State of California
California Natural Resources Agency
DEPARTMENT OF WATER RESOURCES

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

37th Annual Progress Report to the
State Water Resources Control Board in
Accordance with Water Right Decisions 1485 and 1641

June 2016

Edmund G. Brown Jr.	**John Laird**	**Mark W. Cowin**
Governor	Secretary for Natural Resources	Director
State of California	California Natural Resources Agency	Department of Water Resources

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Foreword

This is the 37th annual progress report of the California Department of Water Resources' San Francisco Bay-Delta Evaluation Program, which is carried out by the Delta Modeling Section. This report is submitted annually by the section to the California State Water Resources Control Board pursuant to its Water Right Decision 1485, Term 9, which is still active pursuant to its Water Right Decision 1641, Term 8.

This report documents progress in the development and enhancement of computer models for the Delta Modeling Section of the Bay-Delta Office. It also reports the latest findings of studies conducted as part of the program. This report was compiled under the direction of Tara Smith, program manager for the Bay-Delta Evaluation Program.

Online versions of previous annual progress reports are available at: http://baydeltaoffice.water.ca.gov/modeling/deltamodeling/annualreports.cfm.

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Preface

Chapter 1. Initial Investigation of Inflatable Barrier in South Delta

The agricultural rock barriers constructed in the South Delta, under the Temporary Barriers Program of the California Department of Water Resources, Bay-Delta Office (BDO), are installed to provide increased water levels and improved circulation patterns in the South Delta area.

BDO is investigating the feasibility of using inflatable barriers (i.e., rubber-bladder barriers) instead of the current rock barriers. The potential benefits of the inflatable barriers are lower cost and ease of installation. This chapter provides a summary of the preliminary investigation of using inflatable barriers.

Chapter 2. A New GIS Tool for Creating DSM2 Grid and Cross Sections

DSM2 cross sections are defined using bathymetry data as a guide. The Cross Section Development Program (CSDP) was developed for this purpose and has been used extensively in the past for creating DSM2 cross sections (Tom 2001). CSDP was developed almost 20 years ago when geographic information system (GIS) tools were not very sophisticated. Since then, ArcGIS has developed many features for geospatial analysis and visualization. To leverage these capabilities a tool was proposed for ArcMap that would add cross-section drawing capabilities for DSM2. A contract was executed with Tom Heinzer, GIS Manager/Software Developer, U.S. Bureau pf Reclamation, to implement this new tool.

With the new tool as an add-in to ArcMap, users can use both standard ArcMap functions and the new tool's functions. The add-in allows users to:

- Add, remove, and edit the locations of the nodes.
- Add the flowlines of channels, which are used to determine the length of the channels.
- Cut cross sections from a Digital Elevation Model (DEM) by using a vertical plane's intersection to determine the profile.
- Edit the profiles of cross-section shapes.
- Calculate the area, width, and wetted perimeter for user-defined levels from profiles.
- Export the channel grid and cross-section data in DSM2 format.

This chapter is a brief tutorial on how to use the tool. Delta Modeling Section staff have been using the tool to develop a new refined grid and cross sections.

Chapter 3. DSM2 Extension: A GIS-Based Approach

As with other hydrodynamic and hydraulic models, DSM2 (Delta Simulation Model 2) requires boundary conditions to fully define and drive the system; upstream boundary conditions are usually provided as flow hydrographs while downstream boundary conditions are given as water-surface elevation. Additionally, boundaries are located where observed data is available and are located away from areas of interest that might influence the boundary conditions. For water quality simulations, constituent concentrations must also be provided at all boundaries. In a tidal system, such as the Delta, where most of the salinity originates in the ocean, the salt concentration at the downstream boundary is crucial because it drives the water quality conditions in the Delta.

Situated at the eastern end of the Carquinez Strait, Martinez is the location of the downstream (western) boundary condition for DSM2. While the waterways of the legal Sacramento-San Joaquin

Delta are fully contained within the DSM2 boundaries, depending on the details of a particular study, the boundary condition location at Martinez can be less than ideal.

This chapter describes the investigation of a method for extending the DSM2 grid to San Francisco Bay at the Golden Gate. The method uses a one-dimensional grid, extensive and detailed geoprocessing of geometry data, and sophisticated calibration software. The goal of this grid extension is to reflect the volume of water and salinity transported from the Golden Gate to Martinez for Delta simulations, and it is not intended to provide a detailed model of hydrodynamics and salinity in San Francisco Bay. Preliminary results show promise that the method presented in this chapter can be applied successfully.

Chapter 4. Delta Salinity Simulation with DSM2-GTM

The California Department of Water Resources' (DWR's) Delta Modeling Section is developing a new DSM2 transport module, called the General Transport Model (DSM2-GTM). Progress on this effort was previously reported in Hsu et al. (2014). DSM2-GTM employs a fixed (Eulerian) mesh rather than one that moves with flow and follows virtual parcels of water in a Lagrangian scheme. The fixed grid will make it easier for this model to interact with other models, georeferenced data, data assimilation, optimization, and visualization, as well as to couple inline to DSM2-HYDRO. It is also more straightforward to extend the new model to new physical processes, with sediment, dissolved oxygen, and mercury cycling models that are currently being developed. Because of its extensibility, DSM2-GTM is expected to replace DSM2-QUAL.

This chapter provides a detailed description of the technical background and accomplishment so far of the DSM2-GTM development.

Chapter 5. Estimating Net Delta Outflow, Summary of March 2016 Report to the State Water Resources Control Board

In fall 2015, the State Water Resources Control Board (SWRCB) requested that DWR provide technical guidance on the best available consumptive use models and, more broadly, on the subject of Net Delta Outflow calculations. DWR produced a report, titled *On Estimating Net Delta Outflow (NDO), Approaches to Estimating NDO in the Sacramento-San Joaquin Delta* (California Department of Water Resources 2016) and submitted it to the SWRCB in March 2016. This chapter is a brief outline and a summary of the report.

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Chapter 1
Initial Investigation of Inflatable Barrier in South Delta

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1 Quantitative Calibration of DSM2

1.1 Background

The agricultural rock barriers constructed in the South Delta (Figure 1-1), under the Temporary Barriers Program of the California Department of Water Resources, Bay-Delta Office (BDO), are installed to provide increased water levels and improved circulation patterns in the South Delta area.

BDO is investigating the feasibility of using inflatable barriers (i.e., rubber-bladder barriers) instead of the current rock barriers. The potential benefits of the inflatable barriers are lower cost and ease of installation.

The Old River at Tracy temporary barrier is used as a modeling case study to investigate the feasibility of an inflatable barrier. To increase water levels and improve water quality, the current rock barrier, under normal operating conditions, allows water to flow from downstream to upstream through the culverts with flap gates (Figure 1-2), and over the top of the weir during flood tide events. The ends of culverts, with the flap gates, are on the upstream side of the barrier. On the other hand, the inflatable barrier under consideration will not allow overtopping.

For the inflatable barrier to work in generally the same way as the rock barrier, it has to allow the same flood tide volume of water to flow upstream of the barrier by using only culverts, as opposed to the current configuration, which uses both culverts and overtopping of the weir. If the inflatable barrier does not allow the same flood tide of water to flow upstream of the barrier by using the current amount of culverts, then additional culverts may have to be installed to match that flow.

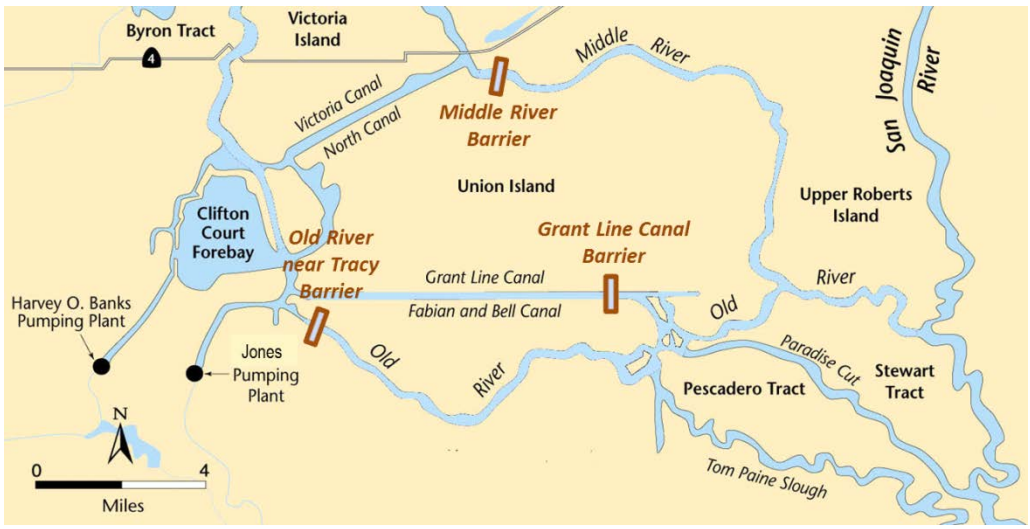

Figure 1-1 Agricultural Temporary Barriers in the South Delta

Figure 1-2 The Culverts with Flap Gates at the Old River Tracy Barrier

1.2 Purpose

The purpose of this preliminary investigation is to evaluate what percentage of the flood tide flows through the culverts, as opposed to the flow that overtops the weir.

1.3 Modeling Assumptions

The Delta Simulation Model II (DSM2) is a one-dimensional mathematical model for dynamic simulation of hydrodynamics, water quality, and particle tracking in a network of riverine or estuarine channels. DSM2 consists of three modules: HYDRO, QUAL, and PTM. DSM2-HYDRO is used for this investigation. The simulation period is January 1999–December 2011 and includes various types of hydrologic conditions and historical water project operations. Specifically, the culverts of the Old River at Tracy temporary barrier are assumed to be tidally operated. This means that, during flood tide conditions, the pressure of the flood tide forces water against the flap gates on the culverts, and this pressure opens the flap gates on the upstream side to enable water to flow into the channel upstream of the barrier.

DSM2-HYDRO assumes the flap gates of the culverts open immediately when the flood tide is flowing from downstream to upstream side of the barrier. In other words, there is no explicit assumption regarding what hydraulic conditions (e.g., water-level difference) need to be considered in order to open the flap gates under flood tide conditions. In addition, DSM2-HYDRO has not been calibrated to assess how accurately the model estimates flows over the top of the weir and through the culverts because the field data is not available.

1.4 Preliminary Modeling Results and Findings

This investigation focuses on discovering the percentage of water flowing over the top of the weir and through the culverts under flood tide conditions. The hourly flow modeling results are post-processed and summarized for this analysis.

Figure 1-3 shows the numerical range of the water amount flowing over the top of weir and through the culverts during flood tide events and the associated exceedance probabilities. It appears that the flow range of water over the top of weir has a larger range than the flow through the culverts. Note that when interpreting the two exceedance probability curves, for a certain probability value, the flow over

the top of weir and through the culverts does not represent that these two flows occur at the same time. For example, for a 50-percent exceedance probability, the flows over the top of weir and through the culverts are about 250 cubic feet per second (cfs) and 410 cfs, respectively, but these two flows actually occur at different times.

Figure 1-4 is a stacked-column plot showing the portion of water flowing over the top of weir and through the culverts in terms of the percentage of total water flowing from downstream to upstream of the barrier. The results show that about 67.7 percent of the time, the amount of water flowing through the culverts is greater than the water flowing over the top of the weir. Furthermore, the results show that total water flowing from downstream to upstream, in general about 37.6 percent of the total water amount, flows over the top of the weir, and about 62.4 percent of the total water amount flows through the culverts.

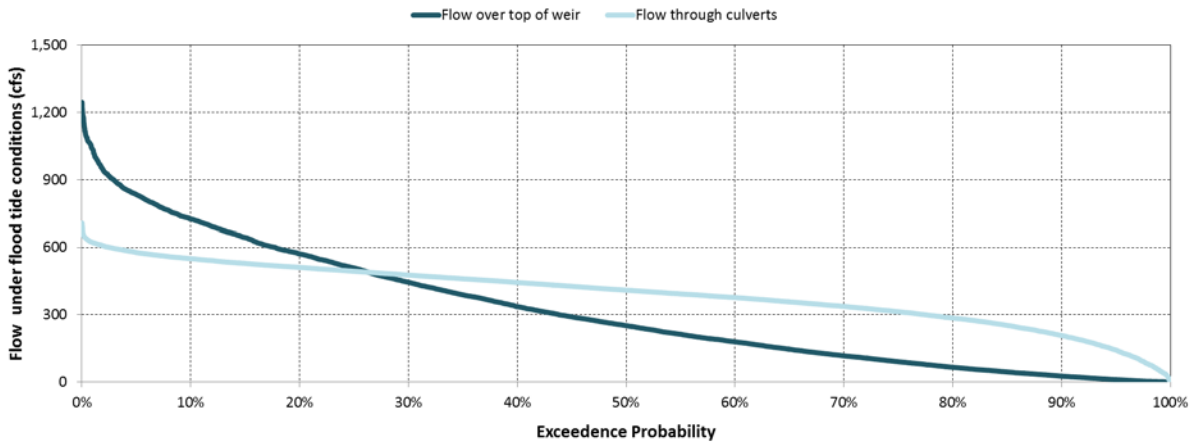

Figure 1-3 Exceedance Probabilities of Flow Over the Top of the Weir and Through the Culverts Under Flood Tide Conditions

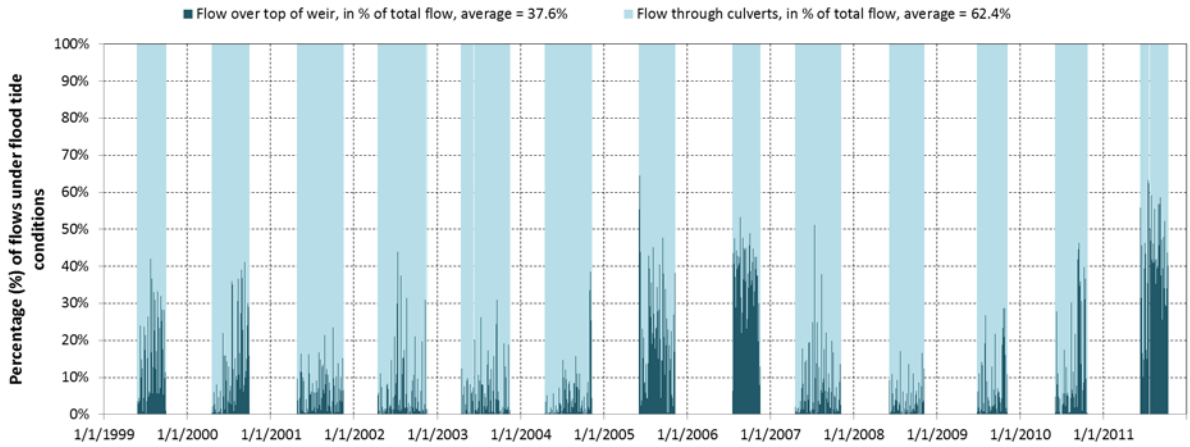

Figure 1-4 Flows Over the Top of the Weir and Through the Culverts in Terms of Total Flow Amount Under Flood Tide Conditions

1.5 Next Steps

As previously mentioned, the key assumption of this analysis is that the flap gates open immediately when the flood tide is flowing from downstream to upstream. Along these lines, the hydraulic conditions

that need to be considered to open the flap gates are not considered in this study. In addition, DSM2-HYDRO has not been calibrated to evaluate the accuracy of estimating the flow over the top of the weir and through the culverts. The modeling results shown in this investigation are very preliminary and need to be further analyzed to determine the next steps (e.g., design and operation purposes) for assessment of the feasibility of using inflatable barriers. Although it is preliminary, the study gives a better idea of the amount of water moving over the weir and through the culverts, and will be used to inform any further analysis. In the past, design of the rock barriers, including the weir heights and number of culverts, has been based on modeling and observation of water levels and flow circulation. If needed, future analysis could also focus on designing the inflatable barriers to meet specified criteria, as this relates to the balance between low water levels and circulation patterns.

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Chapter 2

A New GIS Tool for Creating DSM2 Grid and Cross Sections

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2 A New GIS Tool for Creating DSM2 Grid and Cross Sections

2.1 Introduction

DSM2 cross-sections are defined using bathymetry data as a guide. The Cross-Section Development Program (CSDP) was developed for this purpose and has been used extensively in the past for creating DSM2 cross-sections (Tom 2001). CSDP was developed almost 20 years ago when geographic information system (GIS) tools were not very sophisticated. Since then, ArcGIS has developed many features for geospatial analysis and visualization. To leverage these capabilities, a tool was proposed for ArcMap that would add cross-section drawing capabilities for DSM2. A contract was executed with Tom Heinzer, GIS Manager/Software Developer, U.S. Bureau of Reclamation, to implement this new tool.

With the new tool as an add-in to ArcMap, users can use both standard ArcMap functions and the new tool's functions. The add-in allows users to:

- Add, remove, and edit the locations of the nodes.
- Edit the flowlines of channels, which are used to determine the length of the channels.
- Cut cross-sections from a Digital Elevation Model (DEM) by using a vertical plane's intersection to determine the profile.
- Edit the profiles of cross-section shapes.
- Calculate the area, width, and wetted perimeter for user-defined levels from profiles.
- Export the channel grid and cross-section data in DSM2 format.

This chapter is a brief tutorial on how to use the tool. Delta Modeling Section staff have been using the tool to develop a new refined grid and cross-sections.

2.2 Installation and Tutorial

This tool requires ArcMap version 10.2 or later. To install the tool, copy both files (DSM2_Tools.esriAddIn and XSections.mpk) to your local hard drive and then double-click the DSM2_Tools.esriAddIn file. Then start ArcMap, and a new DSM2 1.5 toolbar will appear.

Then double-click the XSections.mpk file. It should install the map package layers, as shown in Figure 2-1. You may want to modify the DEM property to display the DEM in color. Do this by right clicking the DEM layer and select property, and under the symbology tab, pick a color ramp.

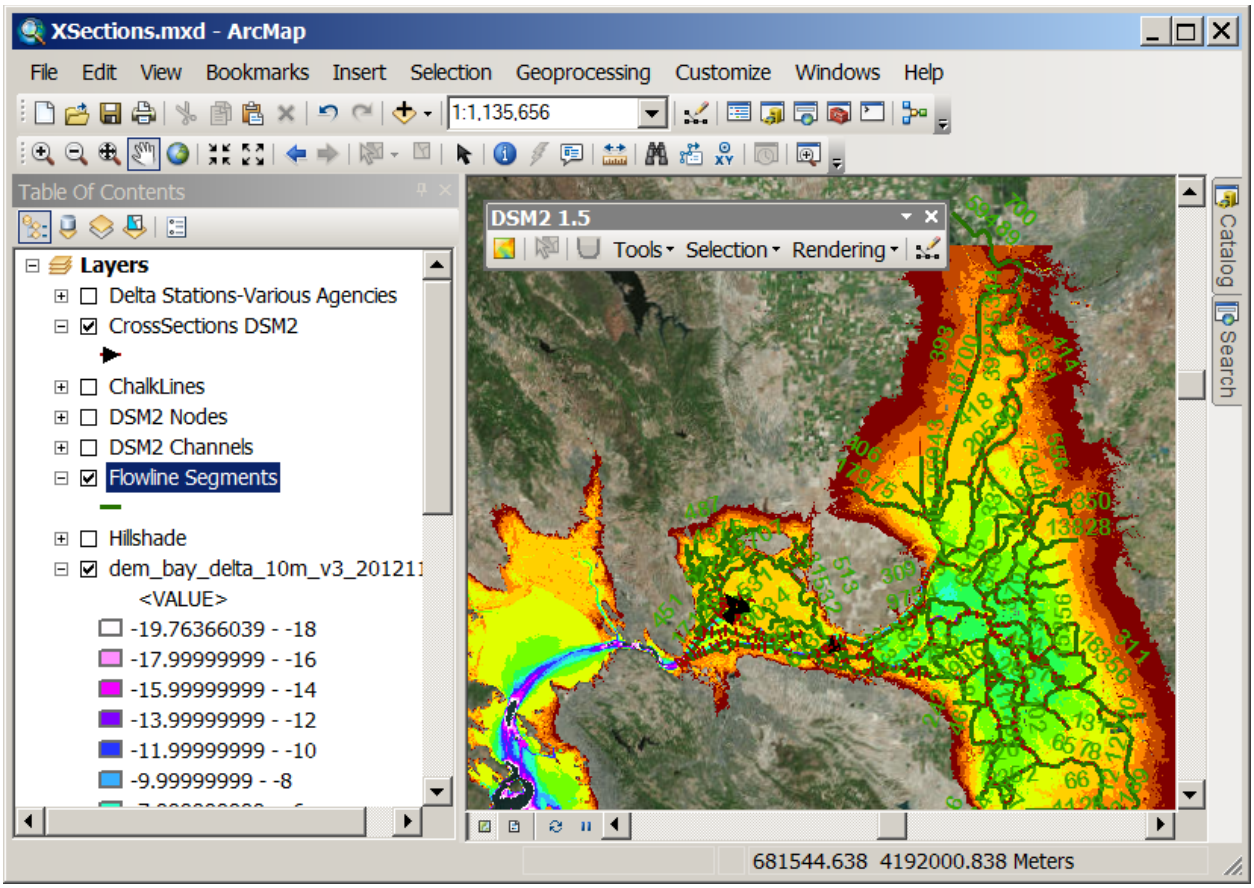


Figure 2-1 ArcMap Window after Installing the Tool and Map Package Layers

Step 1. Click the first icon on the left in the DSM2 1.5 toolbar to set up the necessary parameters (Figure 2-2).

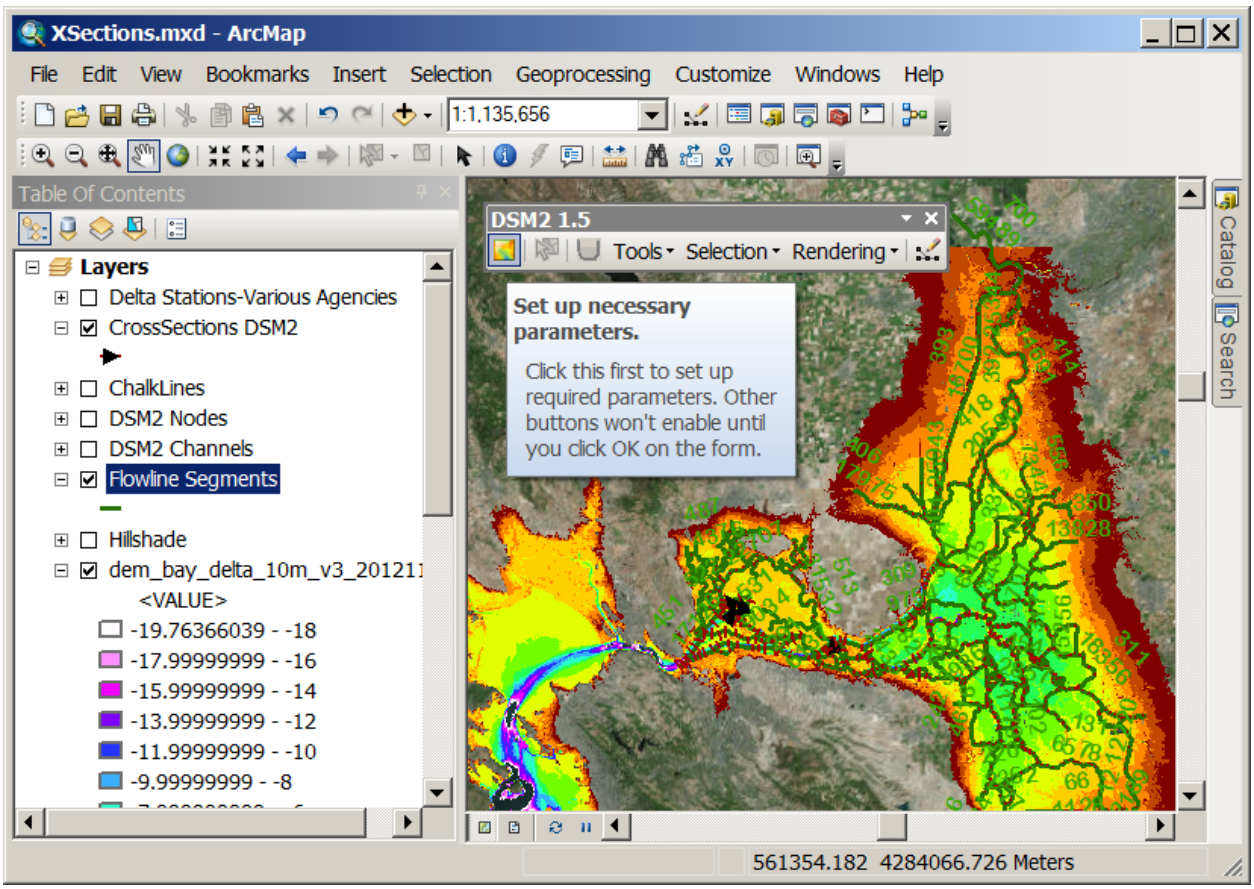


Figure 2-2 First Icon Sets Up the Necessary Parameters

Select the pulldown menu choices for Elevation Layer, Cross-Sections Layer, and Flowlines Layer, as shown in Figure 2-3. Click in the Selectable Only box next to the Cross-Sections Layer pulldown menu and a checkmark will appear. The DSM2 Channels Layer is not used by this tool. Finally, click OK.

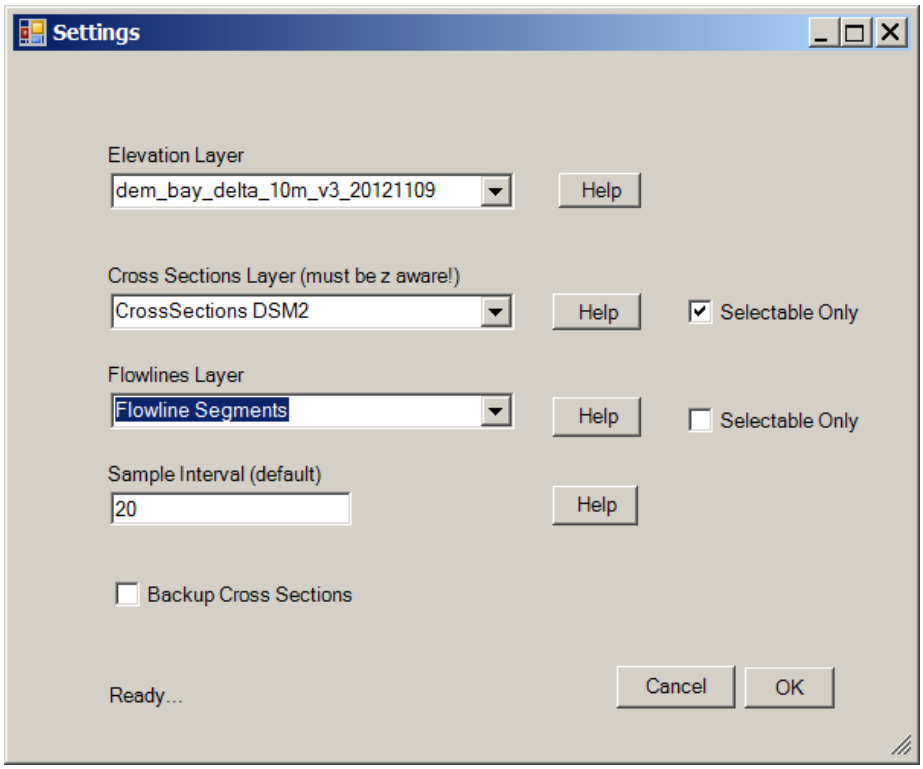


Figure 2-3 Selecting Layers

Step 2. Zoom into a channel by using and click the Select Feature button . Then click on a cross-section to select it. The cross-section line turns a light blue color when selected, as seen in Figure 2-4, where the cross-section in the middle of channel 434 is selected.

