP CK 41	SWP CK 66	DMC CK 12	South Bay CK 7	San Luis Reservoir
N-S	0.20	0.79	0.81	0.64	0.56	0.43	0.34	0.61	0.25

Much more information about DOC performance of the DSM2 Aqueduct Model is in (Liu, 2013).



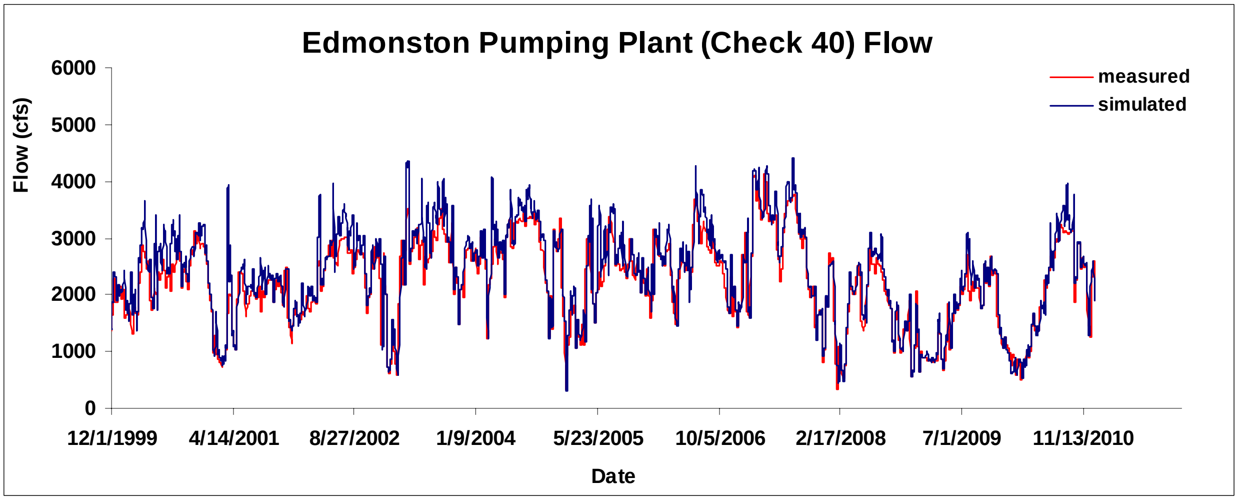
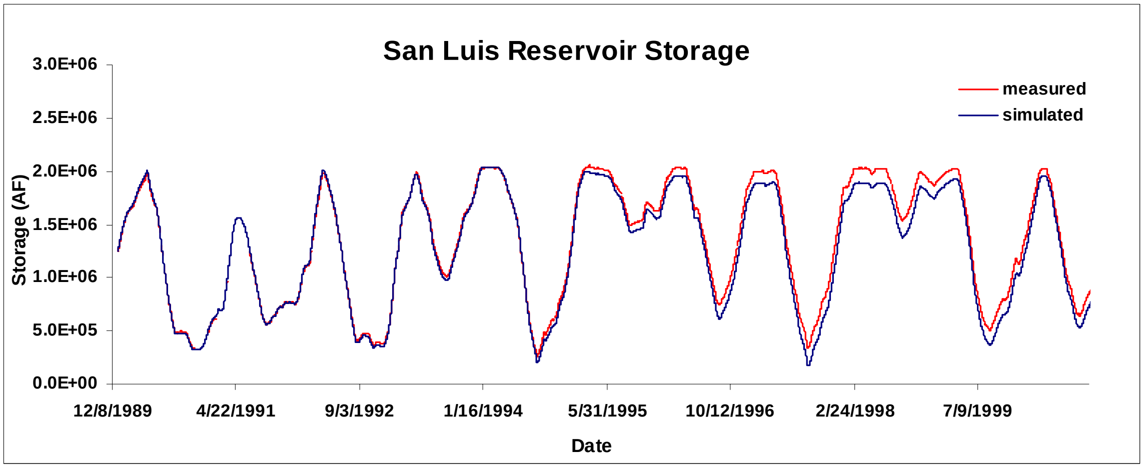


Figure 2-4 Comparison of Measured and Simulated Flow at California Aqueduct Check 40



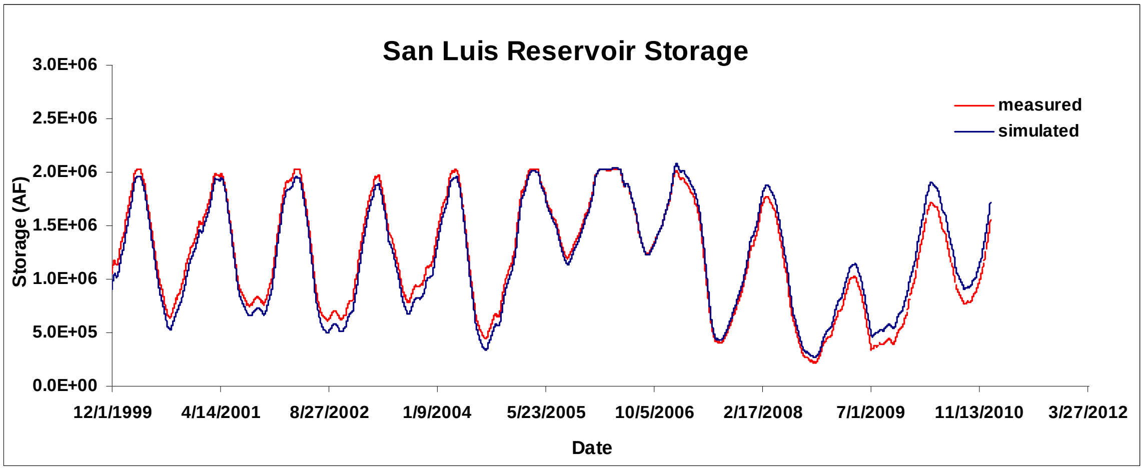


Figure 2-5 Comparison of Measured and Simulated Storage of San Luis Reservoir

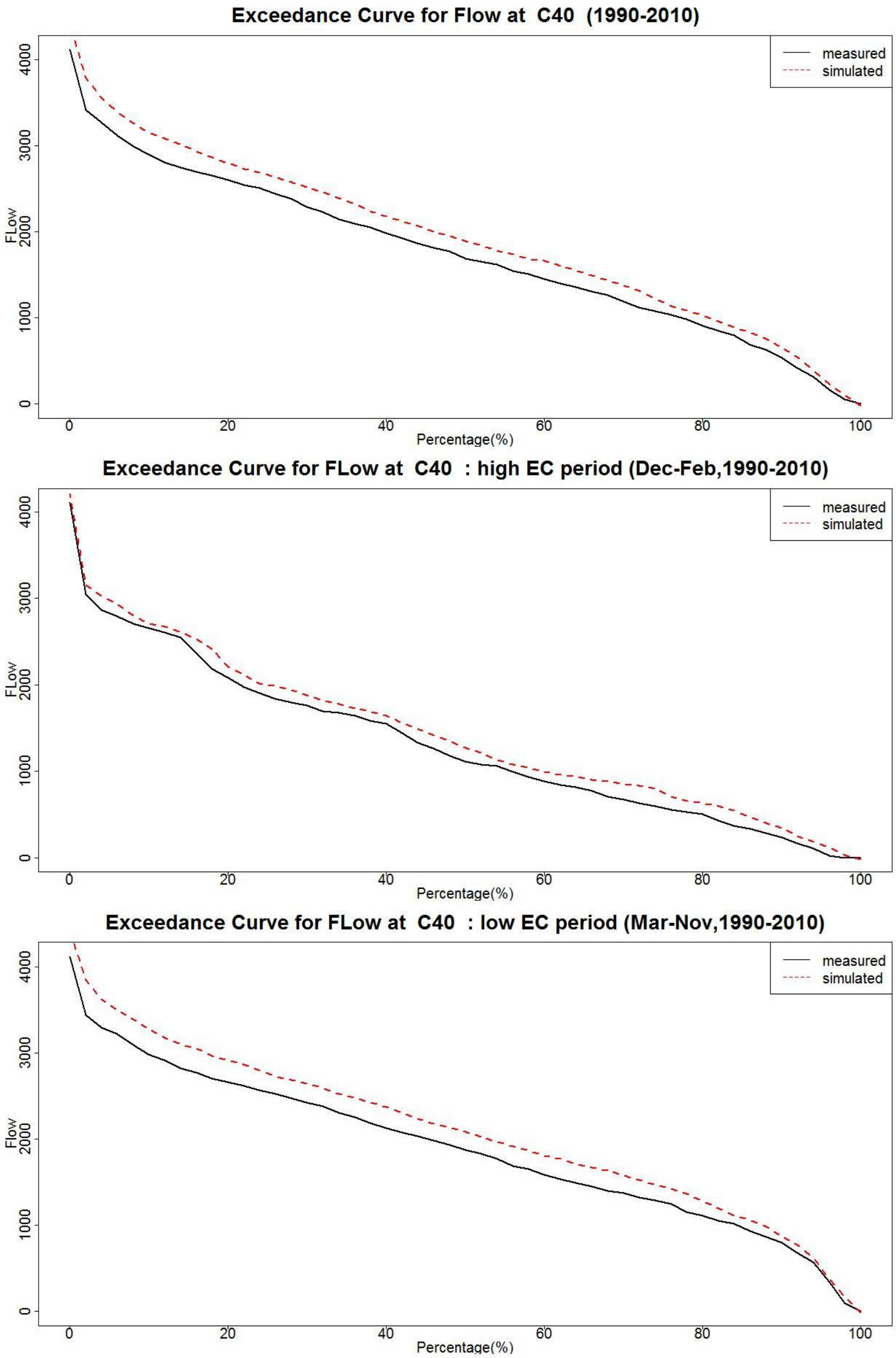


Figure 2-6 Exceedance Curve for Flow at C40