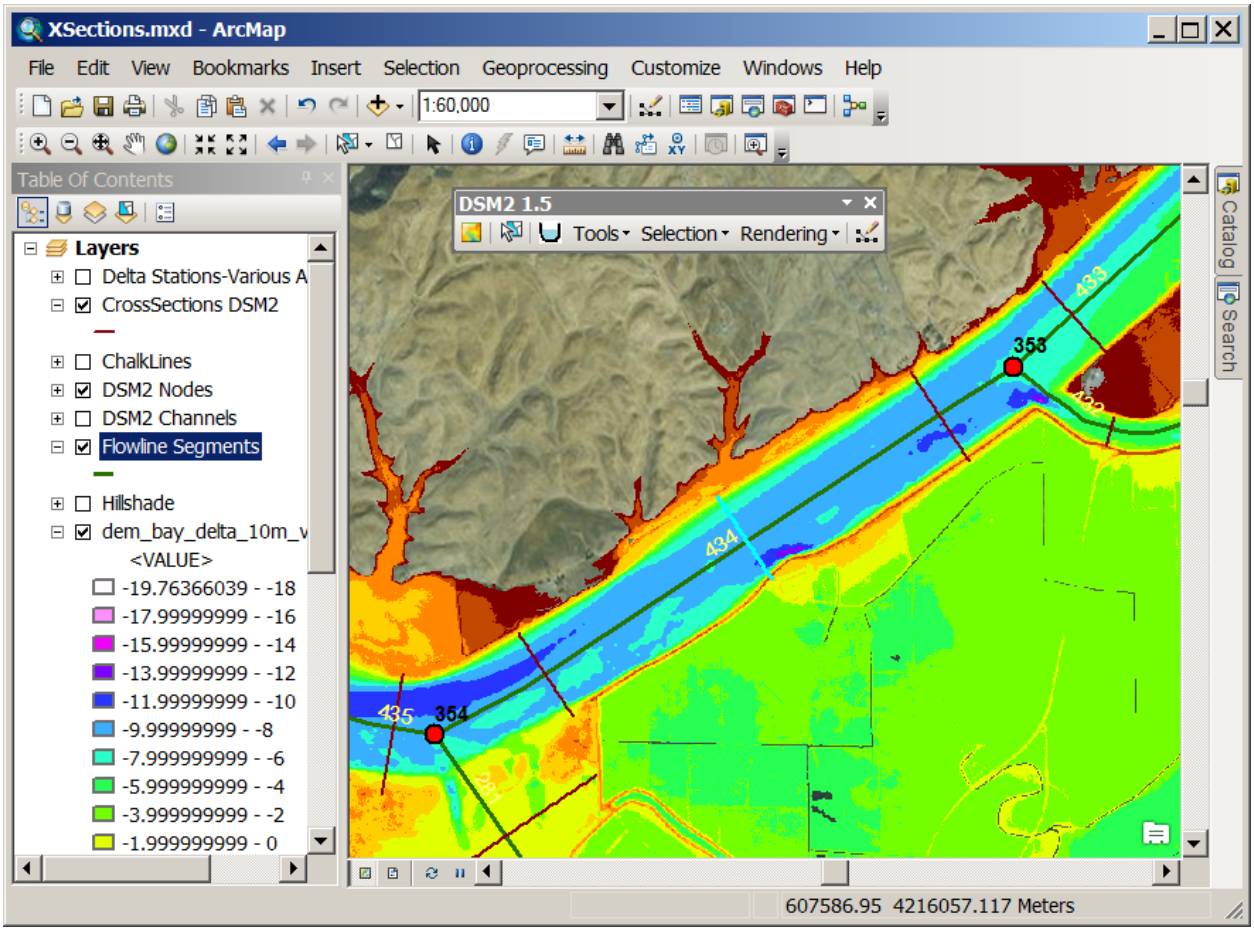


Figure 2-4 Selecting a Cross-Section

Step 3. Click the View/Edit Selected Cross-Section tool (Figure 2-5).

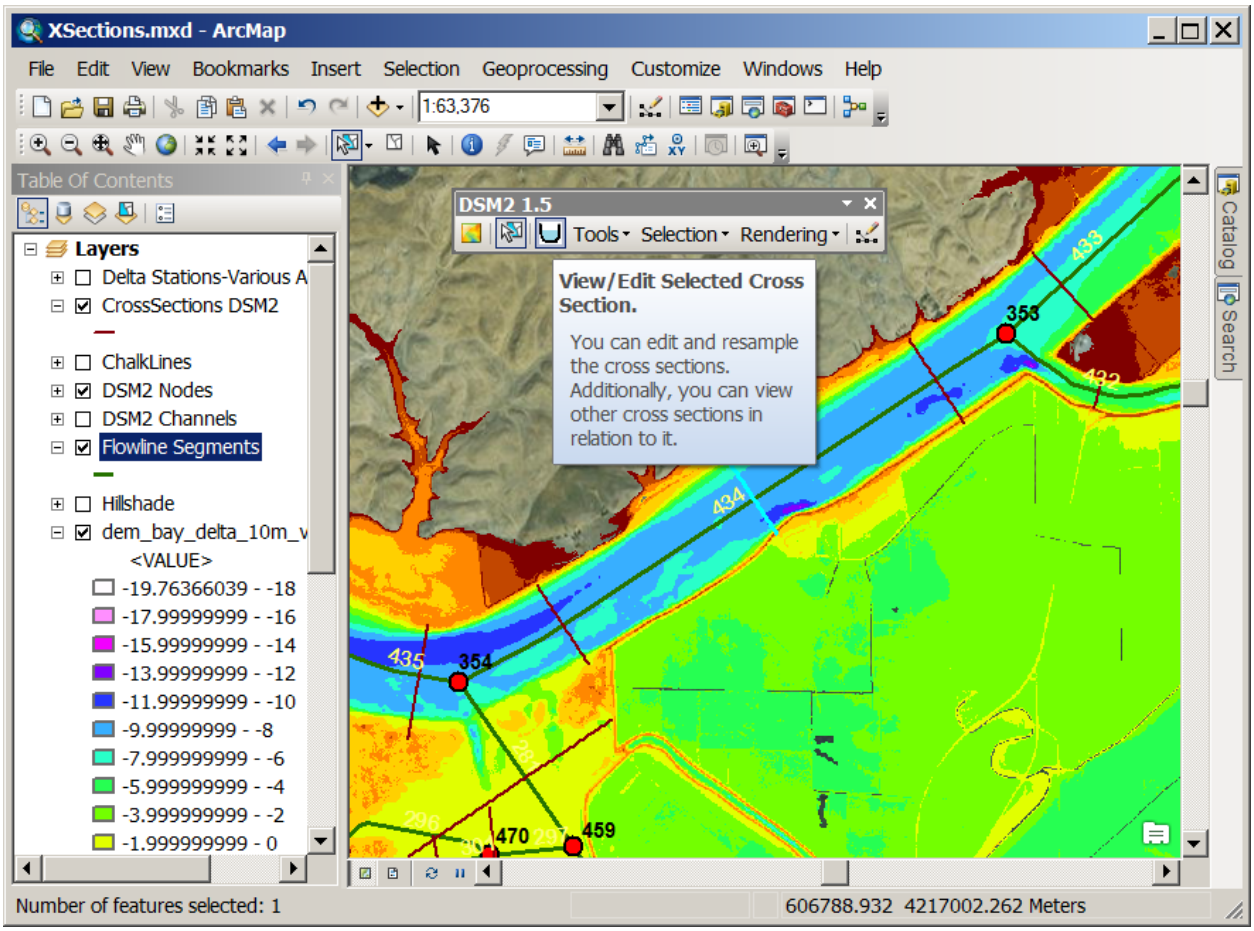


Figure 2-5 View/Edit Cross-Section Tool Icon

The Cross-Section View window will appear (Figure 2-6). First, use the Function button Sample to sample the elevation profile. The sample interval recommended to use is the DEM resolution 10 for 10-meter DEM and 2 for 2-meter DEM. After the profile has been sampled, it is necessary to specify a few levels for the cross section. Click the Go button next to the No. of levels box, and a few uniformly distributed levels will be created (Figure 2-6). The cross-sectional properties (i.e., width, area, and wetted perimeter) will be calculated at these levels. The levels can be interactively dragged up or down, added, or deleted using the mouse to better represent the channel. Keep in mind that DSM2 uses a trapezoidal rule to calculate channel area, so well-placed levels will yield more accurately calculated areas. Near the channel bottom, river bathymetry usually changes abruptly, and a lot of levels might be needed to capture the changes (Figure 2-7). We avoided this difficulty by keeping the area between channel bottom and the lowest level the same as the DEM-calculated area, so no detailed levels are needed near the bottom. This is achieved by using a post-processing script to calculate an equivalent width at the cross-section bottom, so that the DSM2 calculated area will be exactly the same as the real area from the DEM. Figure 2-8 shows the final levels for this cross section.

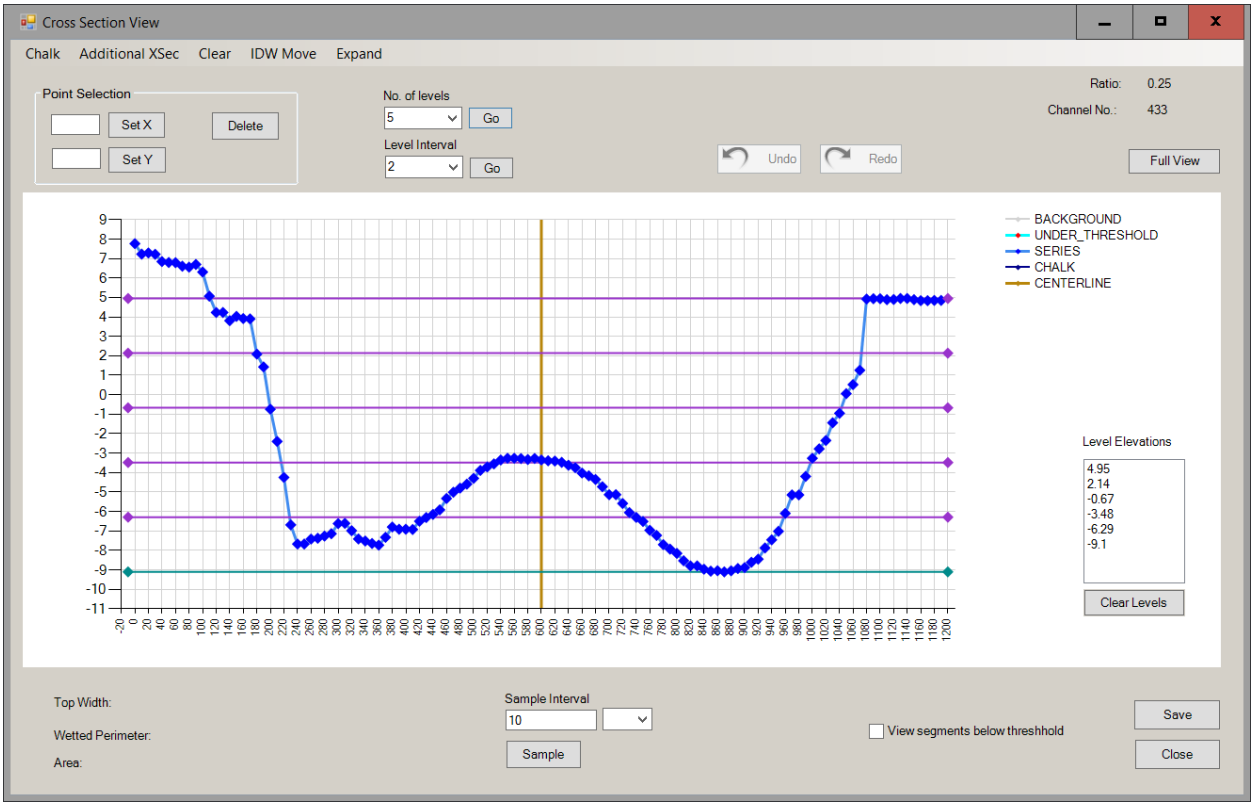


Figure 2-6 Cross-Section View Window

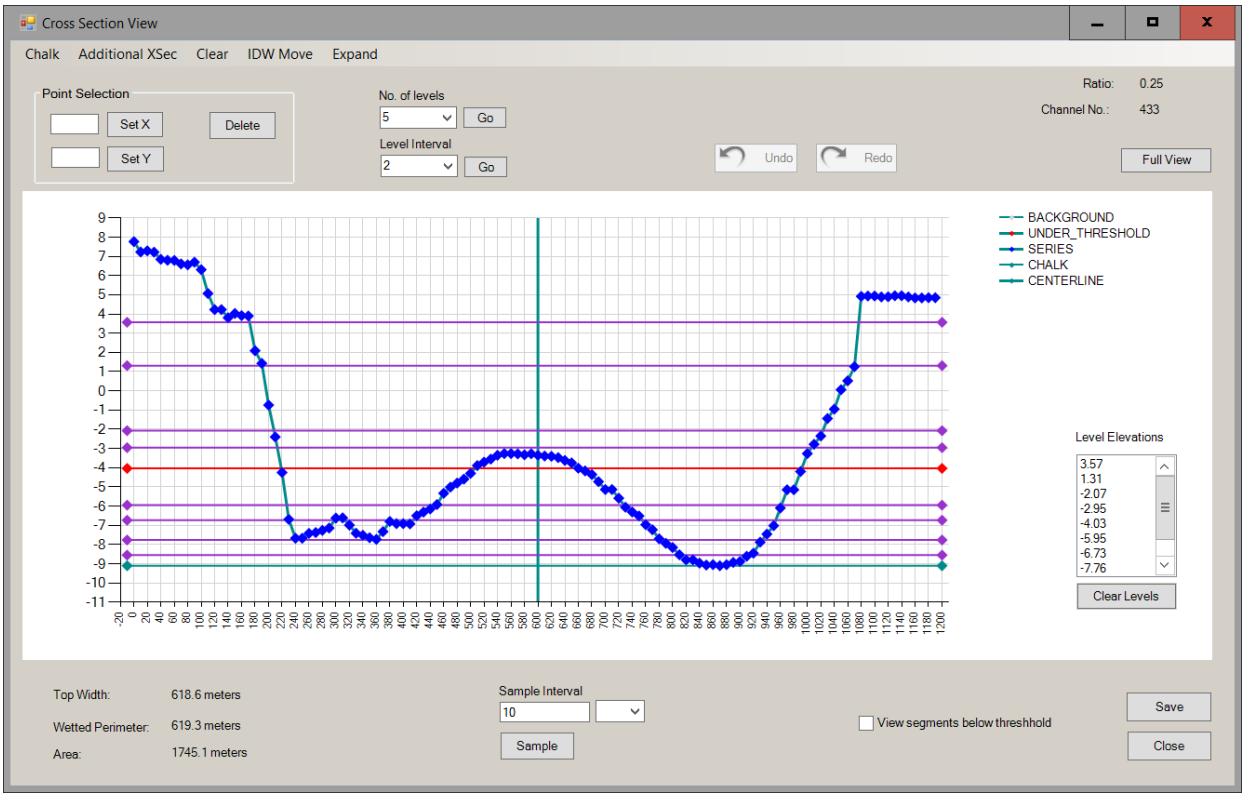


Figure 2-7 Cross-Section View Window

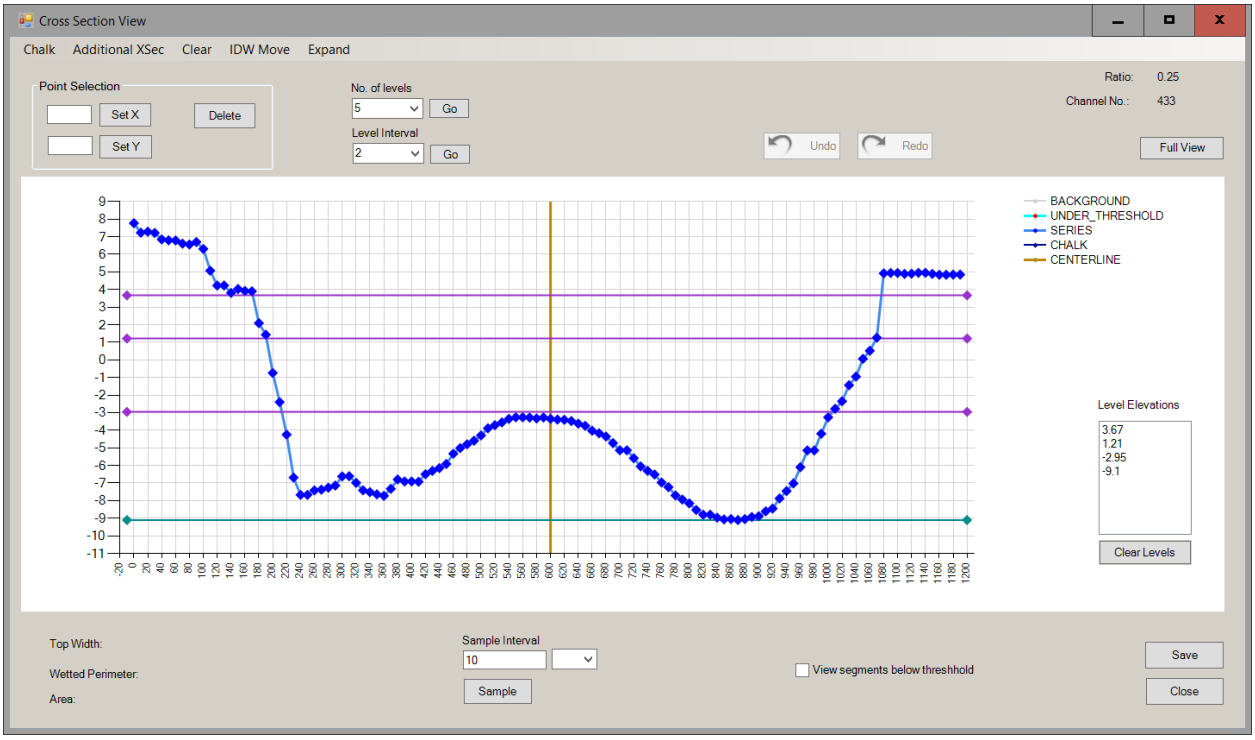
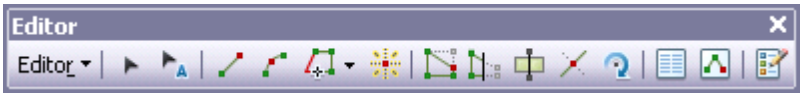


Figure 2-8 Cross-Section View Window

Step 4. To add new cross sections or change flowlines, use the standard ArcMap editor. Click on the DSM2 1.5 tools menu, which is the last icon on the right, to show the Editor toolbar.



Under the Editor menu, select Start Editing, and the Start Editing window will appear (Figure 2-9). Select CrossSections DSM2, and click OK to start editing (e.g., drawing new cross sections or changing sections as shown in Figure 2-10). The node locations can be adjusted and flowlines can be drawn interactively using the mouse. Once editing is completed and saved, use the Cross-Section tool to view/sample the cross sections.

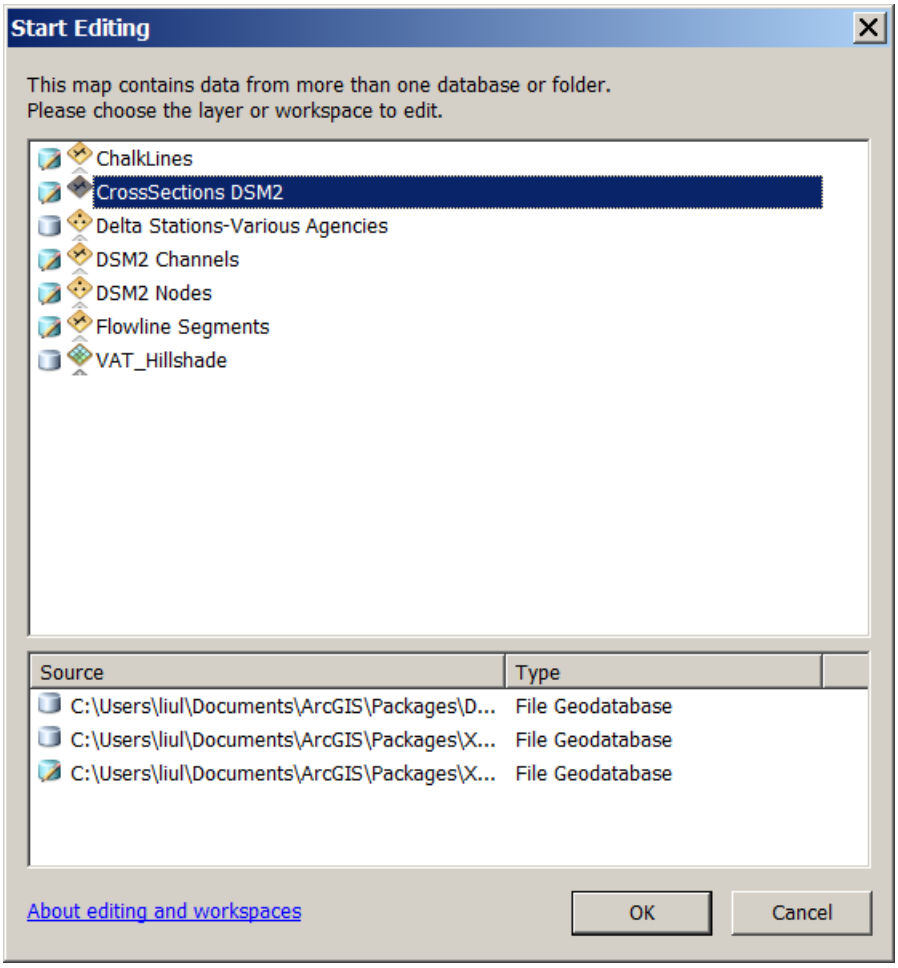


Figure 2-9 Start Editing Window

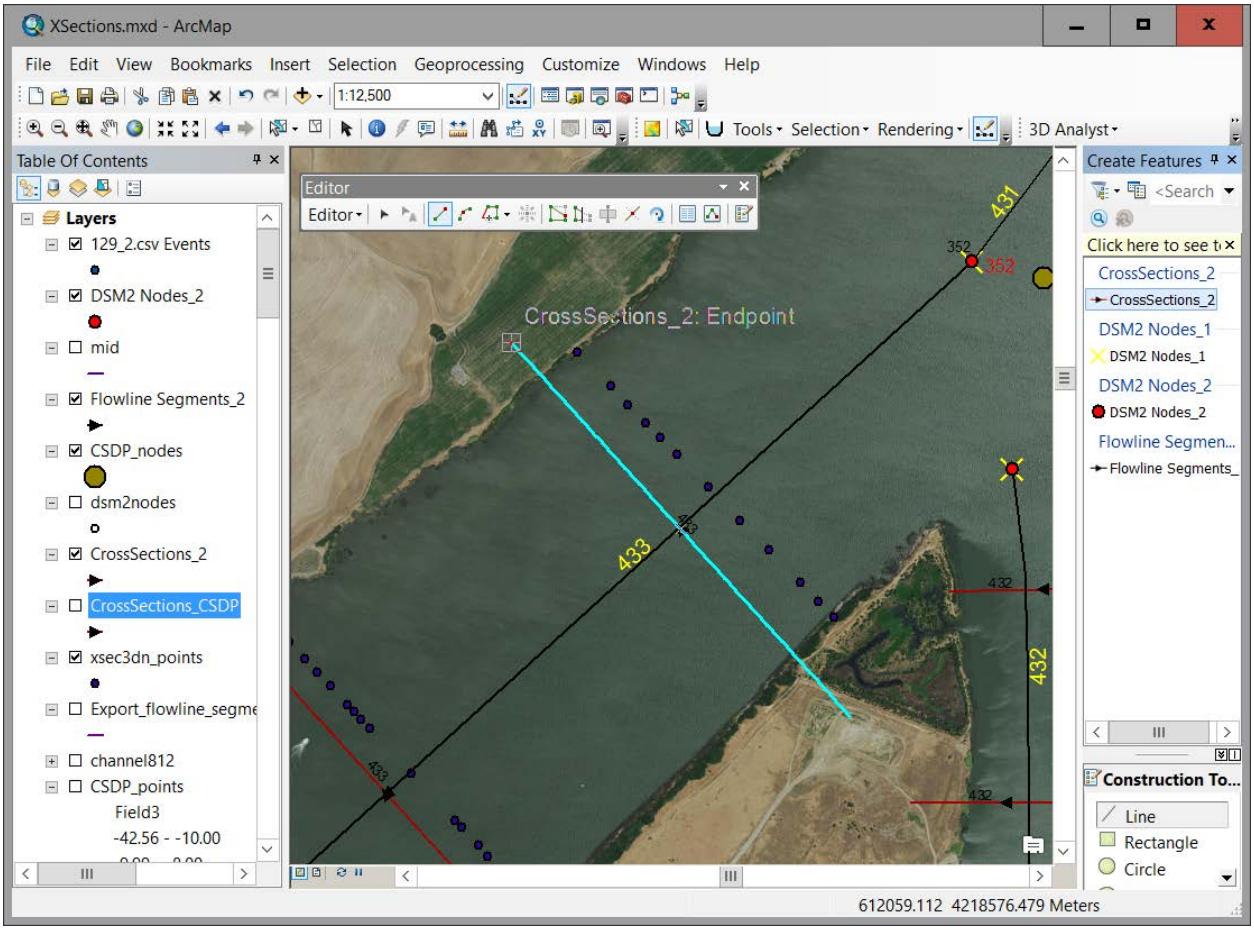


Figure 2-10 Editing Window

Step 5. There are a few helpful tools that can be used for batch processing under the DSM2 1.5 Tools menu (Figure 2-11). Some or all cross sections can be sampled together. Select all the cross sections you want to batch process, then click the Sample Elevation Model tool. Levels can also be created together for all selected cross sections by using the Create Levels for the All Selected Cross-Section tool. The Transect Generator tool generates cross sections at user-defined spacing and width. We suggest generating cross sections at the computational grid locations. For computational grid details, see Delong et al. (1997) and Liu et al. (2012).

Step 6. Once the editing is done and the files are saved, the cross sections can be exported to DSM2 format, as shown in Figure 2-10.

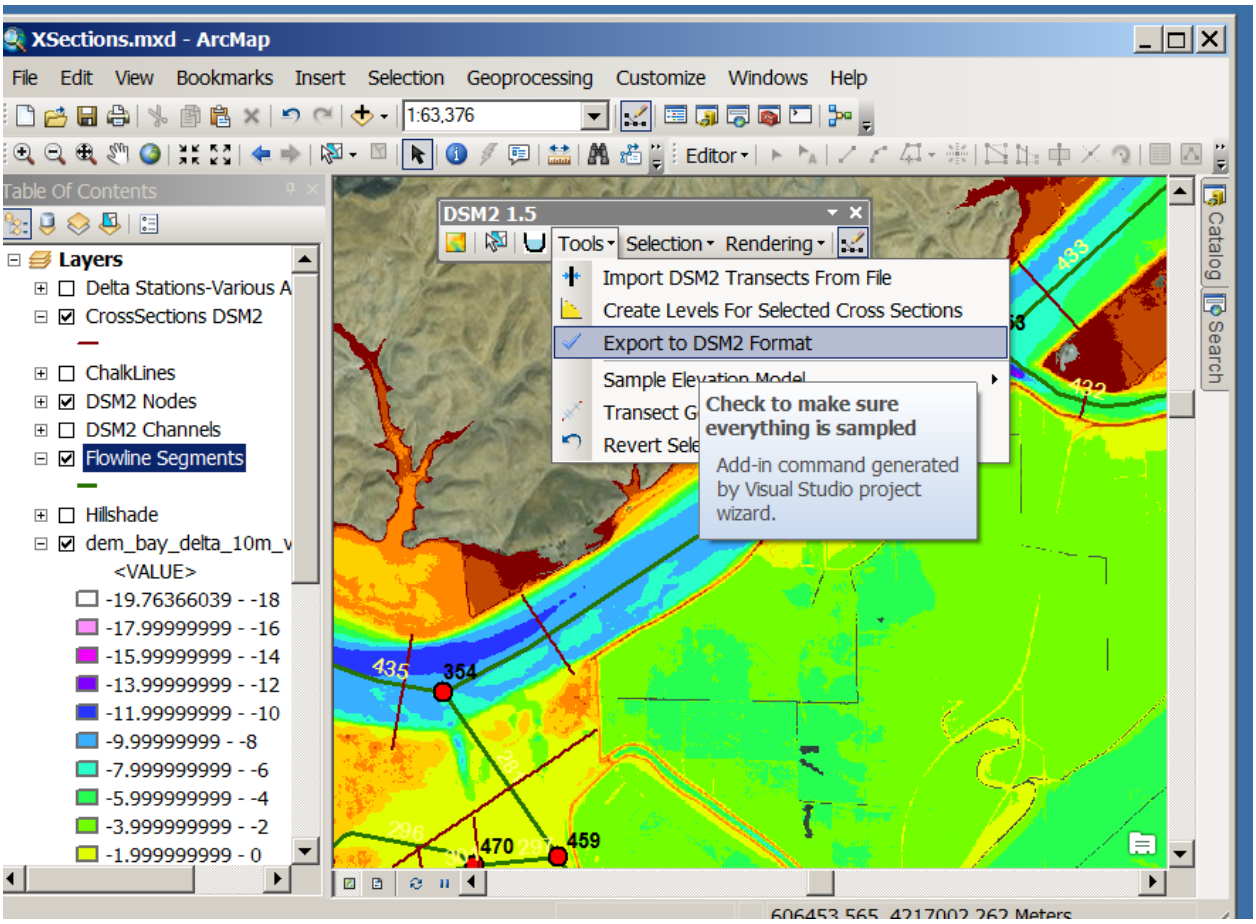


Figure 2-11 Tools for Batch Processing

Although it is very useful, this tool has some limitations and could be improved in the following ways.