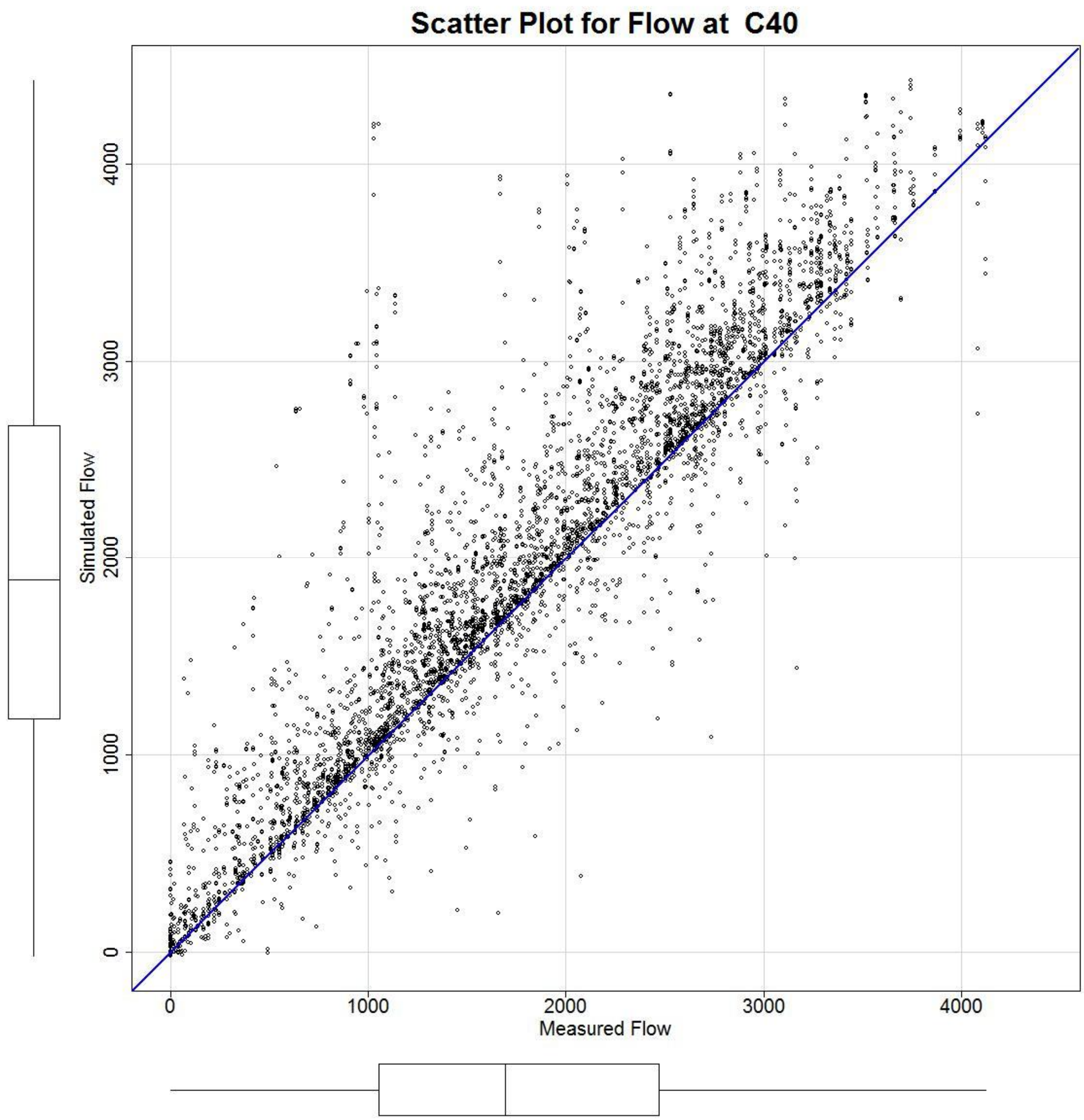


Figure 2-7 Scatter Plot for Flow at California Aqueduct Check 40

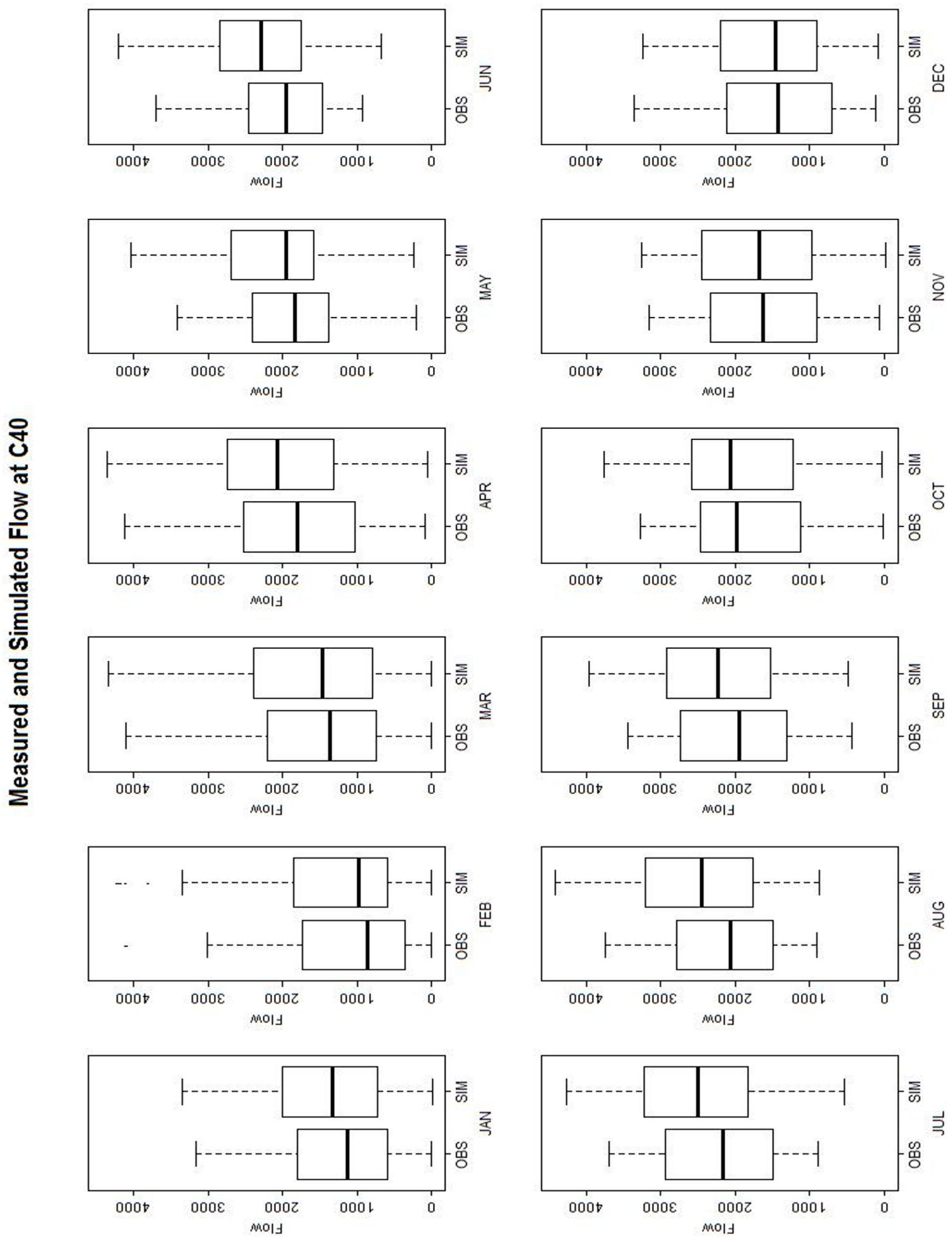
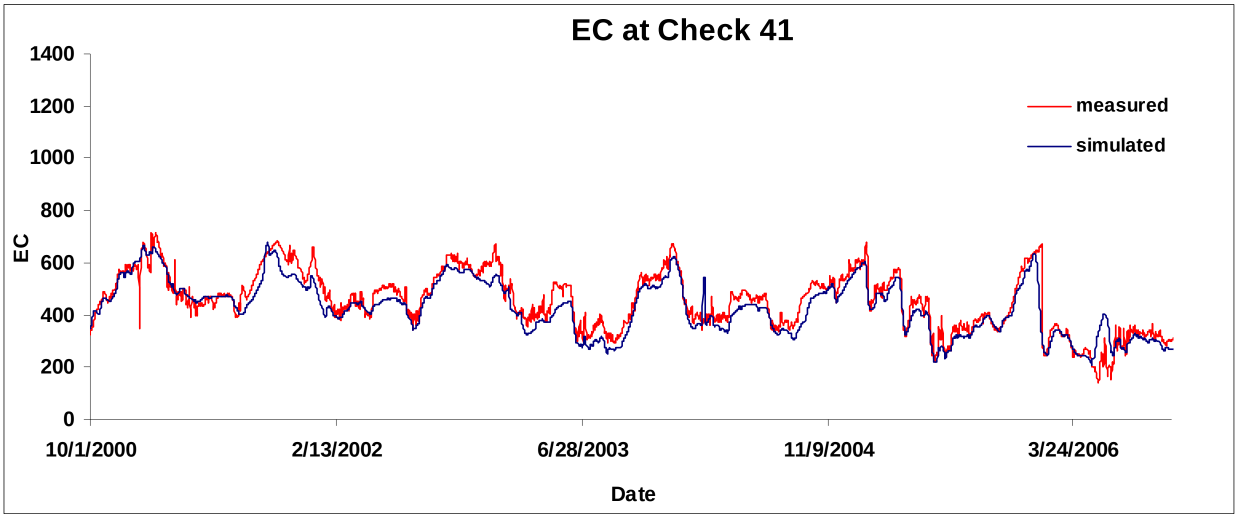