1. In some channels, flowline segments need to be disconnected from nodes to represent the real channel length.
2. Only three decimal places are necessary in the exported DSM2 cross-section file.
3. The complete channel input file could be exported. Manning's N and dispersion coefficient fields must be added to do this.
4. Fix existing bugs.
    a. When resampled, the cross-section is slightly reduced and should be its original size.
    b. The Expand function causes the program to close at times.

5. Add more GIS coverage.
    a. Add gate coverage to show gates on the map with gate information in a table.
    b. Show open-water areas and connections on a map.
    c. Show consumptive-use (DICU) nodes.
    d. Show DSM2 output locations and add an export function for the output location file.

2.3 Summary

Delta Modeling Section staff have been using this tool to create a refined DSM2 grid and cross-sections to better represent the channels. This tool leverages ArcMap functionality to provide a robust and complete working environment to view/edit the DSM2 channels, nodes, and cross-sections. The tool helps to automate many of the tasks of determining cross-sections. Nonetheless, the tool requires manual manipulation to be totally effective. Each cross section needs to be checked and the levels need some manual adjustments to better represent the channels. In addition, cross sections could be modified for dredging or other planning purposes rather than be derived from the DEM.

2.4 Reference

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

37th Annual Progress Report
June 2016

Chapter 3

DSM2 Extension: A GIS-Based Approach

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DEPARTMENT OF WATER RESOURCES

STATE OF CALIFORNIA

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3 DSM2 Extension: A GIS-Based Approach

3.1 Introduction

As with other hydrodynamic and hydraulic models, DSM2 (Delta Simulation Model 2) requires boundary conditions to fully define and drive the system; upstream boundary conditions are usually provided as flow hydrographs while downstream boundary conditions are given as water-surface elevation. Additionally, boundaries are located where observed data is available and are located away from areas of interest that might influence the boundary conditions. For water quality simulations, constituent concentrations must also be provided at all boundaries. In a tidal system, such as the Delta, where most of the salinity originates in the ocean, the salt concentration at the downstream boundary is crucial because it drives the water quality conditions in the Delta.

Situated at the eastern end of the Carquinez Strait, Martinez is the location of the downstream (western) boundary condition for DSM2. While the waterways of the legal Sacramento-San Joaquin Delta are fully contained within the DSM2 boundaries (Figure 3-1), depending on the details of a particular study, the boundary condition location at Martinez can be less than ideal, as we discuss below.

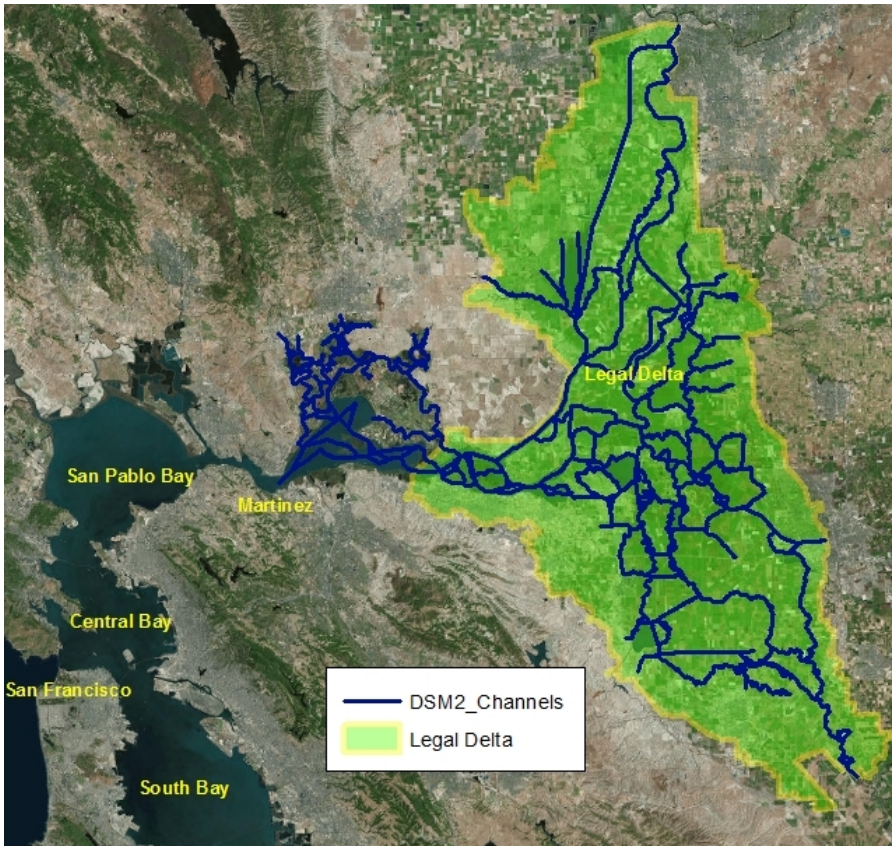


Figure 3-1 Map of Area Modeled Including Legal Boundaries of the Sacramento-San Joaquin Bay-Delta

This project investigates a method for extending the DSM2 grid to the Golden Gate. The method uses a one-dimensional grid, extensive and detailed geoprocessing of geometry data, and sophisticated calibration software. The goal of this grid extension is to reflect the volume of water and salinity transported from the Golden Gate to Martinez for Delta simulations, and it is not intended to provide a detailed model of hydrodynamics and salinity in San Francisco Bay. Preliminary results show promise that the method presented in this chapter can be applied successfully.

3.2 Motivation

DSM2 is generally run in one of three modes: historical, planning, or real-time forecasting. For historical models, the location of the DSM2 downstream boundary conditions at Martinez is adequate for the periods in which observed data at Martinez is available.

Planning studies, however, are the most frequent studies for which DSM2 is used. Planning studies are simulations based on the historical hydrology and infrastructure that are modified to reflect a specific level of development. Planning studies are used to evaluate the effects of proposed changes to regulatory constraints or the physical system (e.g., new facilities). As such, historical data cannot be used directly, and tidal and salinity boundary conditions at Martinez must be determined prior to running DSM2.

Methods for estimating Martinez boundary conditions have been developed and are used for planning studies. Martinez boundary-condition values are calculated using Delta inflows from planning models, such as CalSim II, which is an operations planning model of the State Water Project (SWP) and the Central Valley Project (CVP), combined with empirical or semi-empirical methods (Anderson and Miller 2005; Ateljevich 2001a, 2001b).

In the case of real-time forecasting, a mixture of recently observed data, forecasted tides based on astronomical tides, and a model of the residual tides are used to predict short-term tides at Martinez (Ateljevich 2000).

Consequently, when a large influx of ocean water is expected and/or the area of interest is close enough to Martinez to influence the boundary values, the boundary condition location at Martinez becomes less than ideal for planning studies. An example of such a study, *Long-Term Salinity Impacts from Permanently Flooding Delta Islands* (Ferreira and Anderson 2013), which has received much attention recently, is the evaluation of the salinity impacts of long-term flooding of Delta islands. Under such circumstances, a large volume of ocean water is expected to be quickly drawn into the Delta and flood the islands, most of which are several feet below mean sea level. Another example of a study that needs an extended boundary is a sea level rise study, which takes into consideration the changes in sea level rise from the ocean as water moves through San Francisco Bay and into the Delta. When the boundary location at Martinez is unsuitable, an extended grid version of DSM2 could provide another tool for these types of studies. Note that the extended grid is intended to represent the volume of water and salt transported from the Golden Gate to Martinez and is not intended to be a detailed model of San Francisco Bay. Because tides at Golden Gate are predominantly astronomical (Ateljevich 2001a), and salinity is relatively constant with small seasonal variation (Walters et al. 1985), Golden Gate is a better location for a downstream boundary. The placing of a DSM2 downstream boundary condition at Golden Gate would allow for a greater variety of studies to be performed. While it is true that the water-surface elevation at San Francisco Bay is affected by the outflow from the Bay-Delta Estuary, this is generally the case when outflows from the Bay-Delta are extremely high. In such occasions, salinity intrusion in the Delta is not a concern.

Given that the extra computational cost is not an issue for using DSM2, one of the main reasons for keeping the boundary at Martinez is that a one-dimensional grid is not considered to be well-suited to

simulate the hydrodynamics and transport within the bays between the Carquinez Strait and the Pacific Ocean.

Accordingly, one of the challenges of moving the DSM2 downstream boundary from Martinez to the ocean is that DSM2 is a one-dimensional model. While the Delta with its intricate network of braided channels, can be successfully modeled for most studies with a one-dimensional model, the regions downstream of Martinez consist of large bays (San Pablo and Central San Francisco bays), which are typically modelled with two- or three-dimensional models.

Nonetheless, the advent and power of a geographic information system (GIS) and the associated geographical data and geoprocessing tools allow us to represent the physical system with an exceptional level of detail and accuracy. Additionally, the calibration of SCHISM (Semi-implicit Cross-scale Hydroscience Integrated System Model), a 3-dimensional hydrodynamic model of the Bay-Delta (previously called Bay-Delta SELFE) developed by the Bay-Delta Office (Ateljevich 2014), has provided a wealth of data that we can use to understand circulation and salt transport and, more importantly, calibrate the extended grid DSM2 model (Ateljevich et al. 2014). Furthermore, the well-established parameter estimation software PEST can also be used to calibrate the extended grid of DSM2.

It is this wealth of data and tools that we exploit to investigate the possibility of extending the DSM2 grid from Martinez to the Golden Gate by representing the embayments west of Martinez as a network of channels and, in doing so, translate, in run-time, the tides and salinity from Golden Gate to the traditional DSM2 boundary at Martinez. Preliminary results are encouraging.

It is important to note that the main goal of this project is to find an efficient way of translating the ocean tides and salinity to Martinez using DSM 2. For this reason, the calibration will focus on water levels and salinity at Martinez and not at the San Francisco Bay region west of Martinez.

This chapter describes current efforts in extending the DSM2 western boundary to the Golden Gate by using GIS and ArcMap. The methodology and some preliminary results of the investigation into the suitability of extending the DSM2 grid from Martinez to the Golden Gate with a one-dimensional grid by using detailed GIS data are presented below.

3.3 Methodology

In the first phase of this project, a lattice grid was created for the San Pablo and Central San Francisco bays. Some of the larger coves and bays along the connection between the San Pablo and Central San Francisco bays and on the eastern edges of the Central San Francisco Bay are modeled as reservoirs, while the South Bay is currently represented as a single reservoir. Figure 3-2 shows the extended grid as configured at the time of this writing.

Light Detection And Ranging (LiDAR) data was utilized to prepare a Digital Elevation Model (DEM) of the Delta and the San Francisco region (Wang and Ateljevich 2012) resulting in a very detailed characterization of the geometry of the region (Figure 3-3). This data, in conjunction with the geoprocessing software and ArcGIS tools, has enabled a very accurate calculation of volume between Martinez and the Golden Gate and is described below.

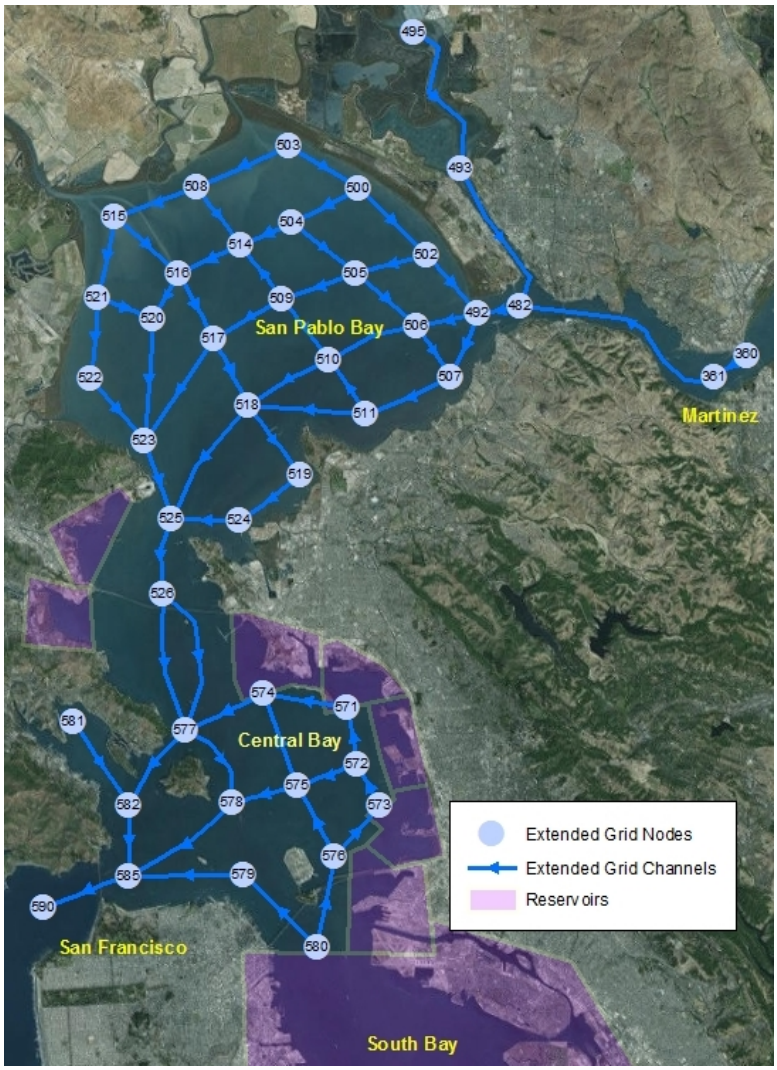


Figure 3-2 DSM2 Grid Extension from Martinez to San Francisco

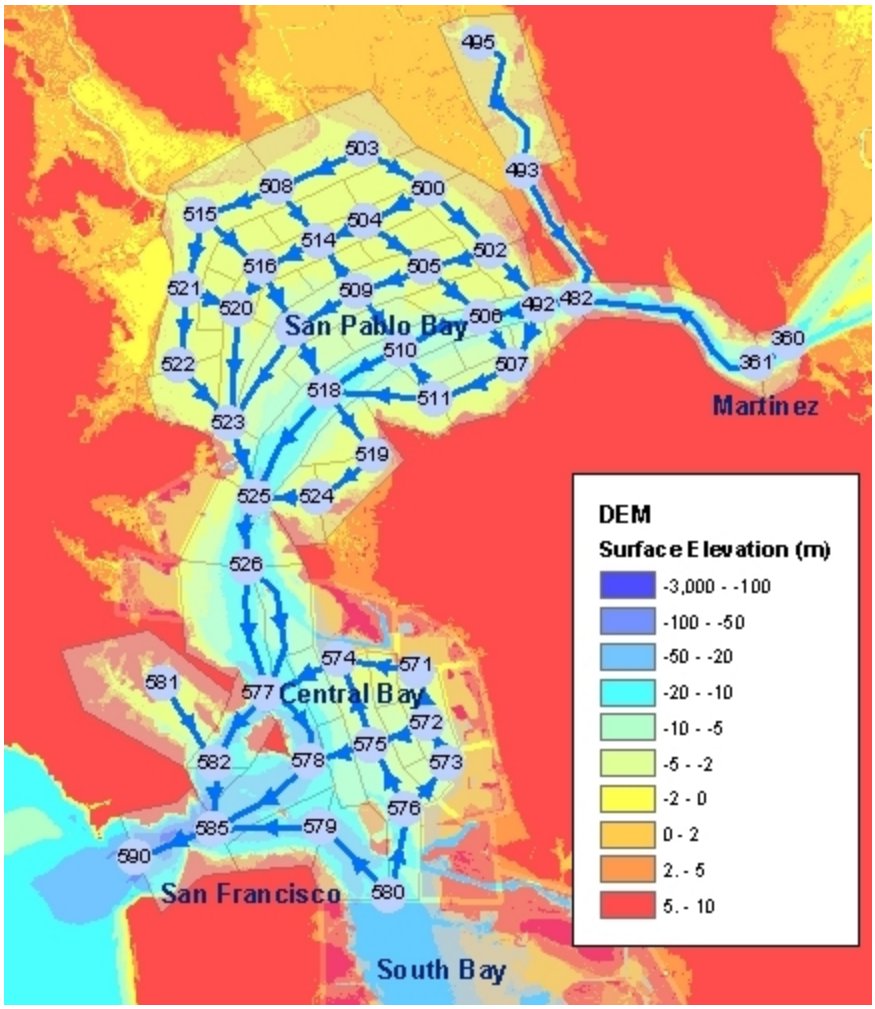


Figure 3-3 Extension Grid showing DEM and "Channel Top Areas"

3.4 Geoprocessing Computations

Extended grid channel reaches and nodes were digitized in ArcMap. Also digitized in ArcMap were the horizontal plane areas, "channel top areas," which are associated with each channel and the cross-section lines. This digitized data was applied to a Python script, which was developed to perform all the necessary geoprocessing computations, which rely heavily on ArcMap geoprocessing tools. Additional computations and code were used to prepare the resulting DSM2 input files.

3.4.1 Cross-Section Profiles

Also computed from the DEM are cross-section profiles for each channel. Each channel has a minimum of two cross sections with additional cross sections added as needed to capture variations in channel width and bathymetry. Cross-sections coordinates are established by intersecting the vertical plane containing the cross-section line with the DEM. Cross-section coordinates from ArcMap are subsequently converted to the required DSM2 format of the channel input file, that is, for each cross section, at various elevations, the associated channel width, flow area, and wetted perimeter are computed and printed to a text file as required by DSM2. Figure 3-4 shows the cross-section coordinate plots for two example cross sections, one at the western end of the Carquinez Strait and the other in San Pablo Bay.

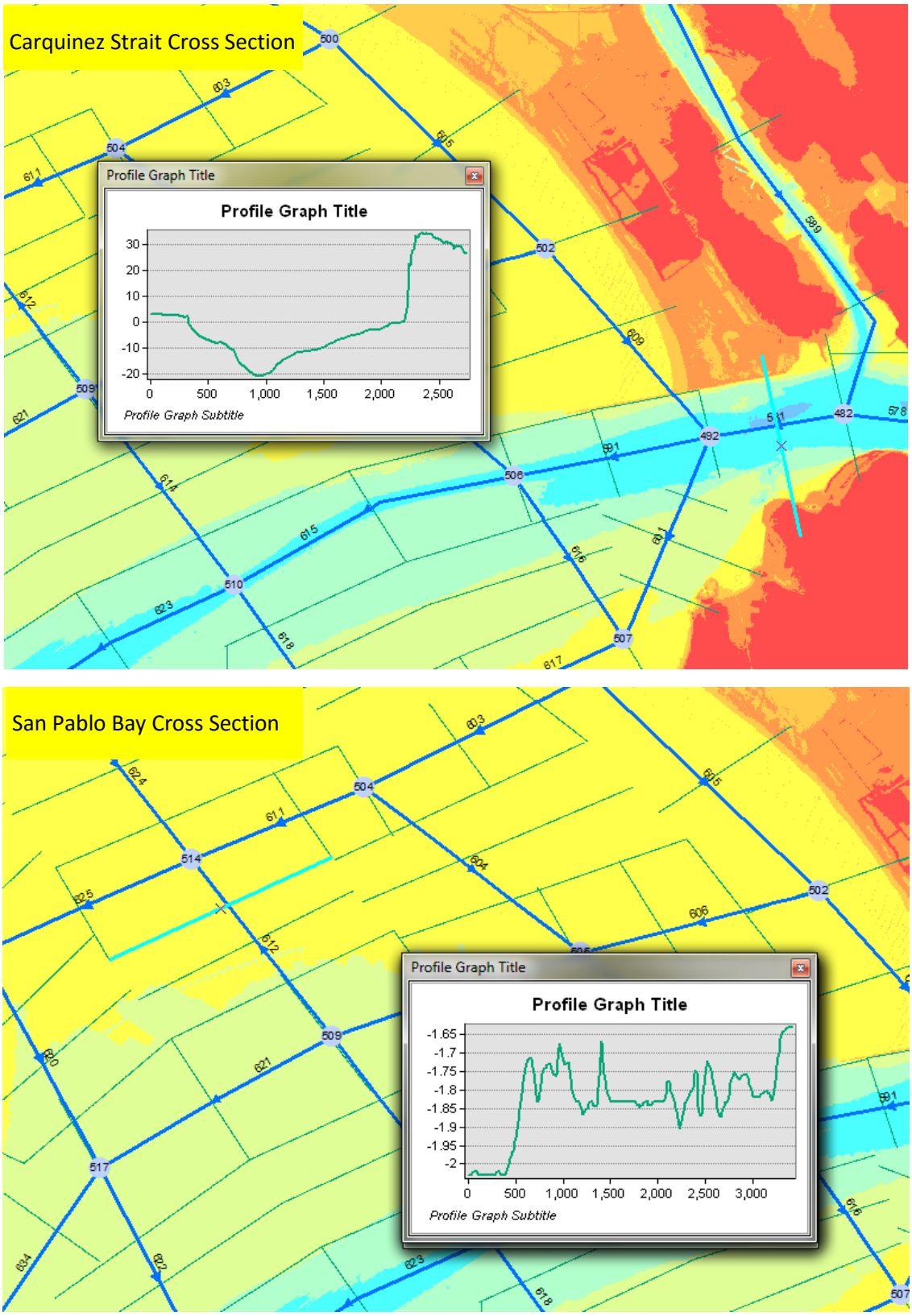


Figure 3-4 Extension Grid Highlighting Cross Sections and Computed Cross-section Profiles Coordinates

3.4.2 Channel Volume

The volume for each channel reach was calculated as the volume between the "channel top area" and the DEM underneath it. Figure 3-5 shows a portion of a "channelized" San Pablo Bay with a few "channel top areas," which are highlighted. This volume is then compared to an estimation of what DSM2 might "see" as volume for each channel, which is calculated as the average of two consecutive cross-sectional areas multiplied by the longitudinal distance between the cross sections. If the relative difference between these two values is greater than 10 percent, the channel length input in DSM2 is modified to maintain the relative difference within 10 percent, thereby keeping the channel reach volume in DSM2 close to the more accurate volume obtained through geoprocessing. Most of the channel length modifications occurred for cross channels, which are those channels that run transverse to the main flowlines parallel to the main channel (thalweg) and for "channel top areas," which diverge from a desired mostly rectangular shape, which is not always possible. Because the bays are not rectangular and because the polygons representing the "channel top areas" must tessellate (i.e., must fit together without gaps or overlap), not all "channel top areas" are rectangular.

3.4.3 Reservoir Surface Area and Bottom Elevation

Reservoir volumes are calculated in the same way as channel reach volumes are calculated. In DSM2, reservoirs are modeled as prisms, that is, uniform bottom elevation and constant surface area with depth. And so, fully defining a reservoir in DSM2 requires surface area and average bottom elevation. Once again, Arc GIS geoprocessing tools are used to calculate these values.

Reservoir connections to network nodes are calculated using the reservoir connection formulas.

$$Q = C_{to}\sqrt{2g(z_{node} - z_{res})}\ for\ z_{res} < z_{node}. \quad (1)$$

$$Q = C_{from}\sqrt{2g(z_{res} - z_{node})}\ for\ z_{res} > z_{node}. \quad (2)$$

Where

- C_{to} and C_{from} are coefficients representing the hydraulic efficiency of the reservoir connection and the nominal area perpendicular to flow, which are estimated through calibration,
- g is gravity,
- z_{res} and z_{node} are the water surface elevations at the reservoir and connecting node (see http://baydeltaoffice.water.ca.gov/modeling/deltamodeling/models/dsm2/reference/reservoir.html).

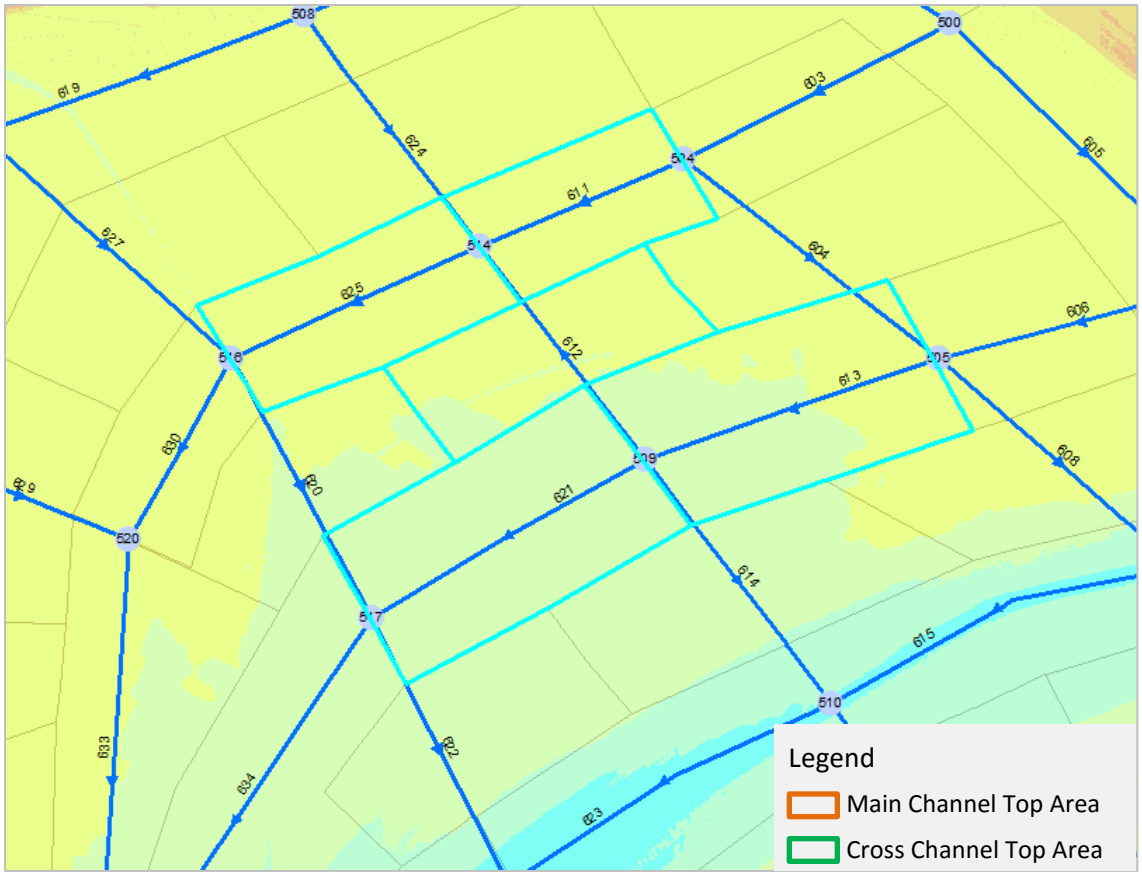


Figure 3-5 Detail of Extension Grid Highlighting "Channel Top Areas"

3.4.4 Calibration

In the first phase of this project, we attempted to translate the tide from the Golden Gate to Martinez. Accordingly, we worked with only the hydrodynamic module of DSM2, which is DSM2-Hydro. Once DSM2-Hydro successfully reproduces the stage at Martinez, we will calibrate the entire DSM2 model (both DSM2-Hydro and DSM2-Qual) to simulate both hydrodynamics and salt transport from the ocean to Martinez.

For DSM2-Hydro calibration, we focused on modifying Manning's n and reservoir coefficients. The procedure was completed using PEST, a parameter estimation software package (Doherty 2010). The DSM2 simulated stage at all extended grid nodes and reservoirs are compared to stage obtained from a historical model of the Bay-Delta by using SCHISM.