Figure 2-8 Month by Month Comparison of Measured and Simulated Flow at California Aqueduct Check 40



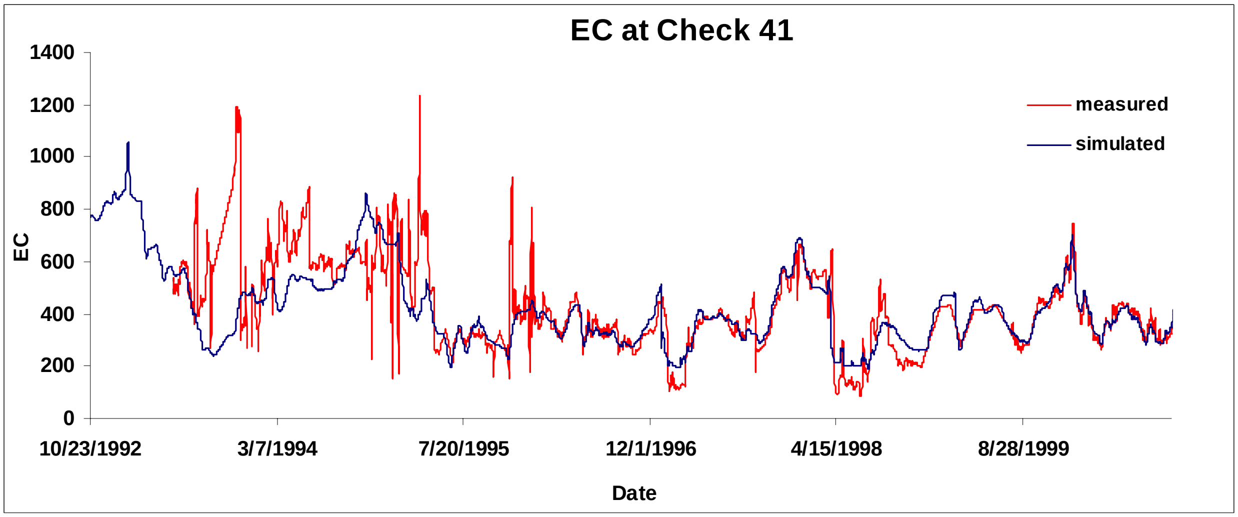
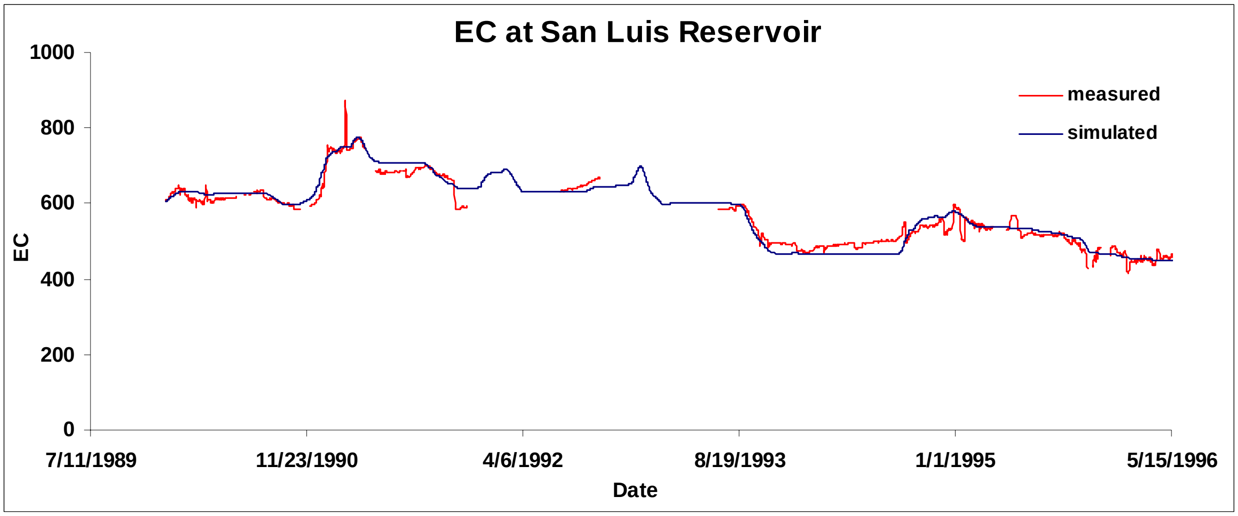


Figure 2-9 Comparison of Measured and Simulated EC at California Aqueduct Check 41



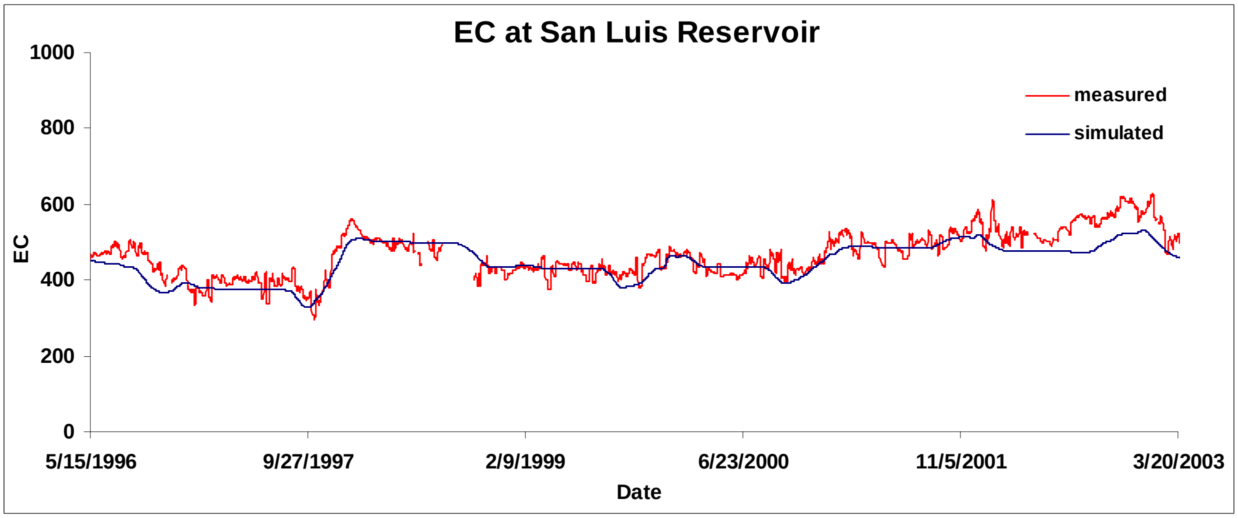


Figure 2-10 Comparison of Measured and Simulated EC at San Luis Reservoir

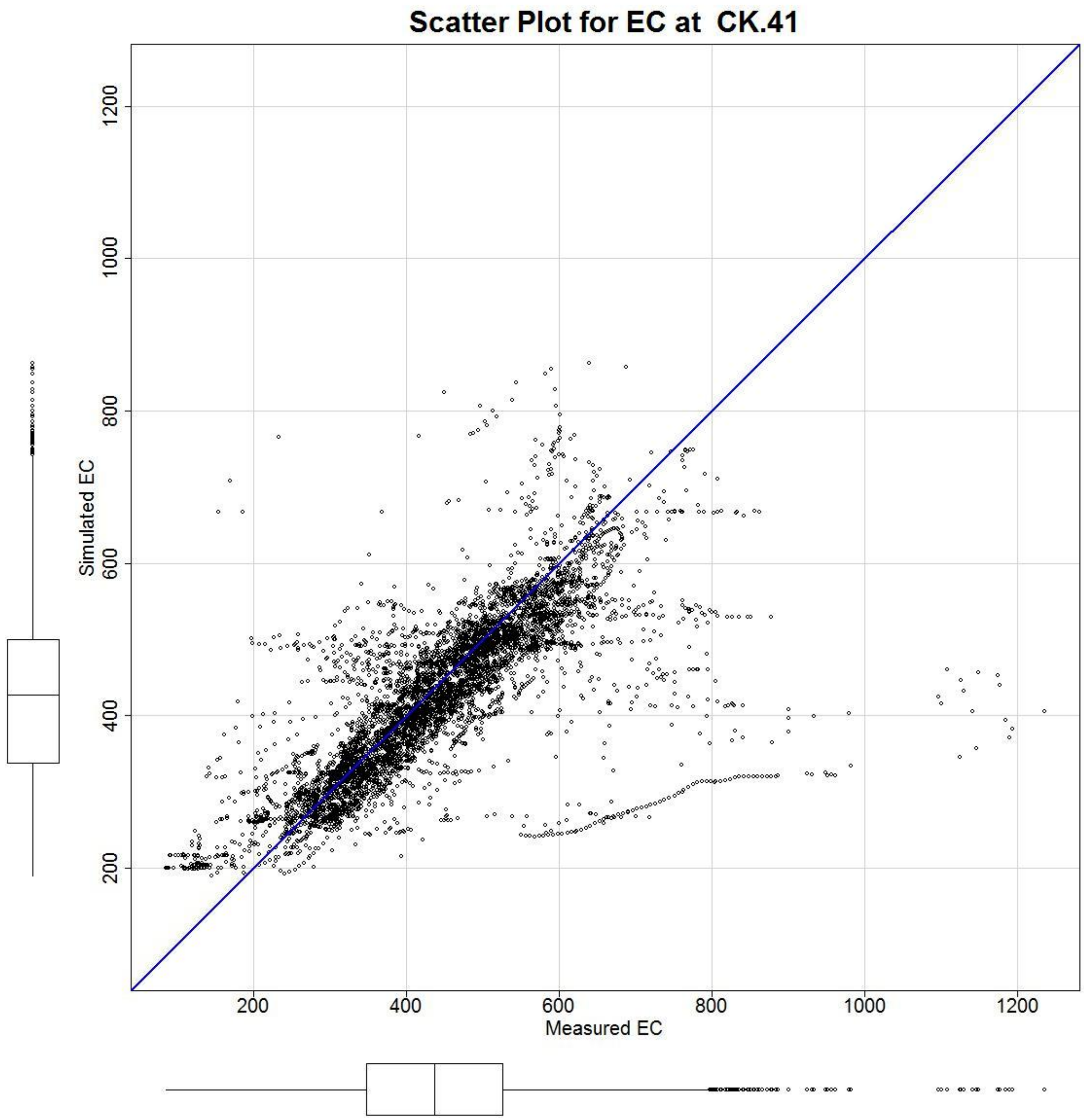


Figure 2-11 Scatter Plot for EC at C41