3.5 Preliminary Results and Next Steps

Results of a preliminary DSM2-Hydro calibration with PEST are encouraging. Figure 3-6 shows the comparison of stage at selected locations in the extended grid from the Golden Gate to Martinez and stage in the DSM2 reservoirs, which represent parts of San Francisco and San Pablo bays. DSM2 was run June 20, 2008–August 2, 2009. The SCHISM operation used to provide "observed" data was April 1, 2009–July 24, 2010. The calibration period was July 2009.

The charts in Figure 3-7 show a very good water-surface elevation match between SCHISM and Extended Grid Hydro (DSM2), particularly considering that we are in the initial stages of calibrating the extended grid model. The relatively small difference between SCHISM and the Extended Grid Hydro is encouraging, indicating that this approach might be viable.

To complete this first phase of this investigation, we will continue calibrating Hydro using PEST, perhaps extending the calibration period to more than one month.

The next stage of this investigation will be to calibrate the extended grid for DSM2-Hydro and DSM2-Qual, followed by a validation of the calibrated model.

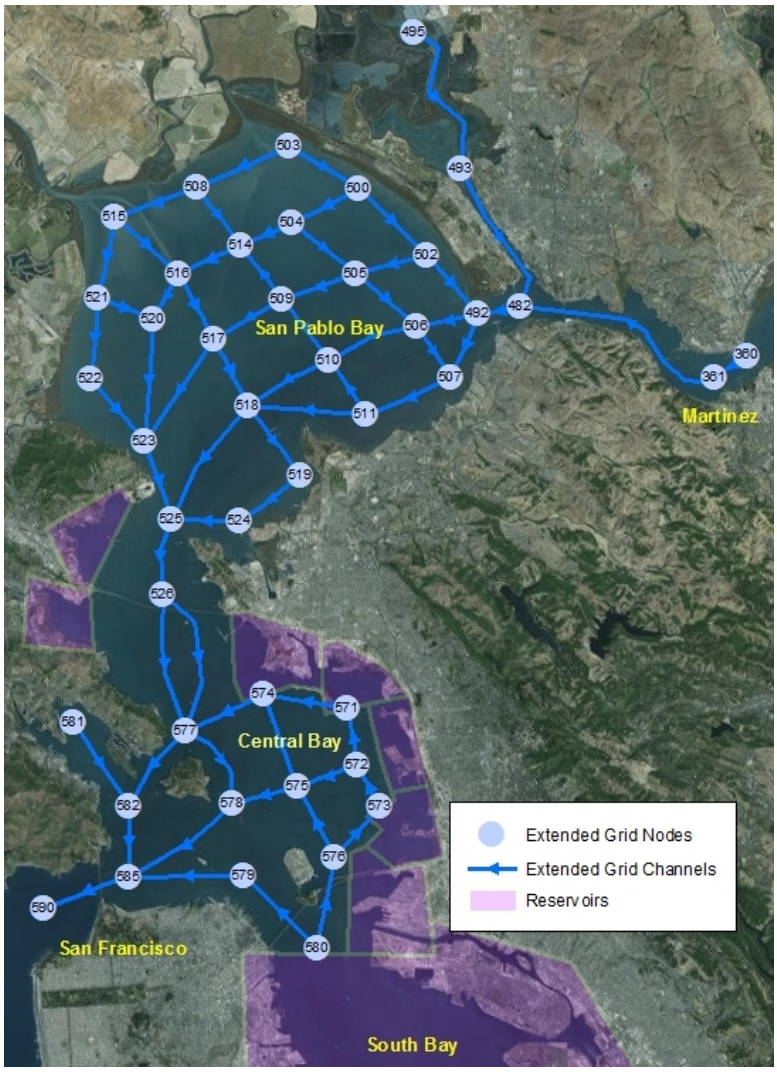
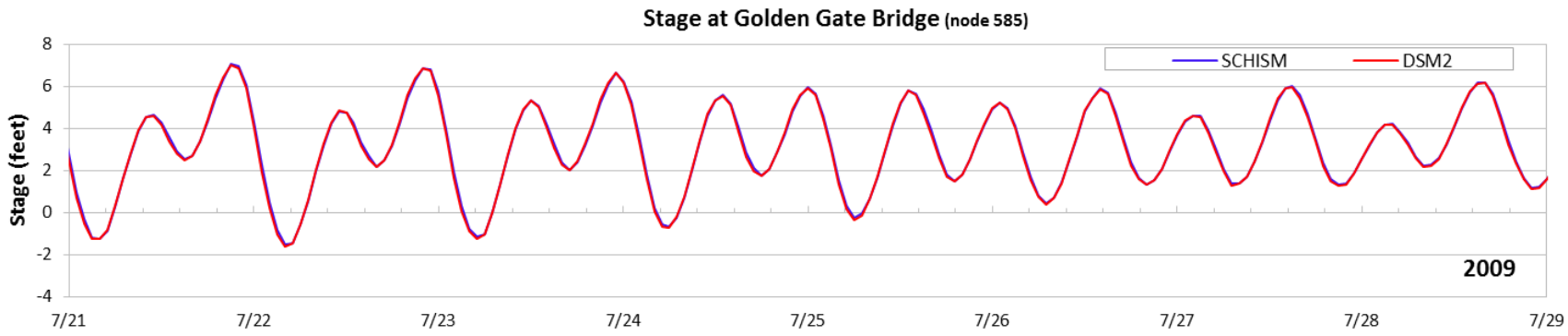
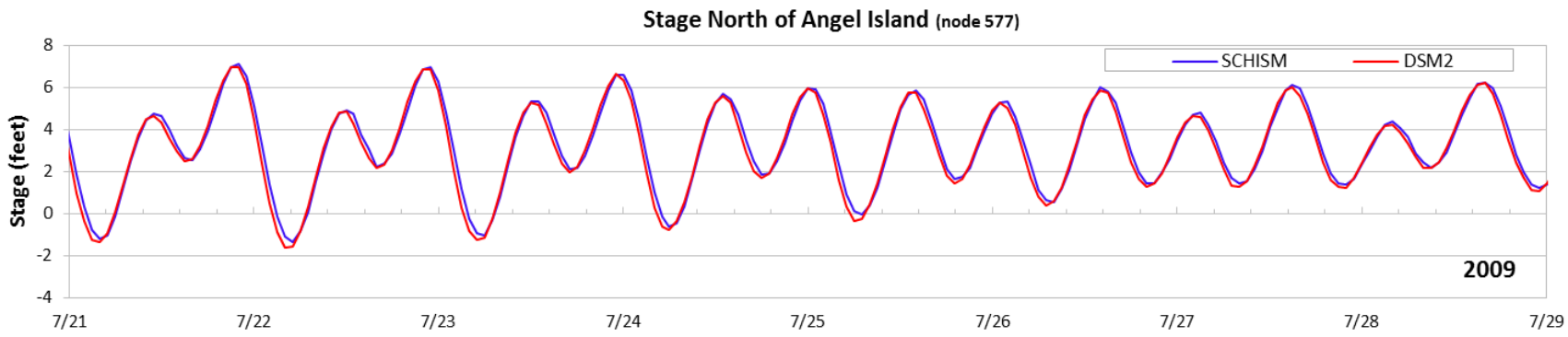
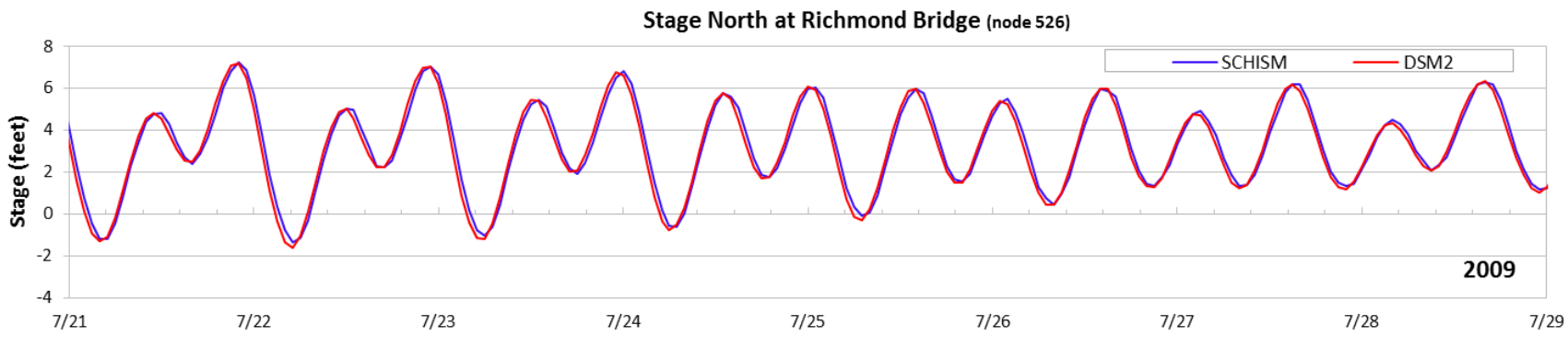
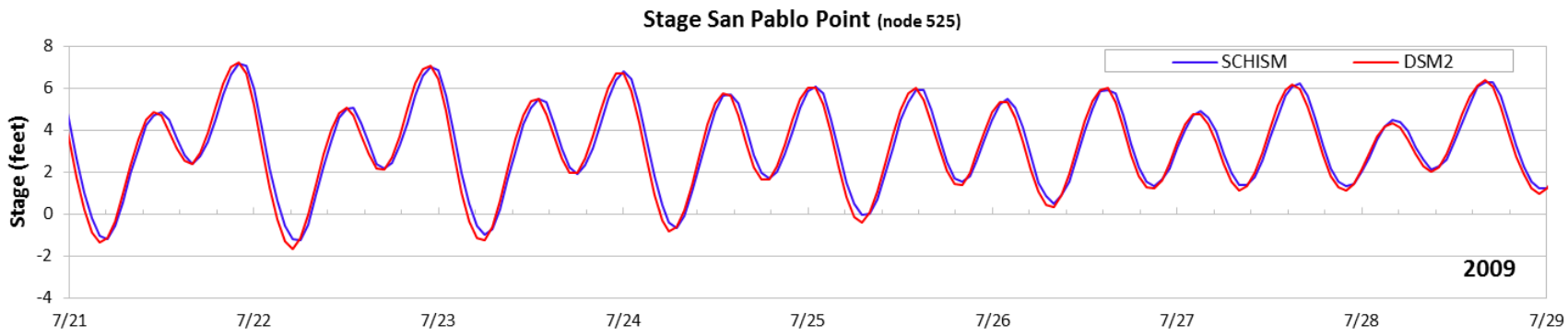


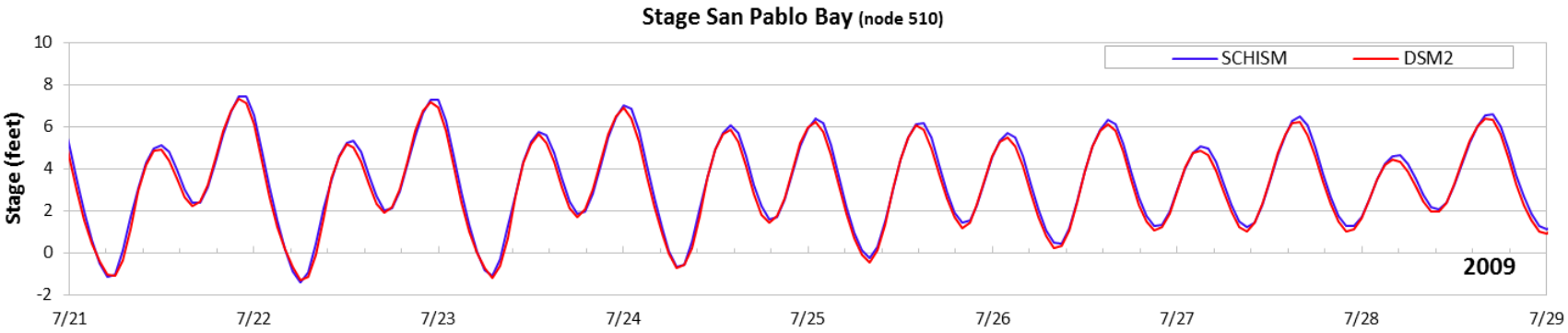
Figure 3-6 DSM2 Grid Extension Output Node Locations for Figure 3-7

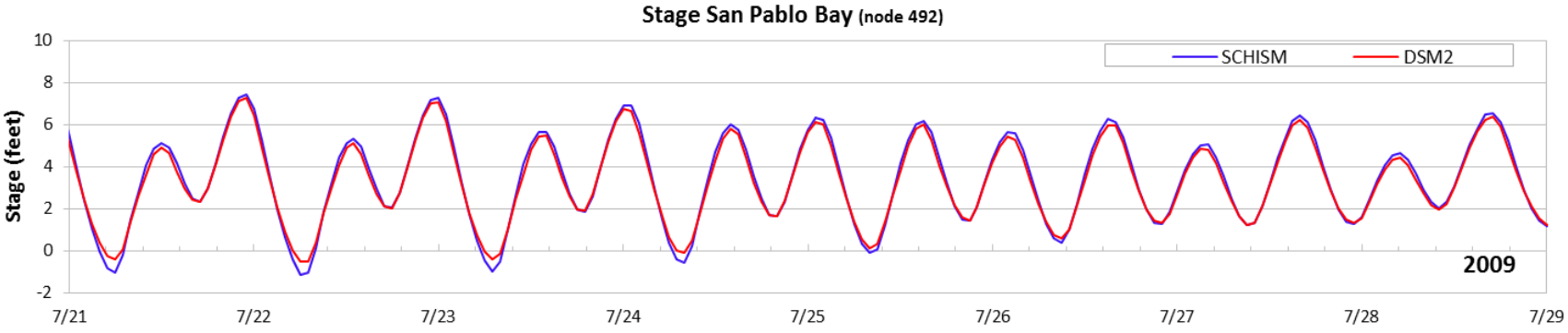

Stage at Golden Gate Bridge (node 585)
SCHISM
DSM2
Stage (feet)
8
6
4
2
0
-2
-4
2009
7/21
7/22
7/23
7/24
7/25
7/26
7/27
7/28
7/29

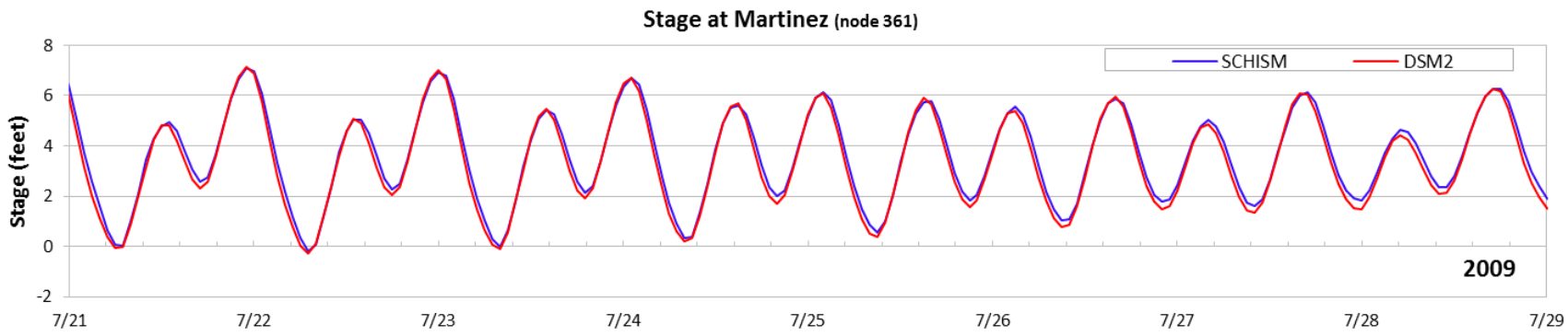

Stage North of Angel Island (node 577)
SCHISM
DSM2
Stage (feet)
8
6
4
2
0
-2
-4
2009
7/21
7/22
7/23
7/24
7/25
7/26
7/27
7/28
7/29

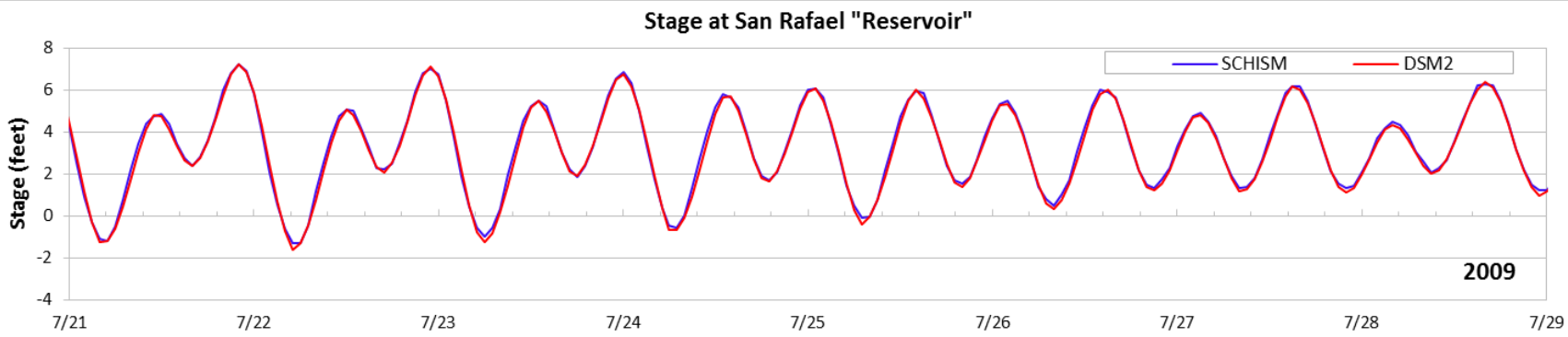

Stage North at Richmond Bridge (node 526)
SCHISM
DSM2
Stage (feet)
8
6
4
2
0
-2
-4
2009
7/21
7/22
7/23
7/24
7/25
7/26
7/27
7/28
7/29

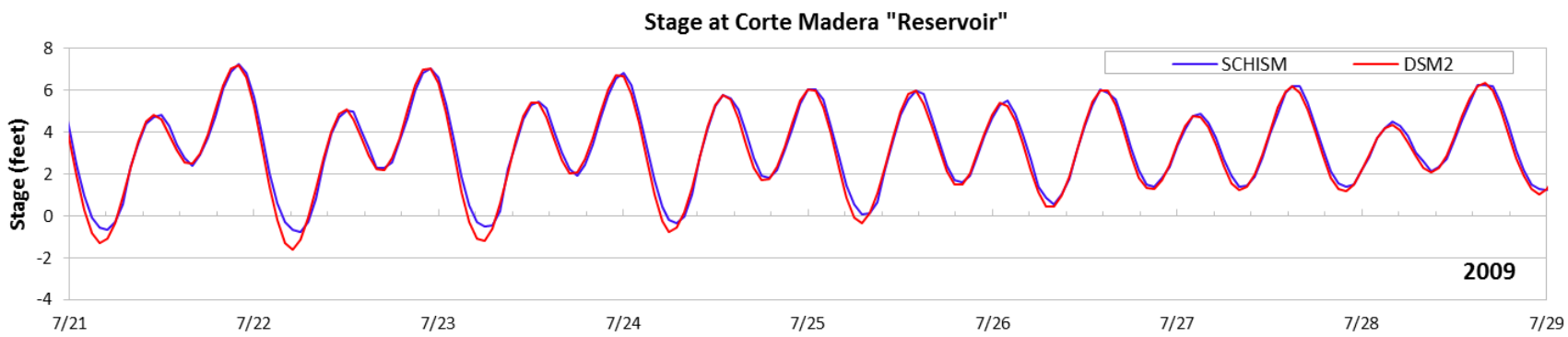

Stage San Pablo Point (node 525)
SCHISM
DSM2
Stage (feet)
8
6
4
2
0
-2
-4
2009
7/21
7/22
7/23
7/24
7/25
7/26
7/27
7/28
7/29

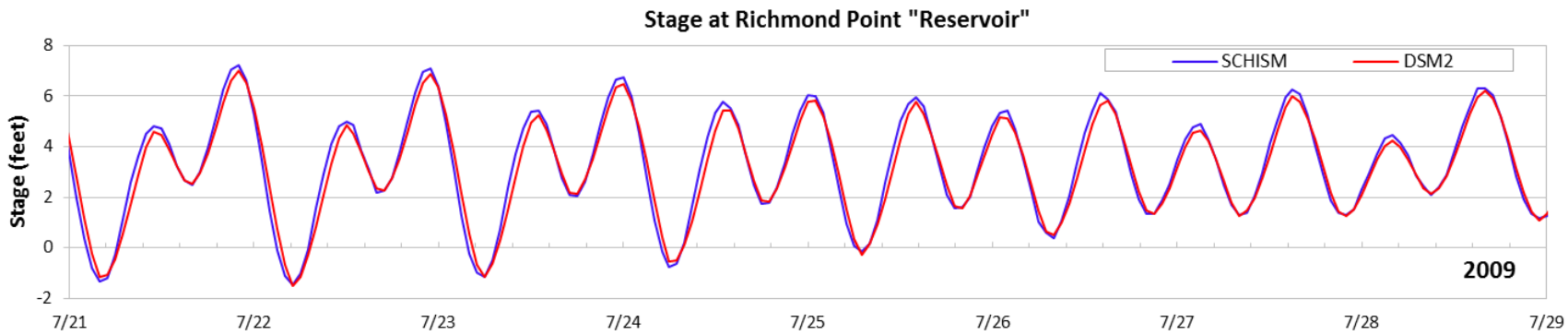

Stage San Pablo Bay (node 510)
SCHISM
DSM2
Stage (feet)
10
8
6
4
2
0
-2
2009
7/21
7/22
7/23
7/24
7/25
7/26
7/27
7/28
7/29

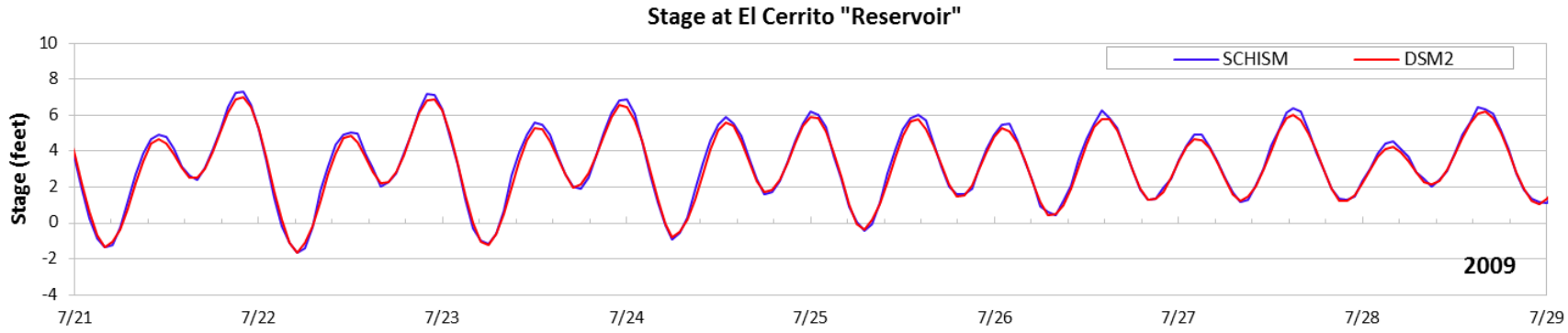

Stage San Pablo Bay (node 492)
SCHISM
DSM2
Stage (feet)
10
8
6
4
2
0
-2
2009
7/21
7/22
7/23
7/24
7/25
7/26
7/27
7/28
7/29

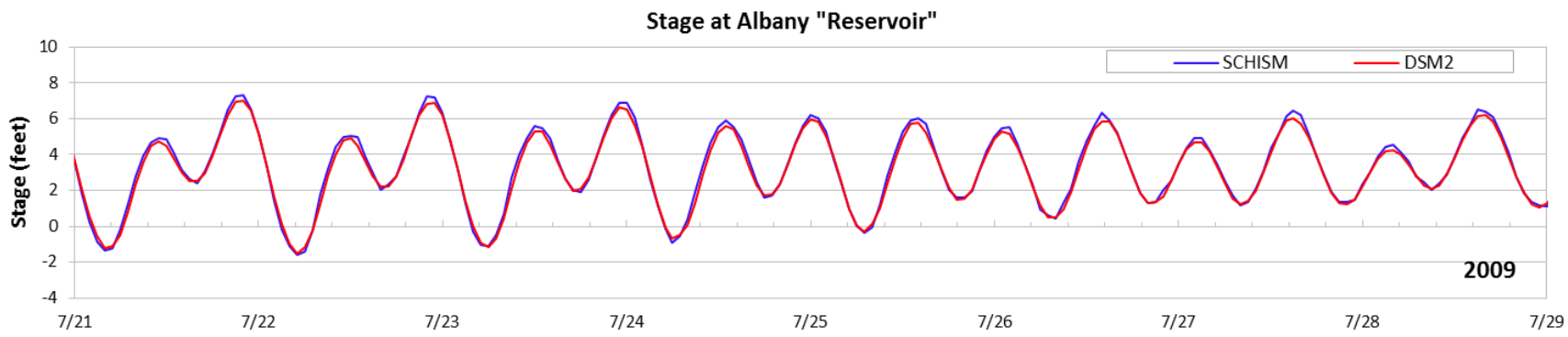

Stage at Martinez (node 361)
SCHISM
DSM2
Stage (feet)
8
6
4
2
0
-2
2009
7/21
7/22
7/23
7/24
7/25
7/26
7/27
7/28
7/29


Stage at San Rafael "Reservoir"
SCHISM
DSM2
Stage (feet)
8
6
4
2
0
-2
-4
2009
7/21
7/22
7/23
7/24
7/25
7/26
7/27
7/28
7/29


Stage at Corte Madera "Reservoir"
SCHISM
DSM2
Stage (feet)
8
6
4
2
0
-2
-4
2009
7/21
7/22
7/23
7/24
7/25
7/26
7/27
7/28
7/29


Stage at Richmond Point "Reservoir"
SCHISM
DSM2
Stage (feet)
8
6
4
2
0
-2
2009
7/21
7/22
7/23
7/24
7/25
7/26
7/27
7/28
7/29


Stage at El Cerrito "Reservoir"
SCHISM
DSM2
Stage (feet)
10
8
6
4
2
0
-2
-4
2009
7/21
7/22
7/23
7/24
7/25
7/26
7/27
7/28
7/29


Stage at Albany "Reservoir"
SCHISM
DSM2
Stage (feet)
10
8
6
4
2
0
-2
-4
2009
7/21
7/22
7/23
7/24
7/25
7/26
7/27
7/28
7/29

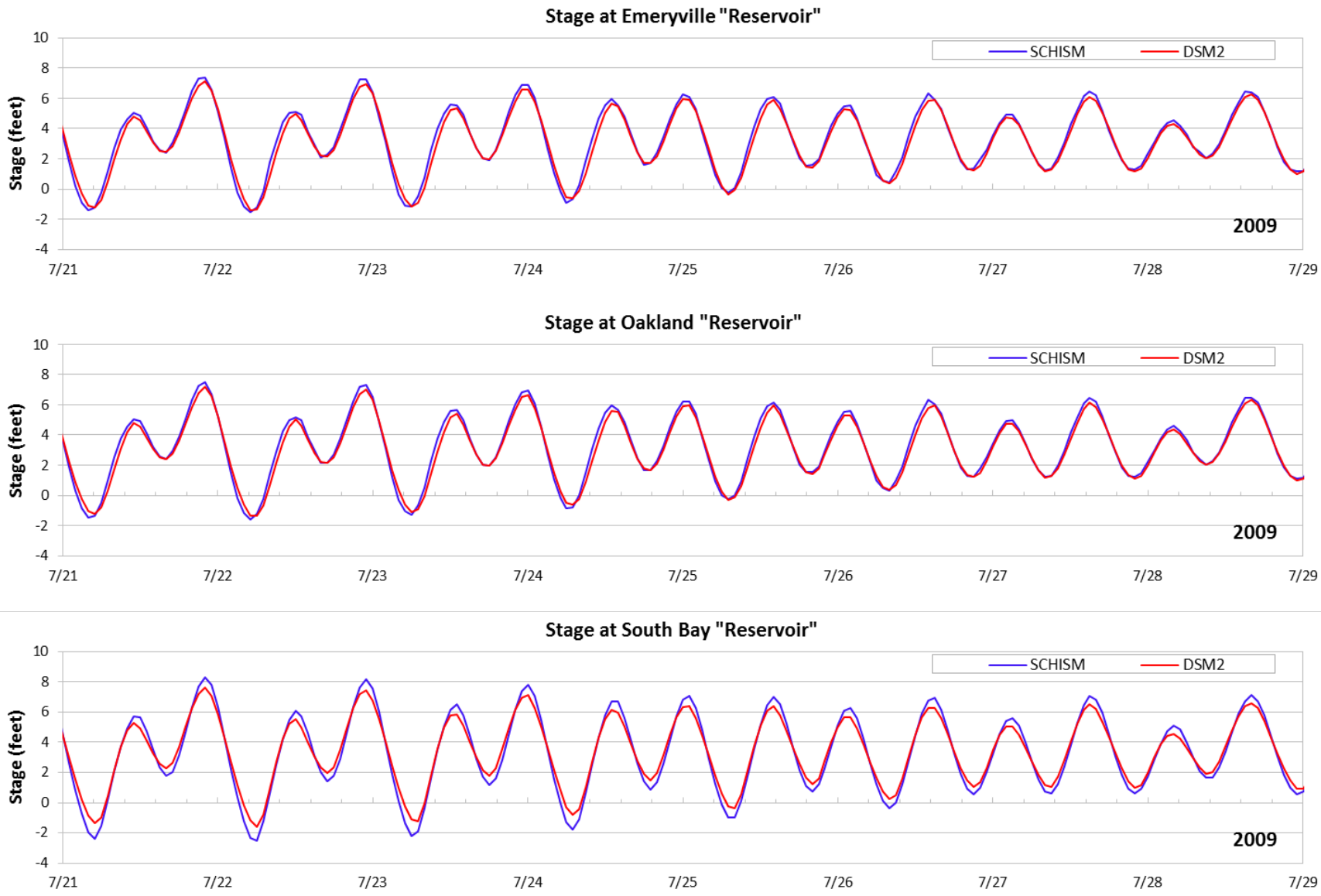


Figure 3-7 Stage Comparison at Different Locations in Extended Grid

3.6 References

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

37th Annual Progress Report
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Chapter 4
Delta Salinity Simulation with DSM2-GTM

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DEPARTMENT OF WATER RESOURCES

STATE OF CALIFORNIA

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4 Delta Salinity Simulation with DSM2-GTM

4.1 Introduction

The California Department of Water Resources' Delta Modeling Section is developing a new DSM2 transport module, called the General Transport Model (DSM2-GTM). Progress on this effort was previously reported in Hsu et al. (2014). DSM2-GTM employs a fixed (Eulerian) mesh rather than one that moves with flow and follows virtual parcels of water in a Lagrangian scheme. The fixed grid will make it easier for this model to interact with other models, georeferenced data, data assimilation, optimization, and visualization as well as to couple inline to DSM2-HYDRO. It is also more straightforward to extend the new model to new physical processes with sediment, dissolved oxygen, and mercury cycling models that are currently being developed. Because of its extensibility, DSM2-GTM is expected to replace DSM2-QUAL.