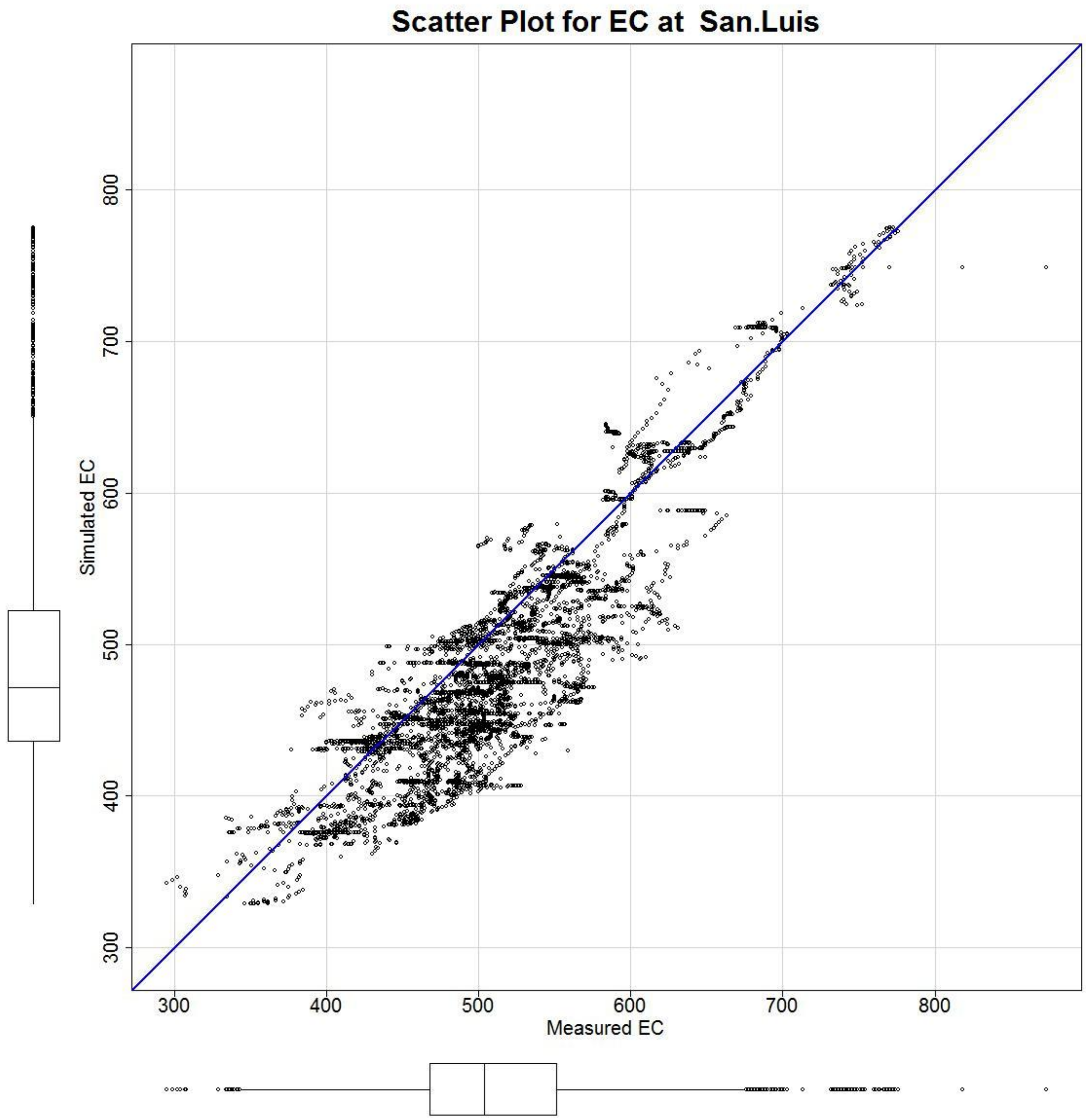


Figure 2-12 Scatter Plot for EC at San Luis Reservoir

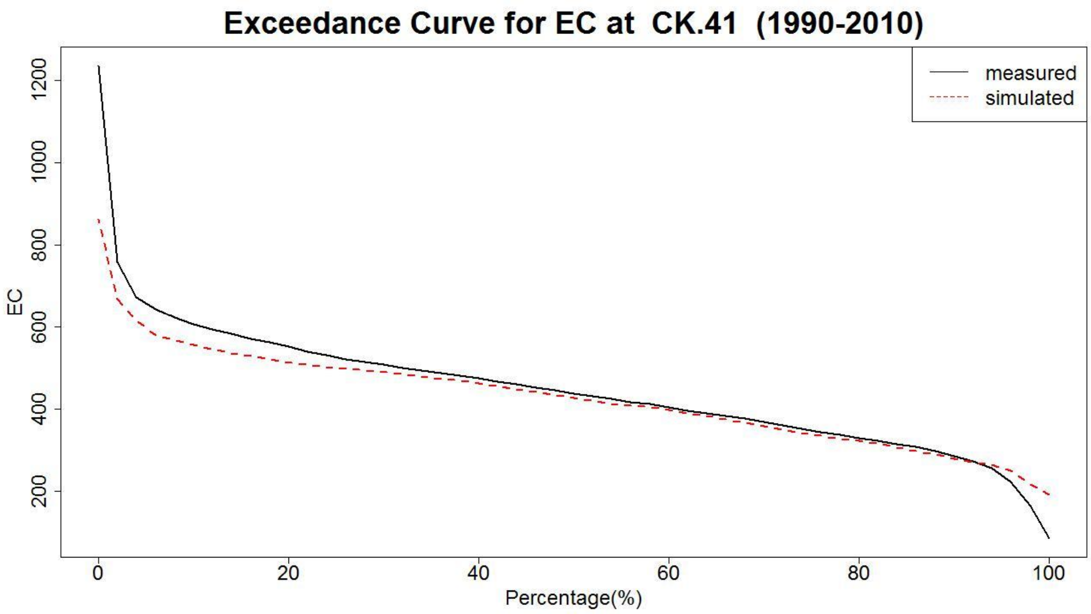


Figure 2-13 Exceedance Curve for EC at California Aqueduct Check 41

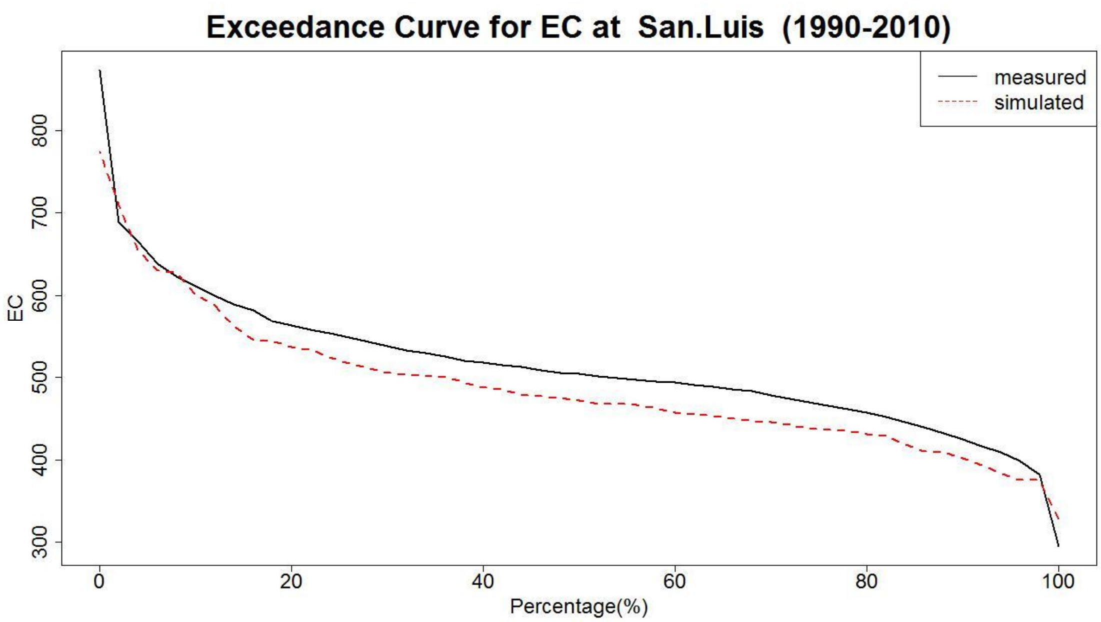