Ateljevich et al. (2011) developed a prototype algorithm that includes a second-order two-step upwind method with a predictor-corrector operator-splitting approach. This is the algorithm employed for DSM2-GTM. Ateljevich et al. (2011) tested the algorithm with uniform, reversing, and synthetic tidal flows for single-channel problems of increasing complexity in terms of nonlinearity and spatial variation of parameters. They established that this algorithm integrates the transport equations with minimum numerical diffusion, and they also verified formal convergence properties of the scheme.

To extend the work to field-scale Delta problems and hydrodynamic data, changes were made to accommodate flow on a network of channels with varying cell size in different reaches to present an understandable interface and to improve the linkages with the DSM2-HYDRO model. To make the user transition from DSM2-QUAL to DSM2-GTM simpler, we intentionally imitated the input interface from DSM2-QUAL as closely as possible. The extra parameters, which have to be specified in DSM2-GTM, are requested cell size (dx) to generate the DSM2-GTM grid and time step (dt) to serve as the master time step for simulation. We modified the DSM2-HYDRO tidefile format used to transfer flow fields from DSM2-HYDRO to DSM2-GTM to improve its temporal and spatial resolution. (See Hsu et al. [2014] for details.) DSM2-QUAL dispersion coefficients are reusable in DSM2-GTM without change of scale; they depend on velocity and consequently have an interpretation that is slightly different from the classic constant dispersion factor (e.g., Fischer et al. 1979). This point is addressed in more detail in Liu and Ateljevich (2011). The translation between DSM2-QUAL and DSM2-GTM coefficients and classic dispersion coefficients is described in section 4.4.3.

Presently, DSM2-GTM produces results that are very consistent with DSM2-QUAL, which is an important initial milestone that allows us to release the model. We hope the adoption of the new model will be driven by a rapidly expanding toolset for analysis and by the emerging sediment and dissolved oxygen models.

4.2 Eulerian One-Dimensional Transport Scheme along a Channel Reach

In a collaborative project with University of California, Davis, Ateljevich et al. (2011) developed a second-order upwind one-dimensional Eulerian model of advection, dispersion, and reactions or sources. The advective-diffusive part of model describes basic conservative transport, and the generalized reaction term can be tailored to non-conservative water quality kinetics, including sediment transport.

The important mixing process in 1D channels is shear *dispersion* (see Fischer el al. 1979). On the other hand, in terms of the formulation, dispersion is usually represented by the so-called *diffusion analogy* so that when we talk about the partial differential equation, we use the terms *diffusion* and *advective-diffusion*. The term *numerical diffusion* refers to the spreading and dampening of the real solution

because the numerical method technically is a kind of error. But if it is modest compared with physical mixing, practitioners can absorb it into the dispersion parameters as part of calibration.

In conservative form, these are the equations.

$$\underbrace{\frac{\partial(A(x,t)C(x,t))}{\partial t}}_{\text{Time evolution}} + \underbrace{\frac{\partial(Q(x,t)C(x,t))}{\partial x}}_{\text{Advection}} = \underbrace{\frac{\partial}{\partial x}\left(A(x,t)K(x,t)\frac{\partial C(x,t)}{\partial x}\right)}_{\text{Dispersion}} + \underbrace{A(x,t)S\big(x,t,C(x,t)\big)}_{\text{Source/Reaction}} \qquad (1)$$

where

x is distance along the channel,

t is time,

A is the cross-sectional area,

C is the scalar concentration,

Q is the flow,

K is the longitudinal dispersion coefficient modeled using the diffusion analogy,

S is the source or reaction term (deposition, erosion, lateral inflow, and other forms of sources and sinks) per unit area of a cross-section.

Eq. (1) describes the mass conservation of a pollutant in dissolved phase or suspended sediment away from the streambed. Boundary conditions will be discussed in sections 4.2.4 and 4.3.4.

A software testing framework was also developed for verifying the required accuracy of this solver over an incrementally more complex set of 1D flows, geometry, spatially varying-mixing parameters, and combinations of operators. The testing objective was to verify second-order accuracy, or be close to it, in both time and space on nonlinear problems, anticipating some degradation with more involved boundary conditions or over complex geometry.

An operator splitting-like approach was adopted for the solution, meaning that the advection, reaction, and dispersion processes are integrated sequentially in a specially orchestrated predictor-corrector sequence. The sequence is shown in Figure 4-1. The nature of the problem and the importance of the conservation of mass strongly suggested employing a Finite Volume Method (FVM). The algorithms employed for DSM2-GTM include a second-order two-step unwinding method with a van Leer slope limiter for advection, Heun's method for reaction, and then a final update including dispersion using a semi-implicit time discretization consistent with the Crank-Nicolson method. Although we use the term *operator splitting*, note that there is no succession of concentration updates, which is typical of fractional step methods like those used in DSM2-QUAL. Rather, we always considered all three sequences together, but we worked on advection first, reaction second, and finally on diffusion. This helped us avoid some of the pitfalls of traditional splitting methods, particularly at the boundary.

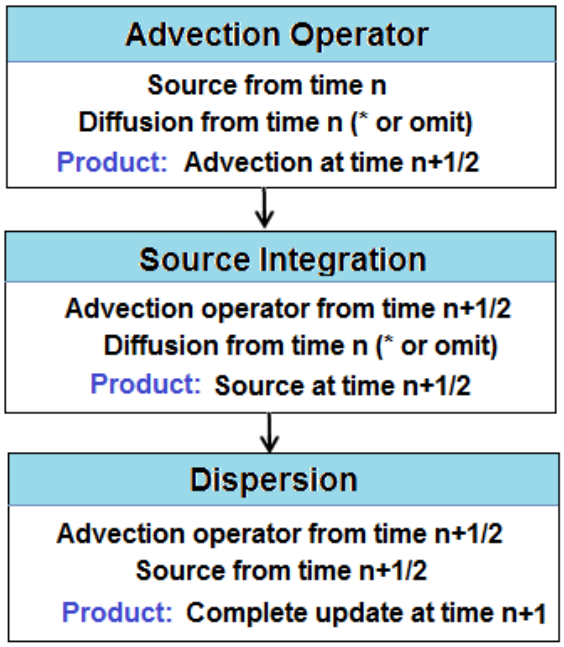


Figure 4-1 Illustration of the Sequence for Operator Splitting

4.2.1 Advection: Two-Step Lax-Wendroff Method

The Lax-Wendroff method is a numerical method for the solution of advection equations based on finite differences or volumes. It is second-order accurate in both space and time. The first predictor step calculates values at half-time step (*n+½)* and half-spatial step ($i \pm ½$). This location represents the face between computational cells in the model. Two estimates are produced for each face, one from the perspective of the cell on each side. In the second step, the upwind flux is selected from each face, and the fluxes in and out of each cell are differentiated to form the flux divergence or the net change because of advection in and out. This dual-face concept is illustrated in Figure 4-2.

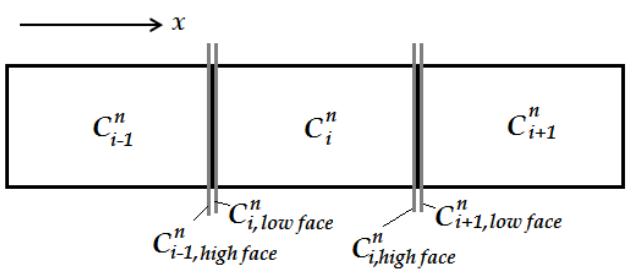


Figure 4-2 Illustration of Discretization for the Lax-Wendroff Method

The predictor step begins by estimating the concentration at the high- and low-side cell faces at the half-time step by using a Taylor expansion around the cell center.

$$C^{n+1/2}_{i\pm1/2} = C^n_i \pm \frac{\partial C^n_i}{\partial x}\frac{\Delta x}{2} + \frac{\partial C^n_i}{\partial t}\frac{\Delta t}{2} \qquad (2)$$

From Eq. (1), $\partial C/\partial t$ can be presented as

$$\frac{\partial C}{\partial t} = -\frac{Q}{A}\frac{\partial C}{\partial x} + \frac{1}{A}D^n + S^n \qquad (3)$$

where

D^ndenotes the explicit central difference discretization of the dispersion term in Eq. (1),

S^n is the source term evaluated at the old time step.

Substituting $\partial C/\partial t$, we can rewrite Eq. (2) as

$$C_{i\pm 1/2}^{n+1/2} = C_i^n + \frac{1}{2}\left(\pm 1 - \frac{\Delta t}{\Delta x_i}\frac{Q}{A}\right)\Delta C_i^n + \frac{\Delta t}{2A}(D_i^n) + \frac{\Delta t}{2}S_i^n \qquad (4)$$

The change of concentration ΔC_i^n is estimated based on the concentration from the adjacent cells *i-1*, *i,* and *i+1* (Figure 4-2) with a second-order flux limiter $D(C_{limited})_i^n$ to avoid local overshoot from the second-order numerical scheme.

$$\Delta C_i^n = \frac{\partial C}{\partial x}\Delta x = D(C_{limited})_i^n \cdot \Delta x_i \qquad (5)$$

We use generalizations of popular slope limiters applicable to our scheme and irregular spatial discretization, such as those studied by Berger et al. (2005). We used the total variation diminish (TVD) limiter in Berger et al. (2005), which gave a good balance between protection from oscillation and overshoot and dampening of the solution in our experiments. The gradients on the boundaries are approximated by one-sided differences with no limiting.

In our ultimate implementation, we currently dropped the explicit dispersion (D_i^n) from the predictor step. The presence of this operator rarely increased accuracy and seemed to be more sensitive to things like the mesh Peclet number, which is the ratio of advection to dispersion strength.

The prior step produces two estimates at each face, one from the cell above and one from the cell below. The “tie” is broken by choosing the estimate from the more-upwind cell according to the local velocity into the face. Once fluxes are determined at faces, the next step is to obtain a guess for the advection operator at time (*n+1*) by using the extrapolated concentrations at half-time and half-space.

$$\left.\frac{\partial (QC)}{\partial x}\right|_i^{n+\frac{1}{2}} \cong \frac{QC_{i+\frac{1}{2}}^{n+\frac{1}{2}} - QC_{i-\frac{1}{2}}^{n+\frac{1}{2}}}{\Delta x_i} \qquad (6)$$

The advection solver requires (or will accept) only a single boundary condition, and it will use the boundary condition only where there is inflow, which may change over time at a tidal boundary. The solver has been tested with Dirichlet (known concentration) boundary conditions. When the concentration at the boundary is known, it is swapped into Eq. (6), leading to a very straightforward calculation of the advective flux into the model.

4.2.2 Reaction: Huen's Method

The next term to be integrated is reaction. A reaction, or source term, could represent decay, interactions between constituents, or sediment suspension. It could also be used to model tributary flow, although we presently do not use it in this way.

Huen's method is used to integrate the source term. In this case, the source term is first calculated at the old time step, and a predictor update is carried out to advance the state variables (concentrations or mass) to the next time step.

$$\overline{AC_i^{n+1}} = AC_i^n - \Delta t \cdot \frac{QC_{i+\frac{1}{2}}^{n+\frac{1}{2}} - QC_{i-\frac{1}{2}}^{n+\frac{1}{2}}}{\Delta x} + \Delta t \cdot D_i^n + \Delta t \cdot AS_i^n \qquad (7)$$

Note that in Eq. (7), we used our prior work on advection, but we still used the explicit representation of dispersion (alternatively, we dropped this term as described above). Once estimated concentrations are available at the new time step, a trial source at the new time ($\overline{S}_i^{n+1}$) can be computed and the final source ($S_i^{n+\frac{1}{2}}$) is an average of the old source and the new trial.

$$S_i^{n+\frac{1}{2}} = \frac{S_i^n + \bar{S}_i^{n+1}}{2} \qquad (8)$$

4.2.3 Dispersion, Crank-Nicolson Method

The last step is the dispersion update. For this update, the advection and reaction updates from above are treated as fixed-source terms at the half-time (*f*).

$$f_i^{n+\frac{1}{2}} = -\frac{QC_{i+\frac{1}{2}}^{n+\frac{1}{2}} - QC_{i-\frac{1}{2}}^{n+\frac{1}{2}}}{\Delta x} + \frac{1}{2} \cdot \left[AS_i^n + A\bar{S}_i^{n+1}\right] \qquad (9)$$

The remaining dispersion equation is calculated with the conventional Crank-Nicolson discretization in the FVM framework. It is unconditionally stable.

For this step, Eq.(1) is treated as follows,

$$\frac{\partial(AC)}{\partial t} = \frac{\partial}{\partial x}\left(AK\frac{\partial C}{\partial x}\right) + f \qquad (10)$$

and discretized as follows in Eq. (11),

$$\frac{(AC)_i^{n+1} - (AC)_i^n}{\Delta t} = \frac{\theta \Delta t}{\Delta x_i}\left\{(AK)_{i+1/2}^{n+1}\left(\frac{C_{i+1}^{n+1} - C_i^{n+1}}{\Delta x_{i+1/2}}\right) - (AK)_{i-1/2}^{n+1}\left(\frac{C_i^{n+1} - C_{i-1}^{n+1}}{\Delta x_{i-1/2}}\right)\right\} +$$
$$\frac{(1-\theta)\Delta t}{\Delta x_i}\left\{(AK)_{i+1/2}^{n}\left(\frac{C_{i+1}^{n} - C_i^{n}}{\Delta x_{i+1/2}}\right) - (AK)_{i-1/2}^{n}\left(\frac{C_i^{n} - C_{i-1}^{n}}{\Delta x_{i-1/2}}\right)\right\} + f_i^{n+\frac{1}{2}} \qquad (11)$$

This can be rewritten in matrix form, which contains calculated coefficients, unknown variables, and calculated right-hand-side value, as shown in Eq. (12).

$$\left[-\frac{\theta\Delta t}{\Delta x_i}\frac{(AK)_{i-1/2}^{n+1}}{\Delta x_{i-1/2}} \quad A_i^{n+1}+\frac{\theta\Delta t}{\Delta x_i}\left[\frac{(AK)_{i+1/2}^{n+1}}{\Delta x_{i+1/2}}+\frac{(AK)_{i-1/2}^{n+1}}{\Delta x_{i-1/2}}\right] \quad -\frac{\theta\Delta t}{\Delta x_i}\frac{(AK)_{i+1/2}^{n+1}}{\Delta x_{i+1/2}}\right]\begin{bmatrix}C_{i-1}^{n+1}\\ C_i^{n+1}\\ C_{i+1}^{n+1}\end{bmatrix}$$

$$= (AC)_i^n + f_i^{n+\frac{1}{2}}\cdot\Delta t - \frac{(1-\theta)\Delta t}{\Delta x_i}\left[F_{i+\frac{1}{2}}^n - F_{i+\frac{1}{2}}^n\right] \tag{12}$$

where the diffusive fluxes (*F*) are given by Eq. (13),

$$F_{i+\frac{1}{2}}^n = -(AK)_{i+\frac{1}{2}}^n\left(\frac{C_{i+1}^n - C_i^n}{\Delta x_{i+\frac{1}{2}}}\right) \tag{13}$$

Dispersion requires a boundary condition at each boundary. The dispersion solver has been tested with both Dirichlet (known value) and Neumann (known flux or gradient) boundaries. For Dirichlet boundaries, the gradients are calculated over half of the cell (between its center and edge) rather than over a full cell (between the center and the neighbor's center). Neumann boundary conditions are implemented by preplacing the flux at the boundary face (say $F_{i+\frac{1}{2}}^n$) directly.

4.2.4 Boundaries for the Full System

Eq. (1) admits exactly one stipulated condition (Dirichlet or known value; Neumann or known flux) per boundary. This is not the same as the requirement for advection, which only allows a boundary at an inflow. There are potential consistency issues between the number and nature of boundary conditions that can be imposed. In particular, if one does what is convenient for the individual operators, the boundaries for the overall problem is likely to be overspecified, underspecified, or inaccurate (see, for instance, Leveque 2003). The symptoms we encountered at relatively active exit boundaries are convergence issues and numerical boundary layers, where concentration tends to pile up at the edge of the domain.

In all our tests, we used specified concentrations at inflow for both constructing the estimate of the advection operator and for diffusion. Then for outflows, we used no boundary for advection, and for diffusion we used a Dirichlet boundary, which is fixed by using extrapolated values from the interior. This treatment is technically underspecified, but seemed to allow second-order accuracy and some stability even with a fairly steep plume exiting the system. Boundaries for the Delta are covered in section 4.3.4.

4.3 Delta Network Enhancements for Eulerian One-Dimensional Transport Scheme

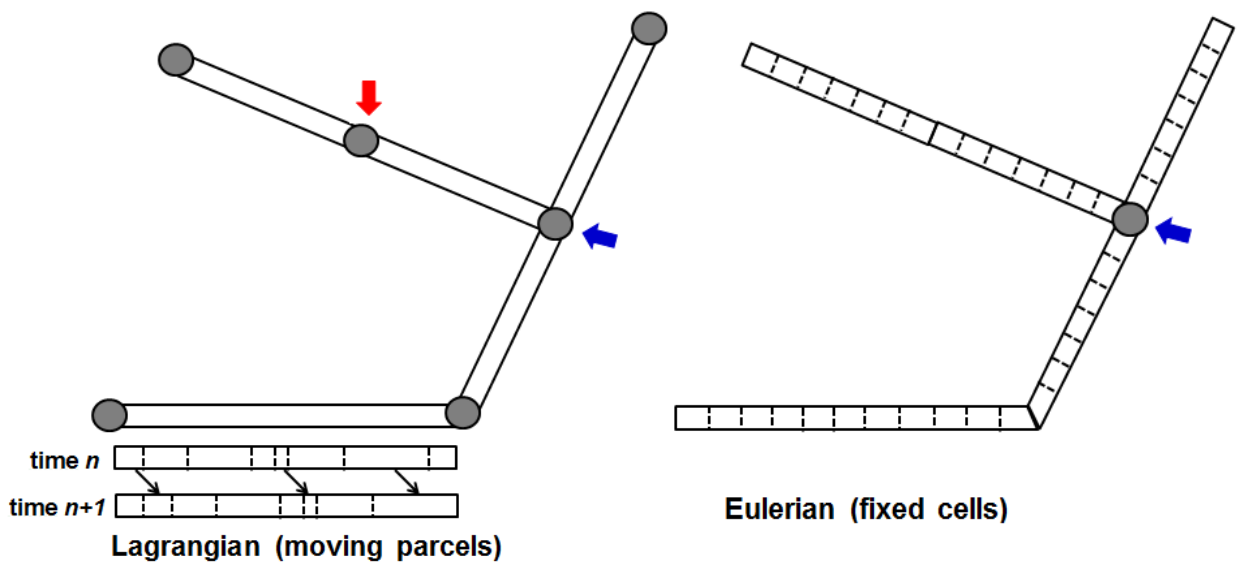
Prior work focused on a single channel with speculative software "hooks," where the algorithm had to be patched together for use in a network. Additional work was needed to make the algorithm workable for production modeling in the Delta, including the provision of a flow field from DSM2-HYDRO, specification of the behavior at junctions, and connection to the DSM2 input system. The assumptions and enhancements are described below.

4.3.1 Delta Network Grid

To apply the scheme to the Delta network, features such as multiple boundaries, junctions, non-sequential cell numbering, gates, reservoirs, and external flows had to be considered.

The DSM2-GTM grid is generated based on the dx (gtm_dx) that is given in the user input. It has to be smaller than DSM2-HYDRO discretization length (hydro_dx) and preferably be at least four times as precise. Current DSM2-HYDRO historical setup has hydro_dx of 5,000 ft. The cell size of DSM2-GTM is created as close to gtm_dx as possible. For example, for a reach length of 5,500 ft and given dx is 1,000 ft, the cell size will be 1,100 ft and there will be five cells in that channel. The cell sizes are uniform within a channel, but vary somewhat over the network around dx. The Eulerian one-dimensional scheme has been modified and tested for varying dx problems, including some modification of differencing approximations and slope limiters.

The DSM2-GTM grid is different in nature from the DSM2-QUAL grid, both in terms of structure and in the way it relates to the DSM2 map that users see. The DSM2-QUAL mesh evolves with flow. The model creates and destroys parcels as water enters and exits mapped channels (Figure 4-3a). The parcel sizes and locations vary at each time step, and the accuracy of the scheme is limited by how well they are tracked and by how many intermediate nodes (red arrow shows this in Figure 4-3a) exist. The blue arrows in Figure 4-3 denote a multi-channel junction. In contrast, DSM2-GTM utilizes an Eulerian fixed grid. The mesh is fixed and is generated in the beginning of simulation based on a requested dx that is given in the input, which generally is finer than that of the hydrodynamic grid (Figure 4-3b). Whereas all the gray dots in Figure 4-3a are treated as junctions in DSM2-QUAL and these interrupt the discretization with special treatment, DSM2-GTM does not break the scheme at intermediate nodes that join fewer than three reaches, such as the one delineated with the red arrow in Figure 4-3a. This is not to say that the nodes have no influence; they force a discontinuity in the spatial discretization (dx) and are also used to introduce agricultural return flows.



a — DSM2-QUAL Grid b — DSM2-GTM Grid

Figure 4-3 DSM2-QUAL Grid in Contrast to DSM2-GTM Grid

Notes: Red arrow = intermediate node. Blue arrow = multi-channel or true junction

4.3.2 Network Implications for Advection

The network implications on advection include modifying dx to be spatially varying in the discretization, alteration of slope limiters, and the treatment of junctions.

The modification of dx in different formulas is fairly straightforward. The irregularity comes into play when analyzing slopes across intermediate nodes (in the sense of Figure 4-3a), where the discretization is continued uninterrupted. Although we call it irregular, the spatial step is actually piecewise constant. It is the same along each channel with discontinuities between channels.

Along with the slopes, themselves, slope limiters also must be modified for spatially varying dx. Slope limiters do exactly what they sound like they do: they limit the gradient of concentration that is assumed to exist in the cell and essentially exert a bound on calculations. They are used to guard against spurious oscillations and negative concentrations. Our original implementation was based on the van Leer limiter for uniform grids. There is no unique generalization to irregular grids; we used the limiter labeled "TVD" from Berger et al. (2005).

Because multi-channel junctions represent internal boundaries at cells adjoining multi-channel junctions (Figure 4-4), gradients are approximated by one-sided differences. For example, in cell i, the gradient is approximated solely from differences on the face shared with cell *i-1*. Multi-channel junctions are not rare, and we expected some trouble from this treatment, but it seems to produce acceptable results in practice. A well-studied alternate assumption is to assign the gradients around a multi-channel junction to be zero for the extrapolation step of the advection algorithm, which is the so-called Godonov first-order approximation. This simplification locally reduces the order of accuracy of advection across the junction. With a tidal system sloshing back and forth, error accumulates over time and becomes noticeable.

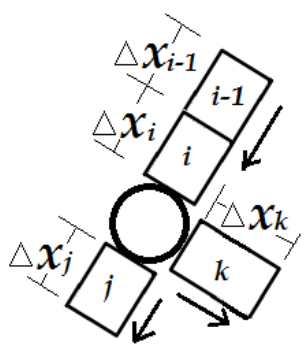


Figure 4-4 Illustration of a Cell that is Located on a Multi-Channel Junction

Notes: $\Delta x_{i-1}, \Delta x_i, \Delta x_j, \Delta x_k$ = cell length of cell *i-1*, cell *i*, cell *j*, and cell *k*, respectively

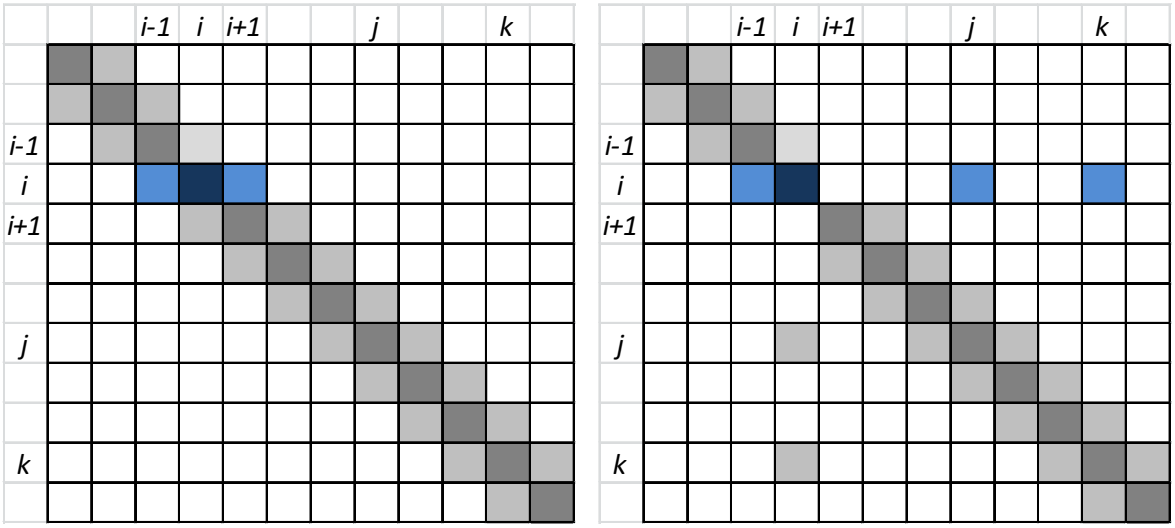
To accommodate junction mixing, the average concentration of donor (upwind) flows moving into junctions is computed and assigned to the receiving cell faces. This is a mild expansion on the upwinding idea. Junction mixing is also used to apply external flows, which are channel depletions from consumptive-use.

Reservoirs are treated as fully mixed stirred tanks. This is the same approach that DSM2-QUAL has taken. The reservoir concentration is updated based on the assumption of instant mixing with all the connected donor flows.

4.3.3 Network Implications for Dispersion

Besides affecting the discretization length (dx), the network potentially changes the nature of the linear algebra that has to be solved. For a single long channel, the dispersion discretization yields a matrix problem that is tridiagonal (Figure 4-5a). For certain treatments of the network problem where

dispersion is modeled across multi-channel junctions, the matrix is not tridiagonal but is merely sparse (Figure 4-5b), with the off-tridiagonal terms representing connections at nodes. To maintain sufficient flexibility to swap network formulations, we had to change solvers. We eventually decided to use the sparse matrix library KLU (Natarajan 2005), which is the same solver used for DSM2-HYDRO, to efficiently solve the sparse matrix. Little significant slowdown was observed by switching the solver and although our current treatment of dispersion can be recast as a series of tridiagonal problems, we prefer the flexibility of the sparse solver.



(a) tridiagonal matrix (b) sparse matrix

Figure 4-5 Illustration of Tridiagonal Matrix in Contrast to Sparse Matrix

Notes: *i-1*, *i*, *i+1*, *j*, and *k* = cell sequential numbers

4.3.4 Network Implications on Boundaries and Junctions

The external boundary and compatibility conditions over a 1D network require reasonable assumptions for implementation. . The following paragraphs describe our initial treatment for various categories of flow.

Inflow. Inflow boundaries are represented using Dirichlet boundaries (known values) for both the advection predictor step and for the final update including dispersion. The concentration, constant or time-varying, is given in the input system.

Outflow. The advection estimate requires no boundary condition. The full equation, along with dispersion, Eq. (1), requires a boundary condition. For the final update with dispersion, a Dirichlet boundary is used, but this is based on spatially extrapolated values rather than on input concentration. This treatment prevents the development of a numerical boundary layer because of the conflict between what is naturally emerging from the domain set off by strong advection and the stipulated boundary. Because no external value is imposed, the boundary is underspecified. Nonetheless, the method produces stable and accurate behavior in our tests, even as a significant plume exits the boundary. Our experiments suggest that alternate treatments only produce different results in a small

neighborhood of the boundary. The results using DSM2-GTM is an improvement over DSM2-QUAL near the tidal boundary during outflow (Figure 4-6). DSM2-QUAL assumes zero dispersion at the boundary.

Intermediate nodes. In many ways, it is fair to say intermediate junctions are not treated as boundaries in DSM2-GTM. Tributary mass sources, such as consumptive-use, are added as part of the junction mixing described above, and a discontinuity occurs in the discretization length (dx). In DSM2-QUAL, no mixing occurs across either intermediate nodes or junctions; at the same time, the junction treatment in DSM2-QUAL provided numerical diffusion, apparently achieving the same end.

Multi-channel (true) junctions. For advection, a multi-channel (true) junction is treated as a coupled inflow and outflow boundary for advection with appropriate mixing, which was elaborated in the previous section. A homogenous Neumann boundary condition (zero diffusive flux) is imposed on dispersion. The zero dispersion assumption is the same one used in DSM2-QUAL at all nodes. The assumption circumvents numerous practical issues defining exactly how dispersion should be defined and how mass should be conserved from both advection and dispersion. The treatment produces acceptable results more than other treatments we tested compared with field data, but it clearly interrupts a physical process and may be a possible area of improvement in the future.

For a Delta simulation, the inflow boundaries are Yolo Bypass and the Sacramento (Freeport), San Joaquin (Vernalis), Calaveras, Mokelumne, and Cosumnes rivers. Martinez is a tidal boundary and is periodically an inflow or outflow. Exports and diversions include the State Water Project (SWP) Banks Pumping Plant, Central Valley Project (CVP) Tracy Pumping Plant, North Bay Aqueduct exports, and Contra Costa Water District diversions. They are treated as outflow boundaries or external flows with junction water mixing depending on whether they lie at the end of a channel.

DSM2-GTM reported the salinity at the Martinez outflow location matched the input boundary data well, while DSM2-QUAL reported artificial drops in salinity because of the limitation of parcel formation. This can be seen in Figure 4-6.

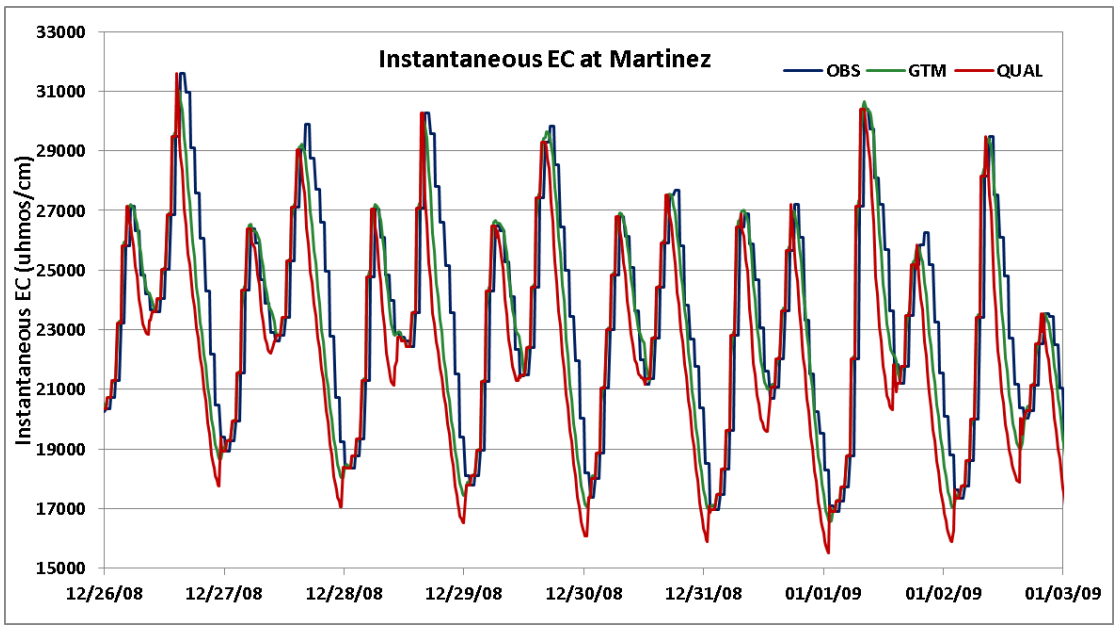


Figure 4-6 Electrical Conductivity Result Comparison at Martinez Outflow Boundary

Notes: OBS = data observed, GTM = DSM2-GTM, QUAL = DSM2-QUAL, EC = electrical conductivity, umhos/cm = micromhos per centimeter

4.3.5 Reservoirs, Gates, and External Flows

Reservoirs are treated as fully mixed volumes. Figure 4-7 is an example of how the connected flows to a reservoir in DSM2 are specified. The calculation is a simple mass-balance equation around a reservoir, as shown in Eq. (14).

$$C_R^{n+1} = \frac{V_R^n \cdot C_R^n + \sum_i Q C_i^{n+\frac{1}{2}} \cdot \Delta t}{V_R^{n+1}} \tag{14}$$

where

V_R^n is the reservoir volume at time (n),

C_R^n is the reservoir concentration at time (n),

the connected flows (Q) include external flows directly dumping into the reservoirs and flows from connected channels.

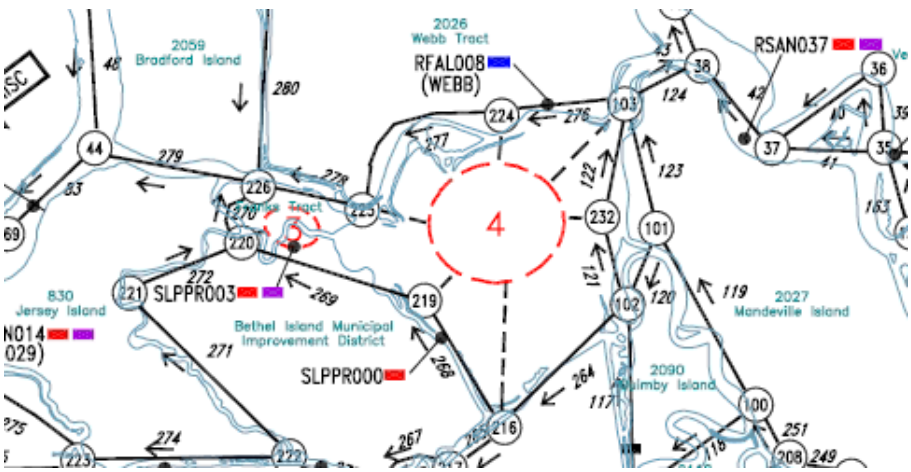


Figure 4-7 Illustration of Reservoir in the Network System

External flows, such as channel depletions from DICU (Delta Island Consumptive-Use), are added to junction mixing, as described previously. The mixed concentration to be assigned to the low face of cell *j* is calculated based on the external flows and concentrations entering from the high face of cell *i* (Figure 4-8). Note that agricultural flows are not implemented using the source term.

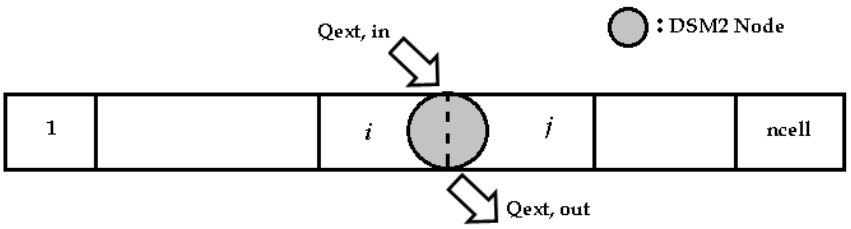


Figure 4-8 Illustration of External Flows in the Network System

Notes: 1, *i*, *j*, ncell = cell No., Qext, in = external flow added to the junction, Qext,out = external flow left the junction

Gates are not treated specially in DSM2-GTM for advection beyond their role in DSM2-HYDRO for determining flow. The dispersion coefficient around the gate is re-assigned to zero to avoid artificial diffusive fluxes across gates.

4.4 Linkage to DSM2-HYDRO and other DSM2-GTM Code Design Considerations

DSM2-GTM is written in Fortran 90 and is intended to be a flexible and reusable model, which enables a relatively easy integration of additional water quality parameters. Constituents can be added by writing a handful of subroutines governing the initialization, reaction, and output of those constituents.

To ease the transition from DSM2-QUAL to DSM2-GTM from a user's perspective, DSM2-GTM adopts an input and output system that is similar to the existing input/output (I/O) in DSM2-QUAL. The input system is based on a text reader using keywords that will seem familiar to users of DSM2-QUAL. Current DSM2-QUAL users can apply their existing studies with minimal changes in the input file.

4.4.1 DSM2-HYDRO Tidefile

This project was considered a good opportunity to update hydrodynamic information included in the DSM2-HYDRO output tidefile, which is the DSM2 name for the file that transmits results from DSM2-HYDRO to DSM2-QUAL. DSM2-HYDRO has already been modified to provide a lossless hydrodynamic representation in the DSM2-HYDRO tidefile (Hsu et al. 2014). Additional changes that have been made are:

- Hydrodynamic spatial representations are output on every DSM2-HYDRO computational point instead of coarser DSM2 map nodes.
- Hydrodynamic representations are instantaneous values rather than theta average quantities.
- Area has been eliminated as a state variable because it was redundant. We now include only water surface, plus sufficient geometry information, to reproduce the calculation of the cross-sectional area in DSM2-HYDRO.

The spatial resolution of DSM2-GTM is much more precise than that of DSM2-HYDRO. Even with a lossless transfer, the flow field provided by DSM2-HYDRO is incompletely specified and requires interpolation. Our approach starts by interpolating water-surface elevation. The area is then calculated based on geometry and water surface. Once area is determined for all grids, flow is obtained by linear interpolation between two DSM2-HYDRO computational points. The interpolation is not conservative, although deviations are minimal. We expect to eventually move to a conservative projection-based model.

4.4.2 Time-Step Restrictions and Subcycling

In transport problems, the Courant-Friedrichs-Lewy (CFL) condition describes the time step required for stability while solving for advection. For a one-dimensional problem, the CFL condition has the following form.

$$CFL = \frac{u\Delta t}{\Delta x} \leq C_{max} \tag{15}$$

where

u is the magnitude of the velocity,

Δt is the time step,

Δx is the space interval,

C_{max} depends on the method used to solve the discretized equation, such as whether the method is explicit or implicit. Typically, C_{max}= 1 for an explicit solver, which for the spatial discretization reported here amounts to a fairly mild restriction.

In intuitive terms, the CFL condition for our algorithm says that fluid may not be transported by the mean velocity more than one DSM2-GTM computational cell in one time step. Since the possibility of this happening somewhere over a large channel network is common and difficult to anticipate, most practical models that use explicit time stepping include some form of subcycling, meaning that the model automatically discovers and uses the largest stable step that effectively divides the overall global time step.

4.4.3 Dispersion Coefficients

The parameterization of dispersion in DSM2-GTM comes from DSM2-QUAL and its predecessor, Branched Lagrangian Transport Model (BLTM). DSM2 Version 8.1 consolidated the mixing formulation for DSM2-QUAL (Liu and Ateljevich 2011) to achieve consistency with an underlying partial differential equation. Advection has been dropped for this discussion. The component used to calculate the parcel exchange diffusive flux is

$$\frac{\partial C}{\partial t} = \frac{1}{A}\frac{\partial}{\partial x}\left(DC \cdot |Q| \cdot \frac{\partial C}{\partial x}\right) \tag{16}$$

where *DC* is a parameter described below. The general accepted form of 1-D river dispersion can be written as

$$\frac{\partial C}{\partial t} = \frac{1}{A}\frac{\partial}{\partial x}\left(A \cdot K \cdot \frac{\partial C}{\partial x}\right) \tag{17}$$

where

C is the concentration,

t is the time coordinate,

K is the classic longitudinal dispersion coefficient.

Comparing Eq. (16) and Eq. (17), we get the following two relationships.

$$DC \cdot |Q| = A \cdot K \tag{18}$$

or

$$K = DC|\bar{u}| \tag{19}$$

where $\bar{u}$ is the mean cross-sectional velocity.

The coefficient *DC* is the one traditionally used as the input dispersion coefficient in DSM2 Version 8.1. In DSM2-GTM, it is converted to *K* by multiplying by velocity magnitude. In most of the Delta, where tidal dispersion and junction mixing prevail as the key mixing factors, the modulation of dispersion by velocity seems reasonable. One advantage to the described approach is that the dispersion coefficient, Eq. (20), is proportional to velocity, which means the mesh Peclet number (*Pe*),

$$Pe = \frac{|u| \cdot \Delta x}{K} = DC\,\Delta x, \tag{20}$$

stays constant over time. The Peclet number measures the ratio of transport because of advection and dispersion. The performance of the algorithm is more consistent when it varies less, which is a point that was also noted as an advantage for QUAL/BLTM (Jobson and Schoellhamer [1987]). The code has been arranged so that it would not be difficult to replace this parameterization with another code, perhaps to recognize the link between longitudinal salinity profiles and mixing.

4.4.4 Multiple Constituents

This transport model has been designed to allow multiple constituents. DSM2-GTM relegates the reactions between constituents to external modules. The modules in development include a sediment, dissolved oxygen, temperature, and mercury cycling module.

4.5 Delta Salinity Simulation Comparison for DSM2-QUAL and DSM2-GTM

In a previous report (Hsu et al. 2014), a number of simple test cases were designed to evaluate the behavior of DSM2-GTM over simple networks, and the results were compared with DSM2-QUAL. Since then, the effort has been on field testing with salinity.

4.5.1 Delta Historical Setup for Salinity Simulation

The historical setup used in this study was obtained from DSM2 Version 8.1, which incorporates the latest improvements to the DSM2 code and a new calibration with NAVD88 datum (Liu et al. 2013). The conversion to NAVD88-stage datum improved the comparison of predicted and observed stages in the Delta. Errors in Clifton Court Gate operation data, Martinez stage data, and Martinez electrical conductivity (EC) data were corrected. Liu concluded that DSM2-QUAL Version 8.1 predicted EC at key stations in the Central Delta (Collinsville, Emmaton, Antioch, and Jersey Point) fairly well. The new results using calibrated DSM2-GTM are generally very close to the historical calibration results.

The simulation period for the tests is January 1, 1999–April 1, 2012. The map of the Delta network and the key locations we used for comparison are shown in Figure 4-9. The setup includes all boundary flows with Martinez boundary stage, SWP and CVP pumping, DICU flows, reservoirs, and gates.

name	Location	Name	Location
RMID027	Middle River at Tracy Rd	RSAC101	Sacramento River at Rio Vista
ROLD024	Old River at Bacon Island	RSAN007	San Joaquin River at Antioch
RSAC081	Sacramento River at Collinsville	RSAN018	San Joaquin River at Jersey Point
RSAC092	Sacramento River at Emmaton	RSAN058	Stockton Ship Canal

Figure 4-9 Delta Network for Historical EC Simulation

4.5.2 Results for Advection Only

To evaluate the diffusive influence of the algorithms and junction mixing, it was of interest to investigate how DSM2-GTM compares with DSM2-QUAL with dispersion turned off, so that salt is transported by advection only. For this test, the upstream concentrations and agricultural sources are set to zero, so that numerical diffusion can be investigated qualitatively.

The results are shown in Figure 4-10 after the model has been integrated for 13 years of simulation. Though the results are associated with field stations, the values at these stations are not representative of field conditions. Ocean forcing could bring a fairly significant salinity amount within a tidal excursion of Martinez, which would be enough to reach Pittsburg or Antioch, but there is generally average flow out of the domain. One criterion of success for this test was extra numerical diffusion from advection would not bring an objectionable flux of salt landward to those points where it might be expected to have a physical effect. The results of DSM2-GTM and DSM2-QUAL are very similar for this test. Both models still show salinity of 300 micro Siemens per centimeter (µS/cm) at Emmaton and some salinity amounts peak around 10 micromhos per centimeter (µmho/cm) at Rio Vista. During high flow season, both model results indicate that water becomes fresh and salt leaves the system. For the low flow season in the inner Delta, the numerical diffusion leads to conductivity of no more than a few µS/cm. Overall, this test, with consumptive-use turned off, suggests numerical diffusion is well controlled, presenting a less-than-first-order effect compared to advection. Other tests with consumptive-use enabled suggest that plume advection around the Delta is also very consistent between models.

The results of this test were encouraging for both models. DSM2-QUAL uses a Lagrangian scheme, which moves salt by simply tracking parcels as they move with the flow. Since the parcels don't spill into one another when the model is operated with mixing turned off, it is often touted as being a perfect numerical scheme with zero numerical diffusion. Be that as it may, the authors were concerned how this label of perfection would hold up in the context of time-varying flow and intermediate junctions. This is because DSM2-QUAL accuracy is limited by the quality of hydrodynamic information, the ability to track the parcels relative to locations of interest, and by certain *ad hoc* features of the model, such as recombination of small parcels. All of these limitations are associated with the treatment of flow as it passes Eulerian landmarks, such as map nodes. In contrast, DSM2-GTM is less affected by extra map nodes, but it is susceptible to numerical diffusion. The consistency between the two schemes in the Western Delta and the low intrusion into the Central Delta during this test confirms that numerical diffusion is sufficiently low in both models, such that numerical diffusion from the advection step is not muddled with dispersive mixing. To the extent that there is numerical diffusion, it likely comes from the common feature of the two models, which mixes fluxes as they flow across multi-channel junctions joining tributaries, as shown in Figure 4-3.

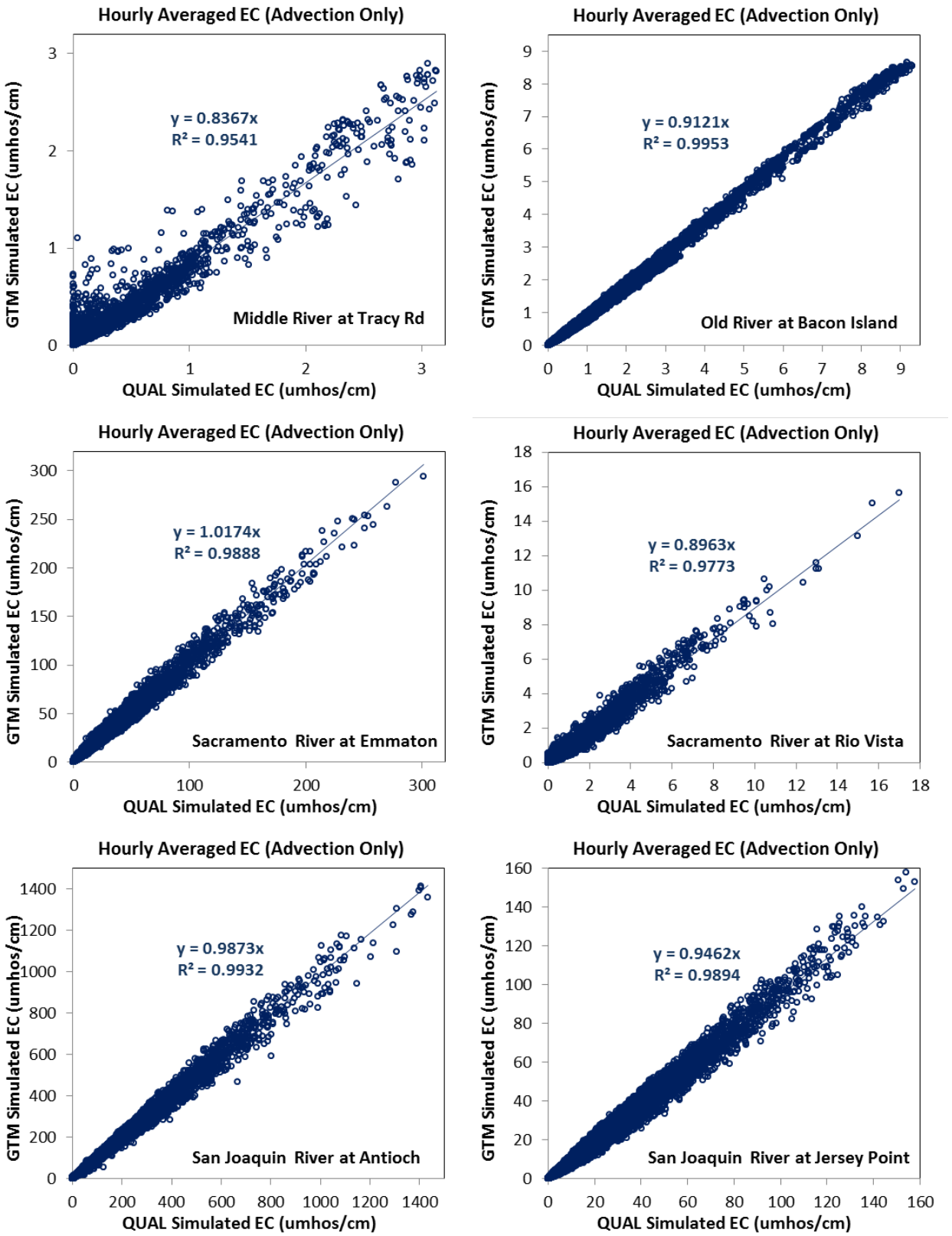


Figure 4-10 DSM2-GTM and DSM2-QUAL Simulated EC Results Comparison with Dispersion Off

4.5.3 Results Using DSM2-QUAL Calibrated Dispersion Coefficients

At this stage of development, DSM2-GTM has not been independently calibrated. The dispersion coefficients used for testing and comparison in this chapter are from the historical calibration for DSM2 Version 8.1 (Liu et al. 2013) that were used in DSM2-QUAL. The calibration period was October 1, 2000—October 1, 2008. All the available stations with good data were used so that the calibration covers most locations of interest.

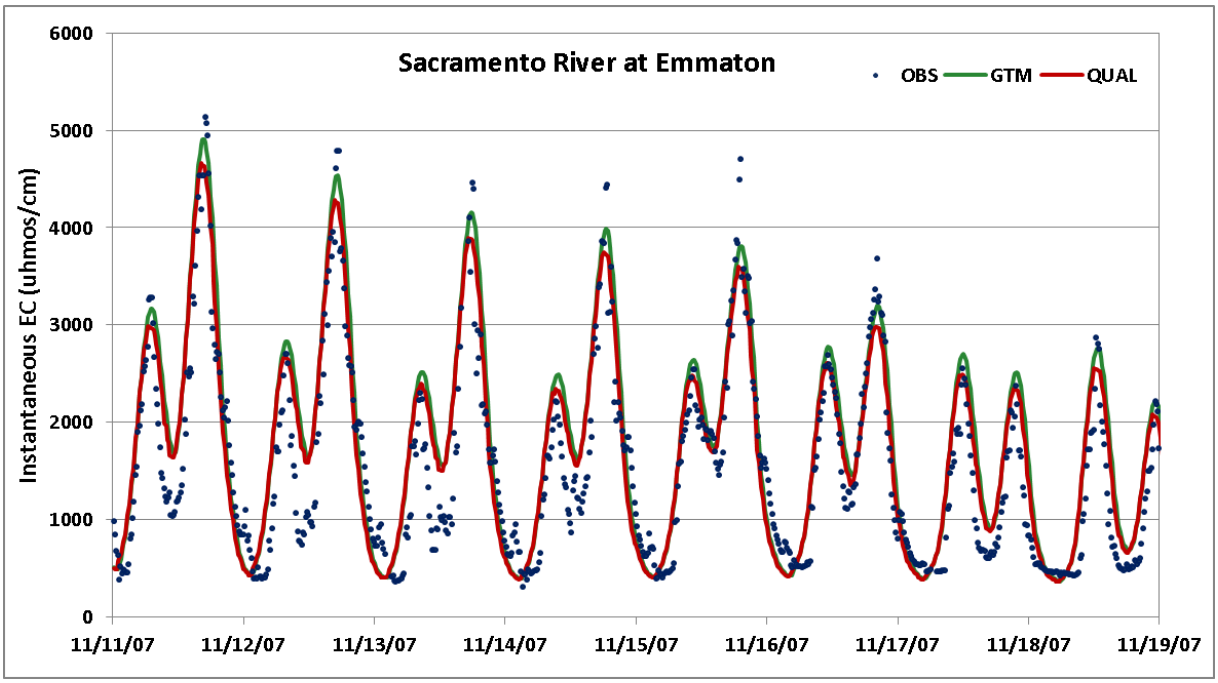
The detailed tidal dynamics can be observed from those 15-minute instantaneous values. The tidal results at Emmaton and Jersey Point are shown in Figure 4-11. The plots indicate that DSM2-GTM and DSM2-QUAL both capture the low/high high tides and low/high low tides fairly well, with respect to the trend and the amplitude.

Figure 4-9 shows the locations in the Delta network by DSM2 output labels for the simulations. Simulation results for Middle River at Tracy Road (RMID027), Old River at Bacon Island (ROLD024), Sacramento River at Collinsville (RSAC081), Emmaton (RSAC092), Rio Vista (RSAC101), San Joaquin River at Antioch (RSAN007), Jersey Point (RSAN018), and Stockton Ship Canal (RSAN058) are shown in Figures 4-12 through 4-19. There are three subplots in each figure. The top right monthly averaged EC time-series plot compares DSM2-GTM results with DSM2-QUAL and observed data (OBS). The top left plot is the scatter plot of monthly averaged EC. The bottom plot is a time-series plot for daily averaged EC. Overall, the simulation results from DSM2-GTM overlap the results from DSM2-QUAL. There have been decades of studies on DSM2-QUAL , which produced improvements and calibrations in DSM2-QUAL, and its ability to match historical data is well understood. DSM2-GTM producing results, which are close to DSM2-QUAL results, is an important milestone.

We also studied reservoir concentration. The computational approach for DSM2-QUAL and DSM2-GTM is the same. As long as the EC results of the connected channels are similar, the reservoir concentration are not expected to differ much. The concentrations for Bethel, Clifton Court, Discovery Bay, Franks Tract, Liberty, and Mildred are shown in Figures 4-20 and 4-21. The results from DSM2-GTM and DSM2-QUAL are fairly close as expected. There is an obvious discrepancy observed for Discovery Bay and that was expected because there are differences between DSM2-QUAL and DSM2-GTM for the channels in that region. This is where DSM2-GTM calibration is needed.