Figure 2-14 Exceedance Curve for EC at San Luis Reservoir

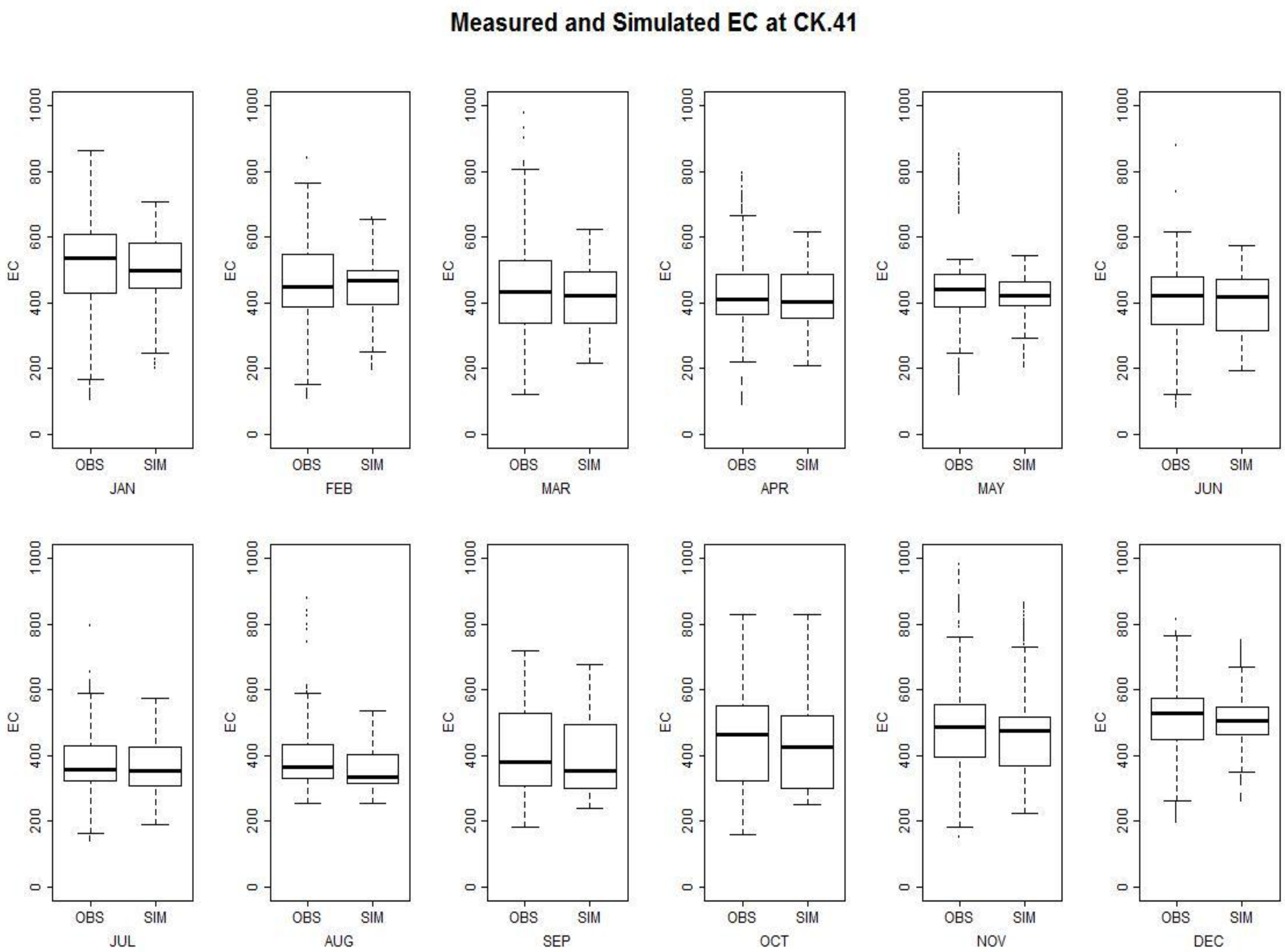


Figure 2-15 Month by Month Comparison of Measured and Simulated EC at California Aqueduct Check 41