Because the parameters from the previous DSM2-QUAL calibrations are initial estimates, this makes calibrating DSM2-GTM easier. There are some problems in South Delta regions to match observed data. These are also problematic areas for DSM2-QUAL to match EC results as well because many of the issues have to do with hydrodynamics and consumptive-use and not the transport scheme or dispersion coefficient.

Judging from Figures 4-12—4-19, it is clear DSM2-GTM often has slightly higher EC values than DSM2-QUAL. There was an attempt to scale this down by multiplying the dispersion coefficient by 0.9. Doing that shifts the EC down a bit for most key locations, but we decided to leave this type of test to full calibration.



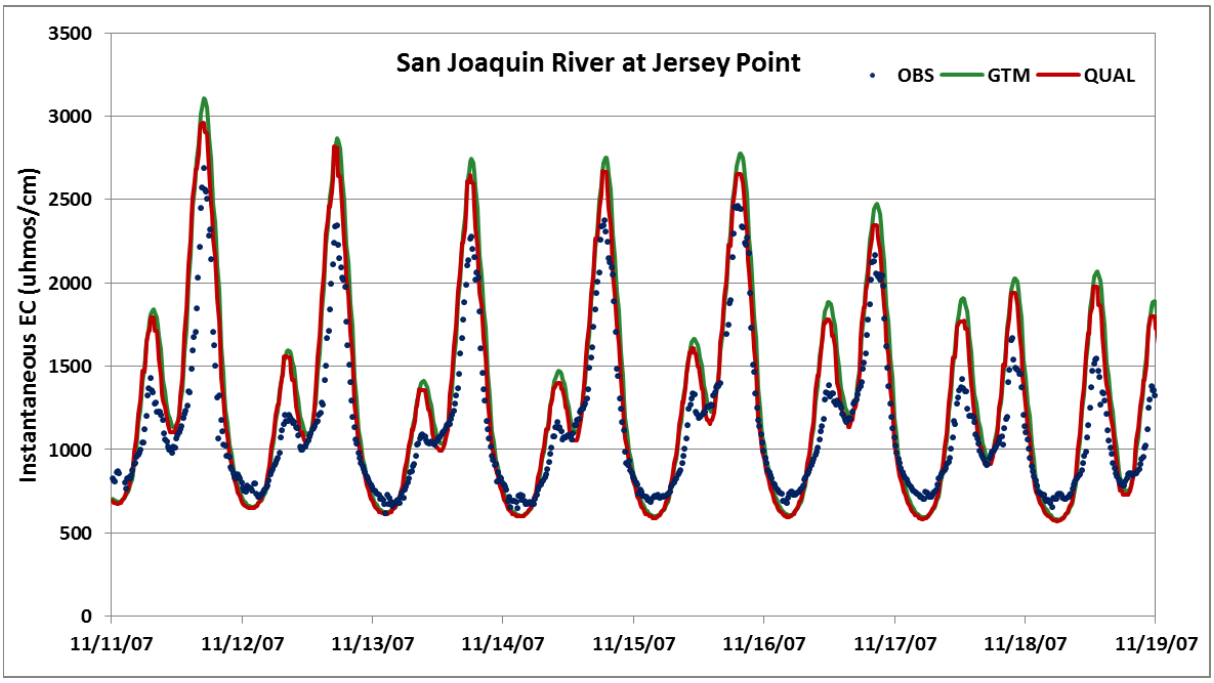


Figure 4-11 EC Tidal Results Comparison among DSM2-GTM, DSM2-QUAL, and Observed Data at Emmaton and Jersey Point

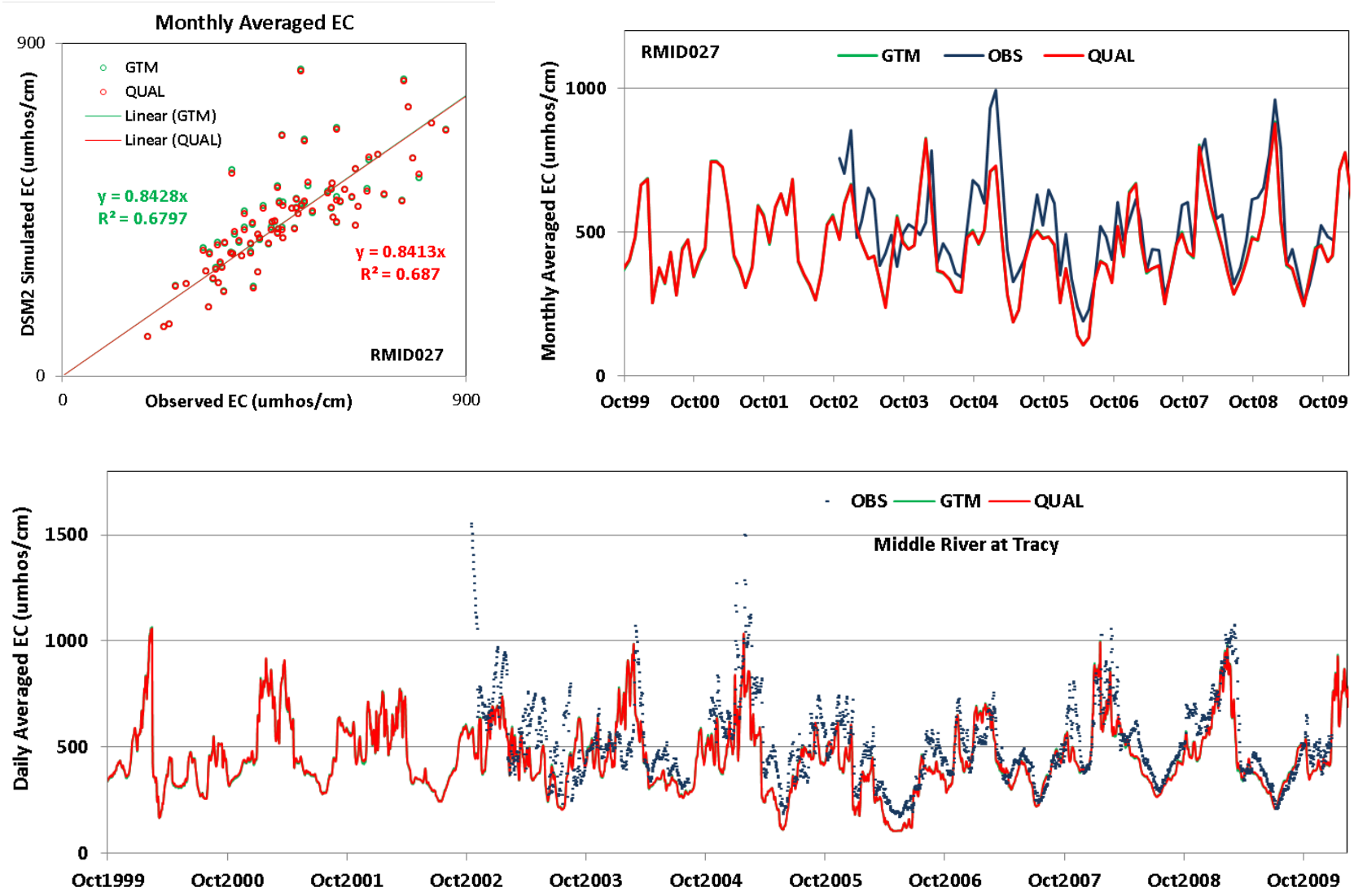


Figure 4-12 EC Results Comparison among DSM2-GTM, DSM2-QUAL, and Observed Data at Middle River at Tracy

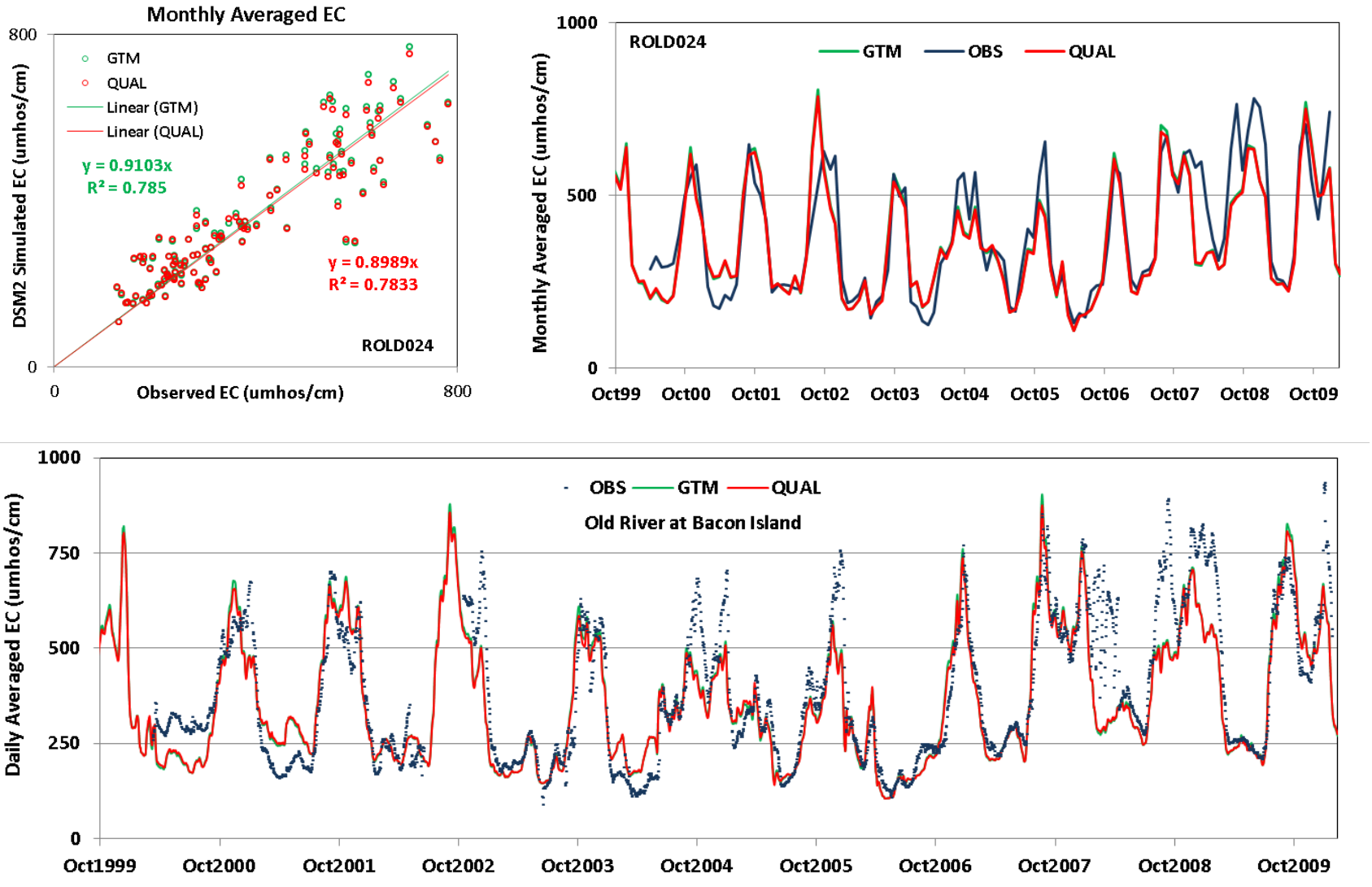


Figure 4-13 EC Results Comparison among DSM2-GTM, DSM2-QUAL, and Observed Data at Old River at Bacon Island

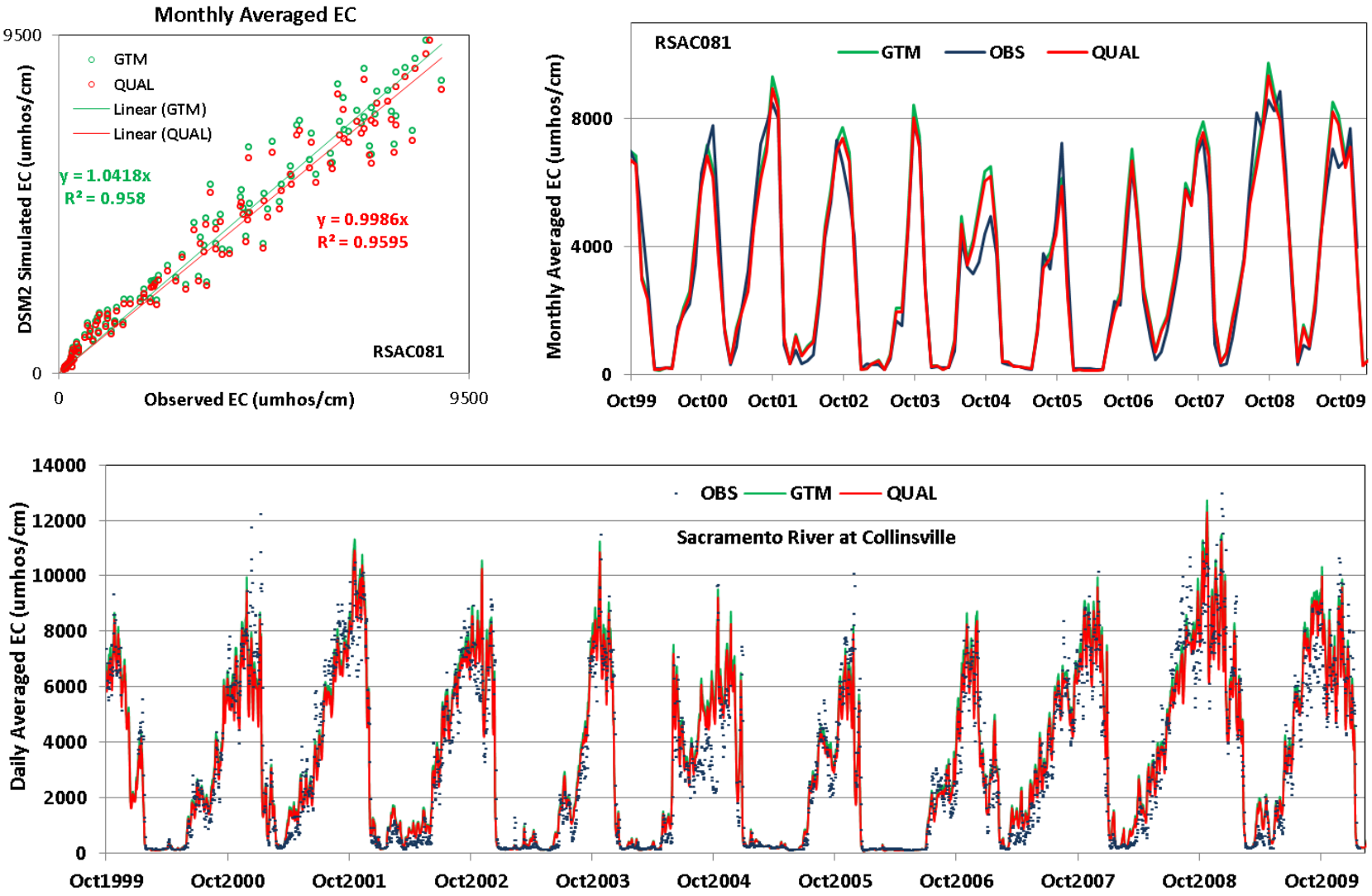


Figure 4-14 EC Results Comparison among DSM2-GTM, DSM2-QUAL, and Observed Data at Sacramento River at Collinsville

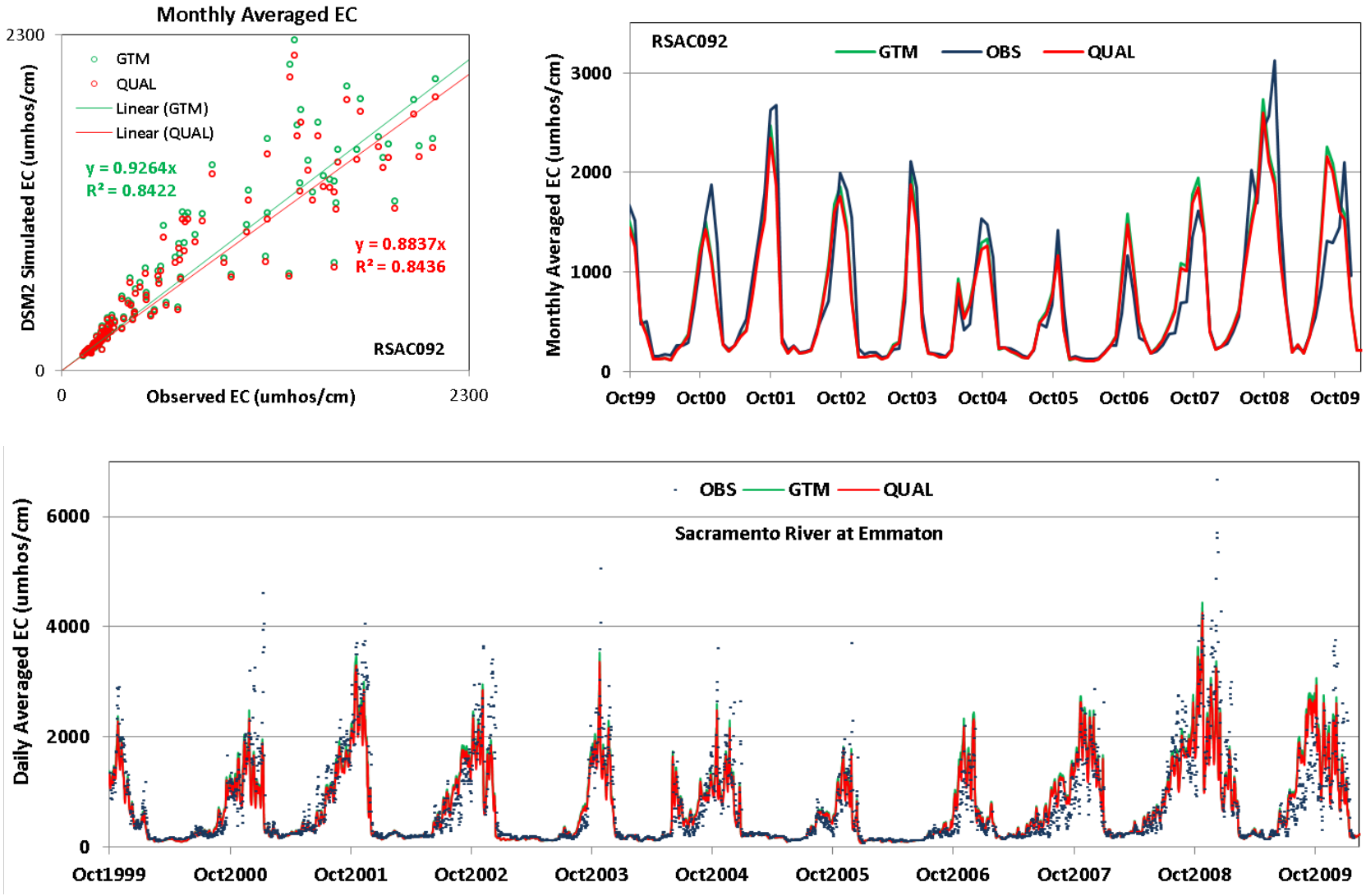


Figure 4-15 EC Results Comparison among DSM2-GTM, DSM2-QUAL, and Observed Data at Sacramento River at Emmaton

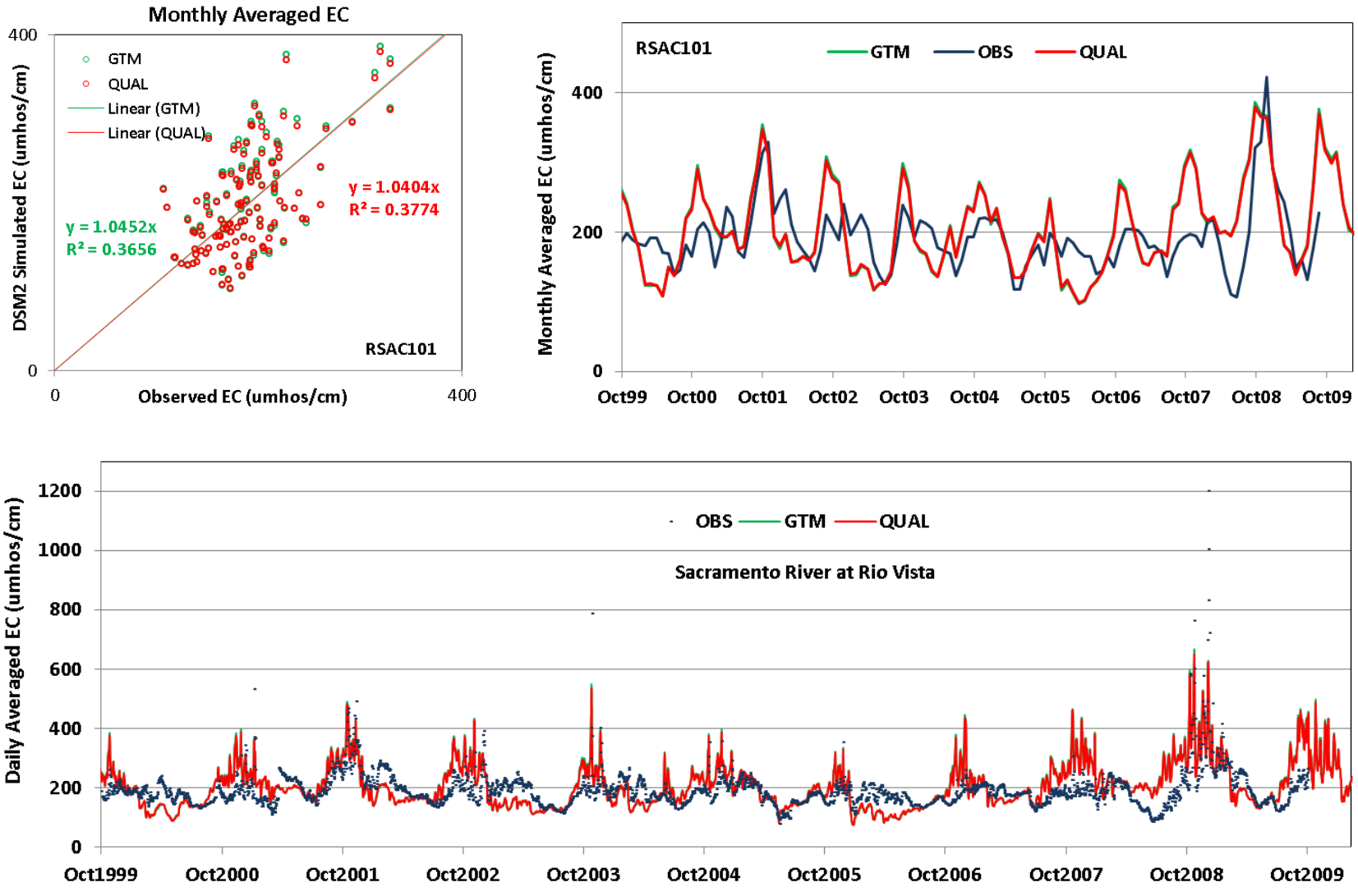


Figure 4-16 EC Results Comparison among DSM2-GTM, DSM2-QUAL, and Observed Data at Sacramento River at Rio Vista

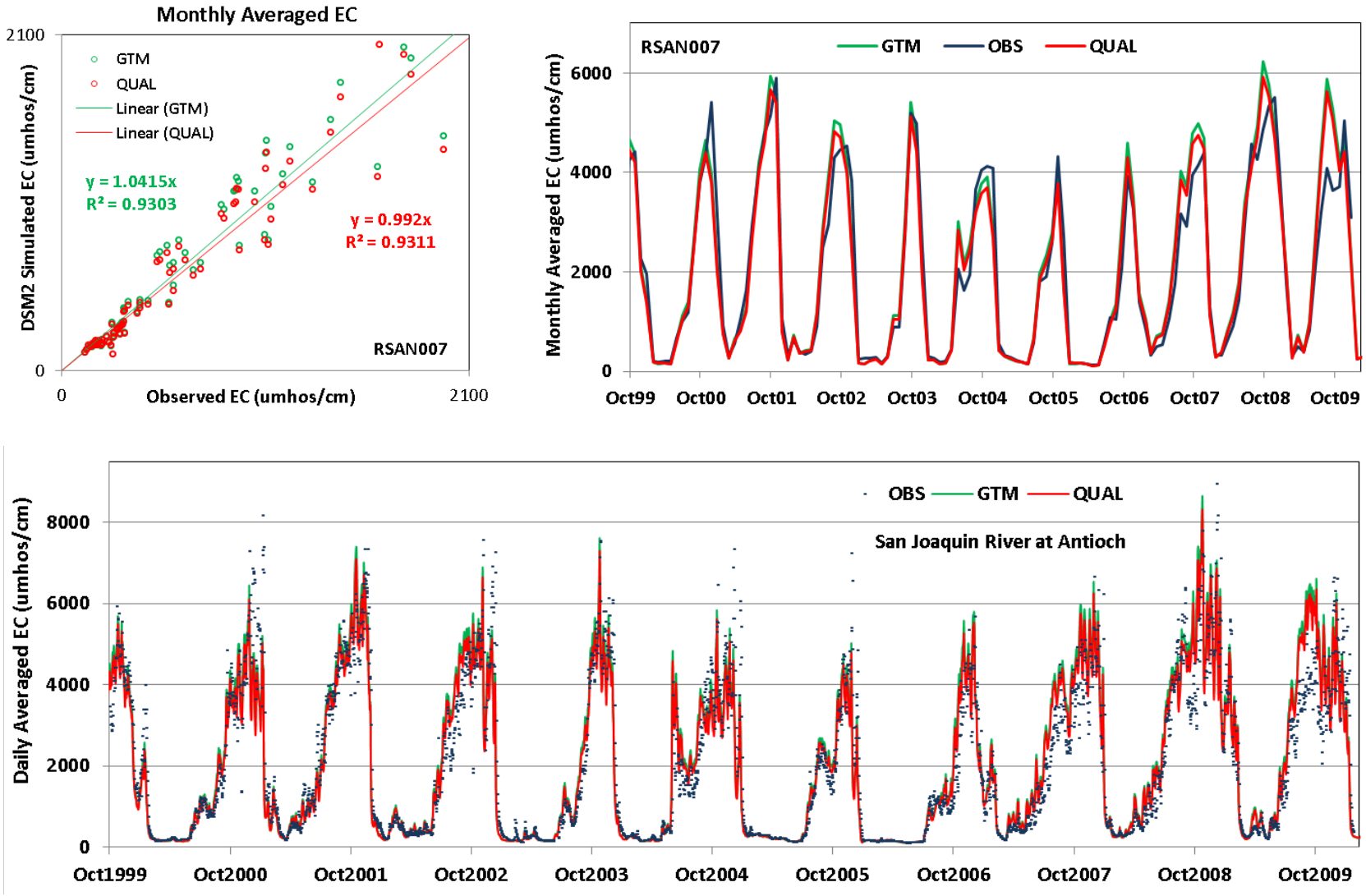


Figure 4-17 EC Results Comparison among DSM2-GTM, DSM2-QUAL, and Observed Data at San Joaquin River at Antioch