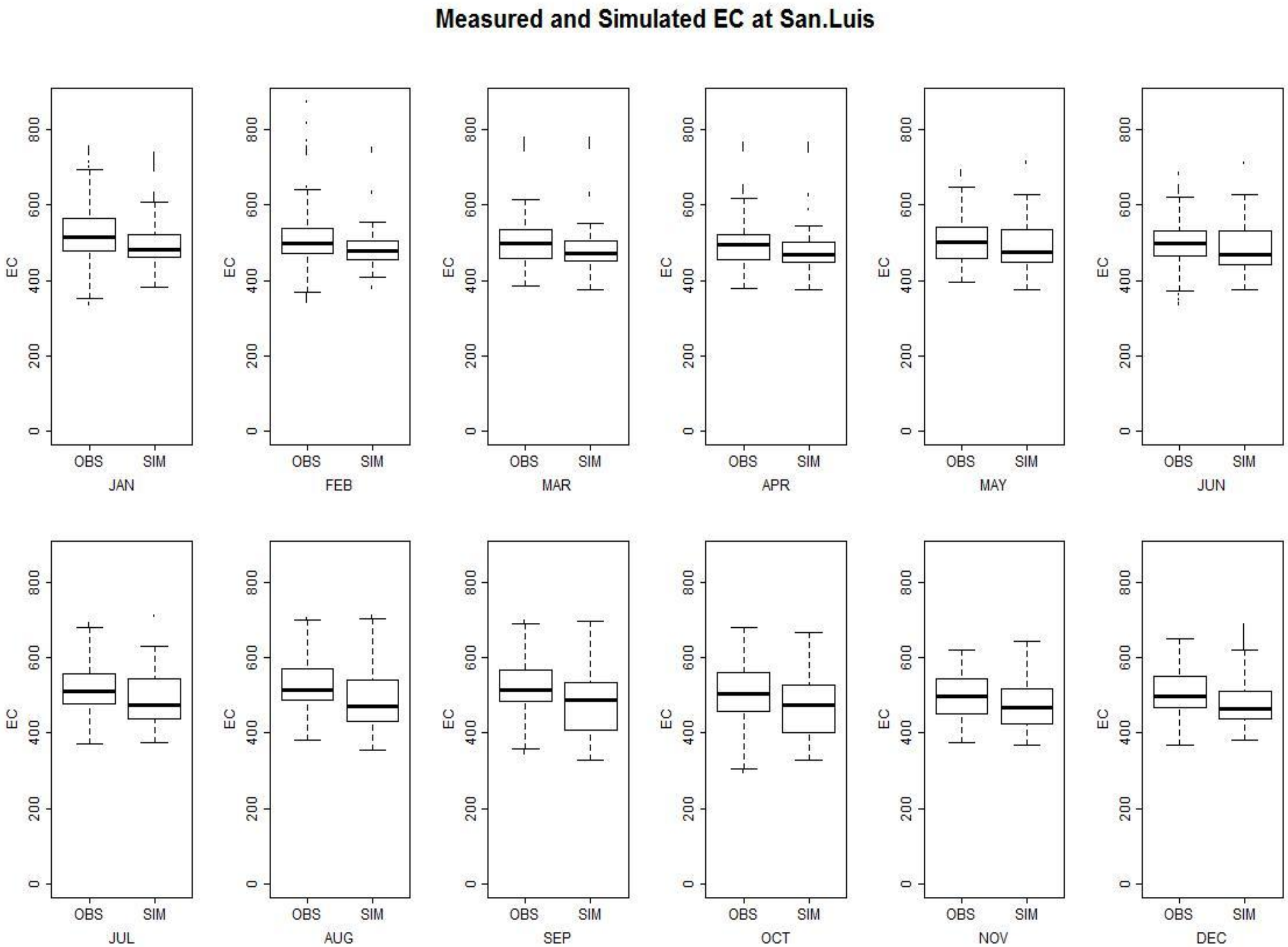


Figure 2-16 Month by Month Comparison of Measured and Simulated EC at San Luis Reservoir

2.7 Model limitations

Like every model of a physical system, the Aqueduct model has its limitations. The model was based on the 1-D DSM2 program. It cannot be used to accurately answer questions that involve more than one dimension. In particular, reservoirs are treated as completely mixed, vertical-walled bodies of water. So for a bay or reservoir, regardless of actual size, there is only one value at a given time of its state variables.

Unlike the Delta-DSM2 model, which has an unlimited water source from the tidal boundary, the water available to the Aqueduct and DMC system is restricted by pumping at Banks and Jones Pumping Plant. Model removed from the system must not exceed water added to the system, so a strict mass balance must be maintained in order for the model to run successfully. This requires that hydrologic inputs, i.e. inflows, outflows, rainfall, evaporation, storage, etc. be consistent. Otherwise, gains and losses are introduced to avoid problems such as channel drying (not enough water), or overbank flow (too much water). The use of gains and losses has an impact on water quality modeling.

In general, the check structures try to maintain a near constant elevation in any given pool. This is the main reason that in the model, the check structures are modeled as broad-crested weirs, with the invert elevations fixed to control flow. DSM2 version 8 allows users to define rules for gate operations. This usually involves specifying flow rates, or stages as conditions for gate operations. BDO staff has spent limited time on trying to use operation rules for gate operations, but without success. The model would not converge for most of the time steps, thus the results cannot be trusted. The reason for this is not clear. Further investigation is needed to find the problem.

There are limitations with diversion flows and some source flows. The data quantifying diversions from the system are aggregated on a monthly basis. These data were used to specify the diversions in the model, and were assumed to remain constant over the month. It is unrealistic to specify daily water quality input for groundwater pump-in and storm water flow. Instead, a constant water quality input is specified for each source flow. In reality, diversions and the quality of groundwater and storm water may have dramatic change from day to day. It is impossible for the model to track the changes because of the limitation of sparse inputs.

2.8 Conclusions

The DSM2 extension model, which was calibrated by CH2MHILL in 2005 to calculate flows and salinity, was verified using 21-year historical hydrologic and water quality data. The model was extended to simulate Bromide and DOC besides EC.

The model can simulate water quality (EC) reasonably well. As expected, the results are less accurate when locations are farther away from boundaries, i.e. Jones and Banks PP. For San Luis Reservoir, simulated EC matched observed EC reasonably well. For the period from 1990 to 2002, and 2010, the model did a good job in estimating EC. For the period from 2003 to 2009, however, the model underestimated EC at San Luis Reservoir by a small amount.

Measured data on Bromide is sparse. Based on limited measured data, the simulated Bromide output matched measured Bromide data well for SWP Checks 13, 21, 29, 339, 41, and 66, DMC Check 12, South Bay Aqueduct Check 7, and San Luis Reservoir. Measured Bromide data shows that Bromide concentration at San Luis Reservoir varied between 0.2 and 0.3 mg/l almost all the time.

The model did not do as well in modeling DOC as it did in modeling EC and Bromide when compared solely with N-S Coefficients. The model underestimated DOC at Checks 41, 66, and DMC Check 12. For San Luis reservoir, the model underestimated DOC for the period between 2004 and 2007; the model simulated DOC reasonably well for the period between 2008 and 2010. DOC decay may play a role in the mismatch between modeled and measured DOC. Another factor may be that DOC was sampled at Pacheco pumping plant rather than at a location near Gianelli Pumping / Generating Plant. Even for locations with low N-S coefficients, the model did a decent job by following trend well. DOC decay from upstream checks to downstream checks is not obvious. No seasonal trend of DOC decay is observed. Models results show that it is reasonable to model DOC as a conservative constituent.

Treating San Luis Reservoir as completely mixed body of water is sufficient for meaningful results. As expected, the magnitude of changes in EC, DOC, and Bromide at San Luis Reservoir is quite small than that of EC, DOC, and Bromide changes at SWP Checks. The model was able to catch the smaller changes.

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