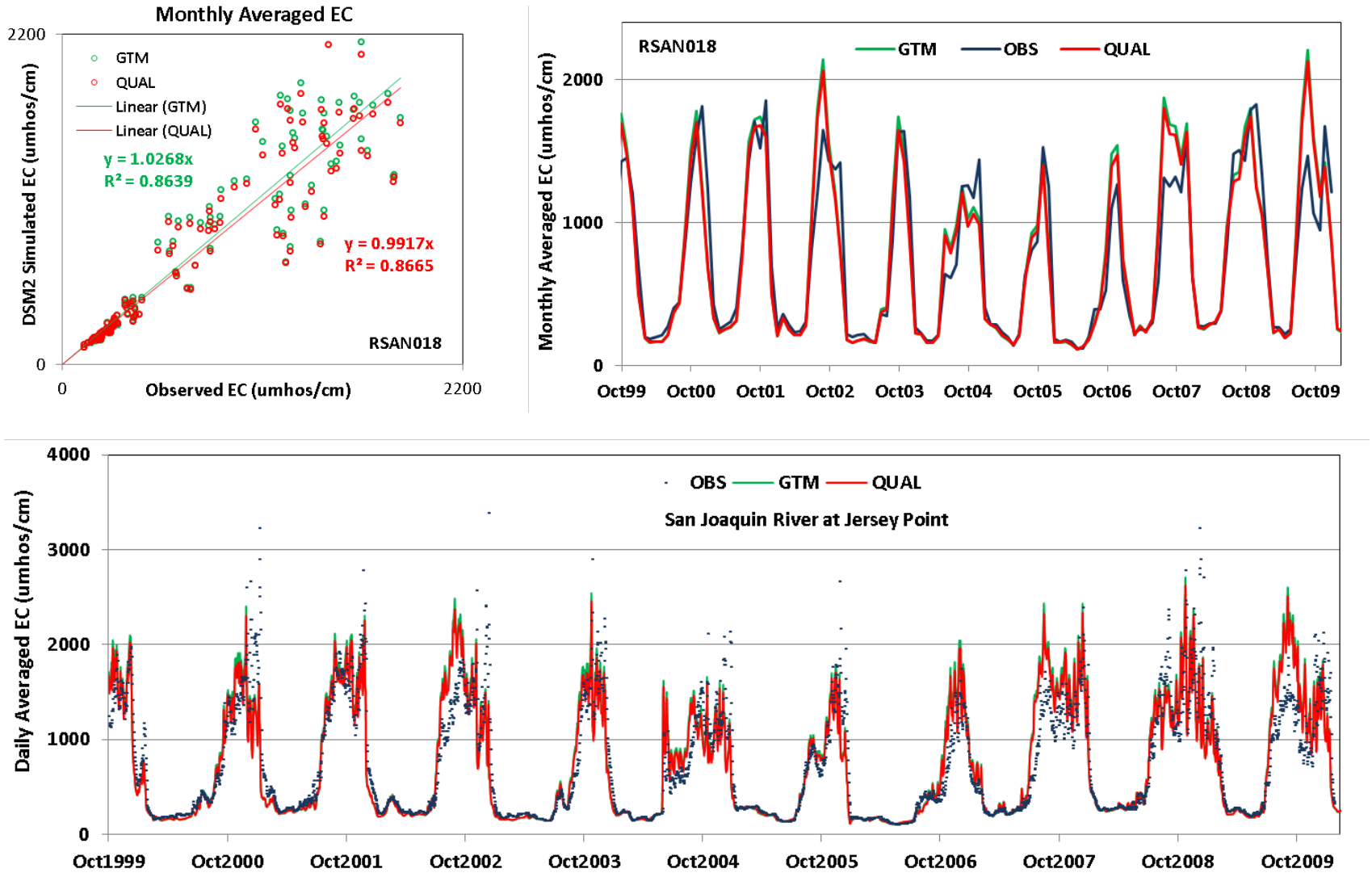


Figure 4-18 EC Results Comparison among DSM2-GTM, DSM2-QUAL, and Observed Data at San Joaquin River at Jersey Point

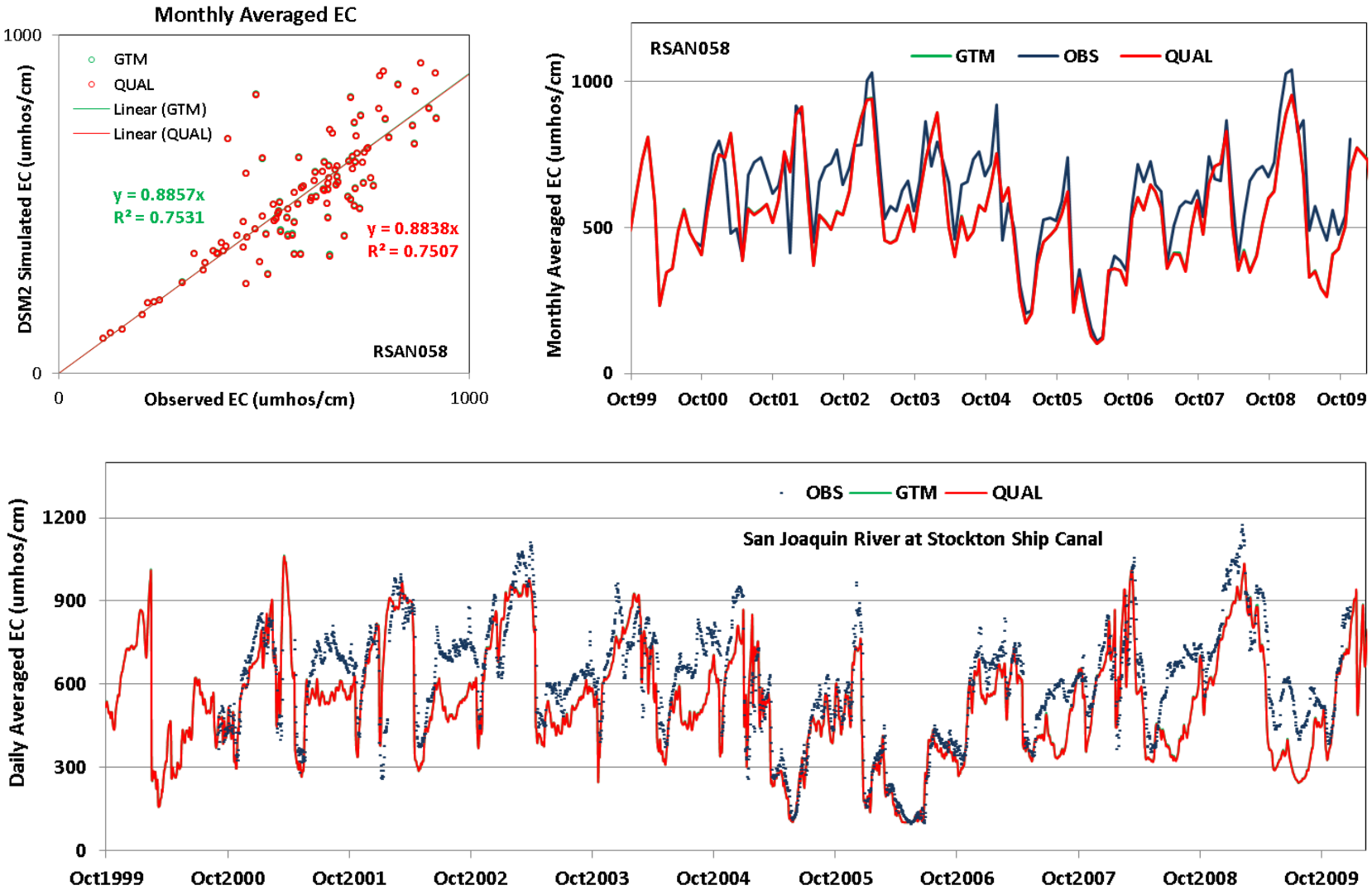


Figure 4-19 EC Results Comparison among DSM2-GTM, DSM2-QUAL, and Observed Data at San Joaquin River at Stockton Ship Canal

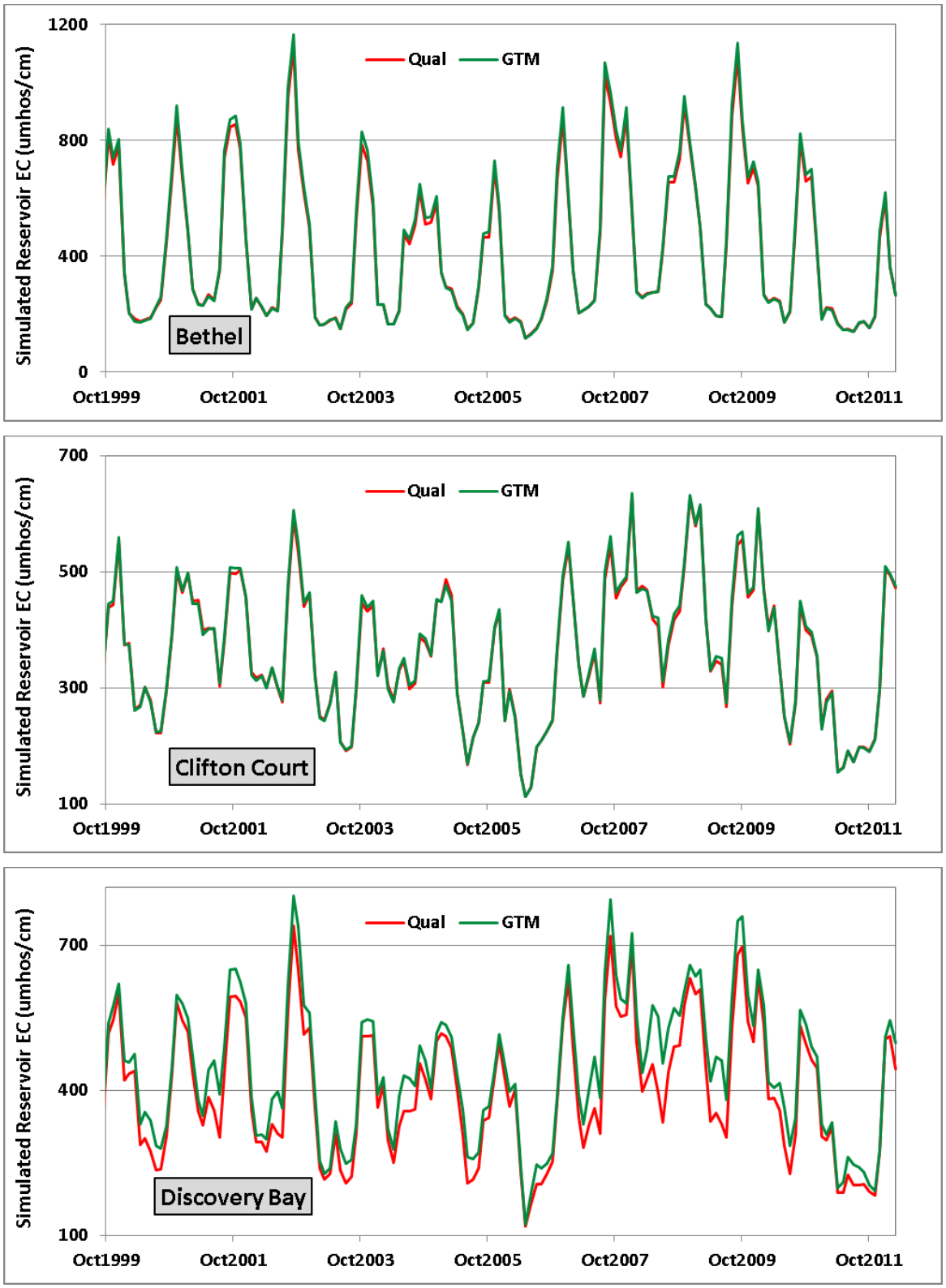


Figure 4-20 Simulated Reservoir EC Comparison (Bethel, Clifton Court, and Discovery Bay)

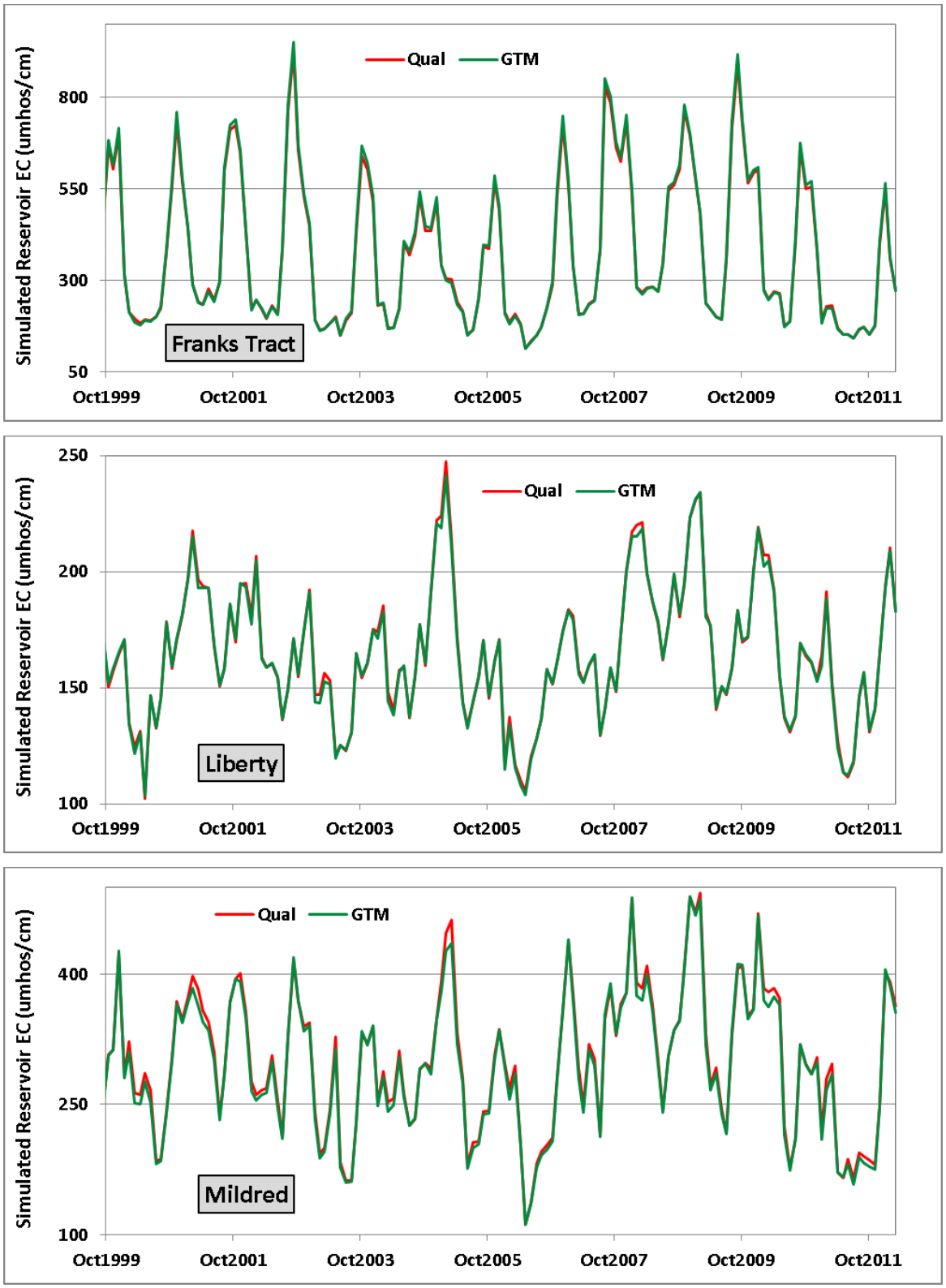


Figure 4-21 Simulated Reservoir EC Comparison (Franks Tract, Liberty, and Mildred)

4.6 Sensitivity and Stability Tests

4.6.1 Sensitivity Analysis

The goal of our sensitivity tests was to ensure that DSM2-QUAL and DSM2-GTM responded to flow perturbations the same way. We performed sensitivity tests around three areas of hydrology: 1) increasing or decreasing Sacramento River inflow by 10 percent, 2) increasing or decreasing SWP pumping by 10 percent, and 3) increasing or decreasing DICU flows by 10 percent.

Figure 4-22 shows sensitivity to changes in the Sacramento River upstream inflow at Emmaton. The monthly average is calculated from tidally filtered results. Under a decrease in Sacramento River flow, salinity is higher throughout the simulation period. Under a decrease it is lower. When Sacramento River inflow is increased, the water becomes less salty as expected. DSM2-GTM and DSM2-QUAL have similar amplitude of sensitivity as the response to the flow variation.

Figure 4-23 shows sensitivity to an increase of SWP pumping at Old River at Bacon Island. The increase in pumping raises salinity. Again, the simulated results with this flow variation, because of pumping, are still very consistent between DSM2-GTM and DSM2-QUAL. The analysis of sensitivity to an increase in DICU channel depletions also yields very similar results.

Overall, these results indicate the response from DSM2-GTM is as anticipated and is in a range that is consistent to the response of DSM2-QUAL.

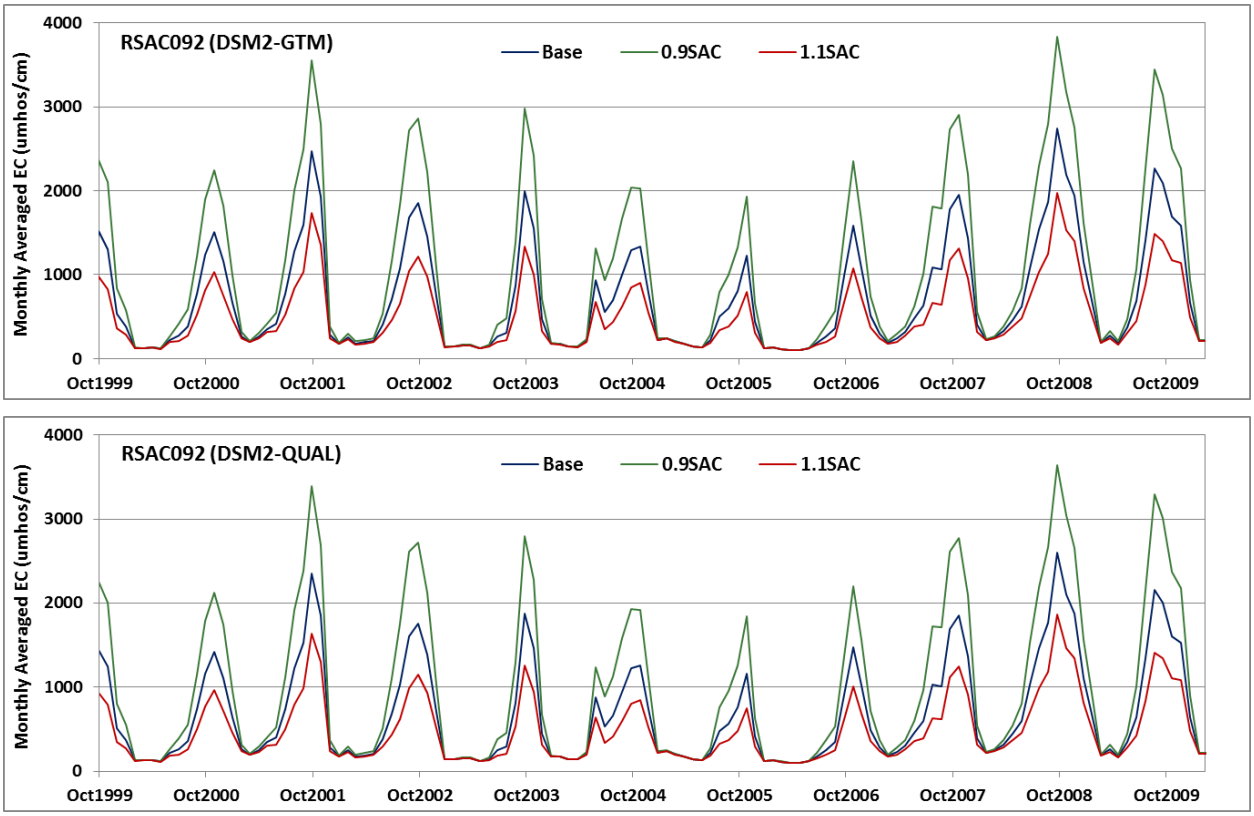


Figure 4-22 Sensitivity Analysis of Varying Sacramento Flow by 10 percent at Emmaton

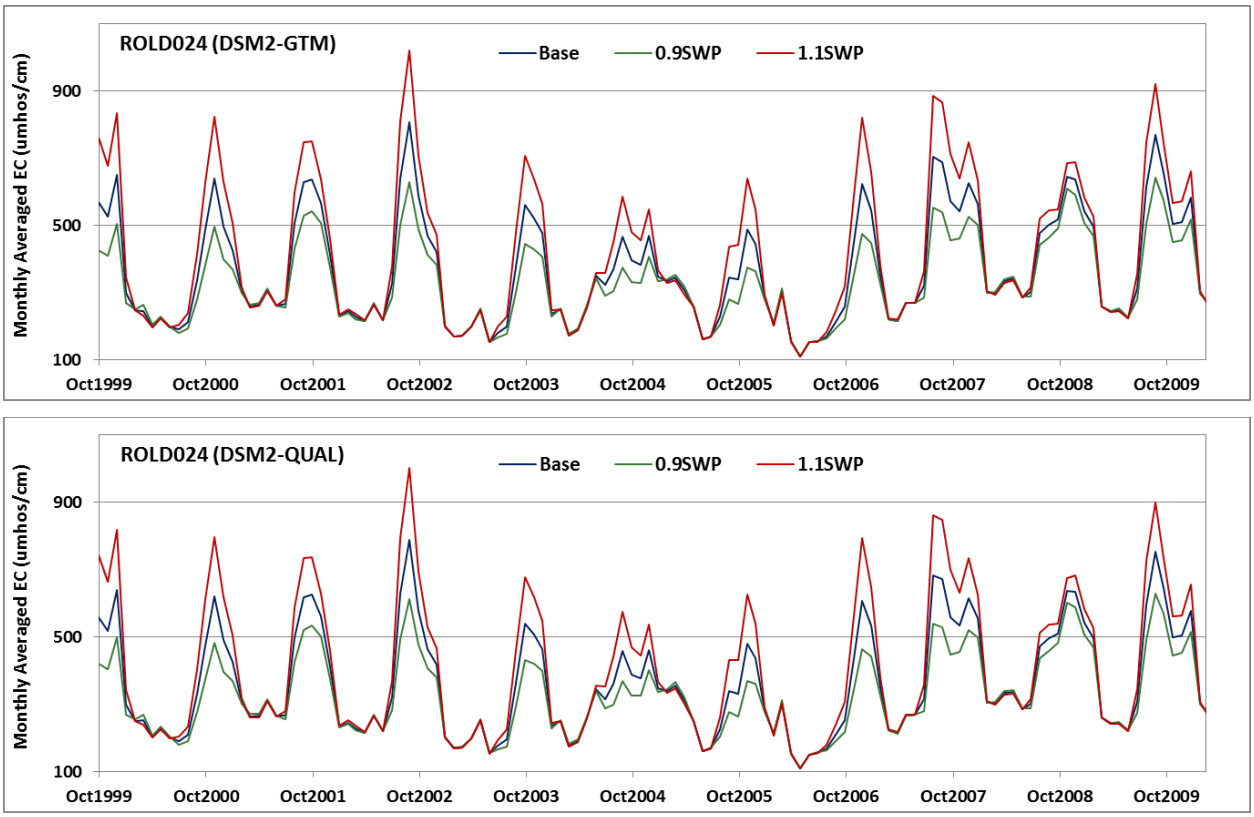


Figure 4-23 Sensitivity Analysis of Varying SWP Pumping by 10 percent at Old River at Bacon Island

4.6.2 Delta-scale Convergence Test

Any solver based on a partial differential equation should converge to the solution of that equation as the spatial and temporal step is refined. The convergence test of the Eulerian scheme on a single reach case was tested by Ateljevich et al. (2011). We verified only that this property of convergence holds over the more complex Delta network system. Note that while convergence testing is considered to be an essential test of the solver and how well it solves its target equations (verification), it is not a test against field data and a test of the success of those equations in modeling reality (validation).

For this test, the hydrodynamic information is obtained from DSM2-HYDRO with a discretization length (hydro_dx) of 5,000 ft and hydro time step of 15 minutes. The spatial step (gtm_dx) for transport in our base study is 1,000 ft. The time step is 5.0 minutes, though subcycling reduces this adaptively.

The purpose of this testing is to examine convergence and stability of this scheme on a network system. The simulation result of dx = 250 ft is used as the benchmark solution. The convergence test is done by assessing change in error under successive refinement of the grid each time by a factor of two. DSM2-GTM internally recalculates the time step based on the CFL number, so that as the spatial step (dx) is coarsened or refined. The time step (dt) will be coarsened or refined approximately in lockstep. The three levels of discretization used to assess convergence are dx = 500 ft, 1,000 ft, and 2,000 ft. The raw data set are 15-minute-instantaneous values that operated for 13 years.

Error norms relative to the benchmark are used as the measure to quantitate the difference, denoted as *e*. The analysis is done at individual location and evaluated separately. Three norms are used: L_1, L_2, and L_{inf}. L_1 norm in Eq. (21) is the absolute difference between two vectors. In a more general case of error measurement, it is scaled by the size of the vector, which is known as Mean Absolute Error (MAS). The L_2

norm in Eq. (22) is the Mean Square Error (MSE). L_{inf} norm in Eq. (23) is the maximum magnitude of the error vector.

$$L_1 = \frac{1}{N}\sum_n |e_n| \tag{21}$$

$$L_2 = \frac{1}{N}\sqrt{\sum_n e_n^2} \tag{22}$$

$$L_{inf} = \max(|e_n|) \tag{23}$$

L_1, L_2, and L_{inf} are calculated for three sets and data (dx = 500 ft, 1,000 ft and 2,000 ft) at each individual site. The order of convergence (*P*) and the ratio of the norms for those key locations are summarized in Table 4-1. To visualize the convergence as the grid goes from coarse to fine, the error norms of L_1 and L_2 against grid sizes are plotted on logarithmic scale in Figure 4-24. By looking at the values of L_1, L_2, and L_{inf} norms in Table 4-1, it is obvious that the error is reduced exponentially. The factor of reduction from dx = 2,000 ft to dx = 1,000 ft is much more significant than that from dx = 1,000 ft to dx = 500 ft. The ratios of the norm differences mostly are greater than 2.0 and the order of convergence is mostly between 1.0 and 2.0 for spatial steps we would consider using for most studies.

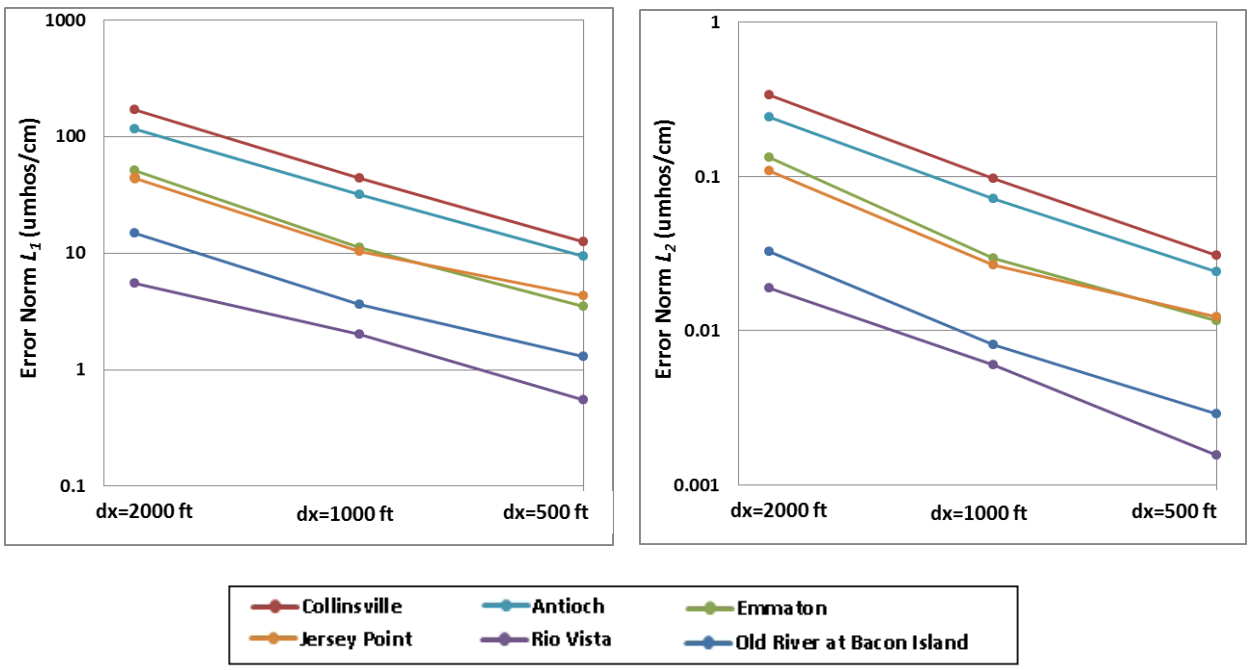


Figure 4-24 L_1 and L_2 Error Norms on Logarithmic Scale Plots

The results for gtm_dx less than 1,000 ft are almost identical on a typical DSM2 flow field of 5,000 ft. Gtm_dx = 2,000 ft is too coarse for the Delta network, whereas gtm_dx = 1,000 ft seems to be a good spatial step for general purpose Delta simulations. Smaller grid sizes cost more in calculation time and should be avoided unless these are needed for particular studies with sharper fronts. The differences from gtm_dx = 500 ft to gtm_dx = 250 ft are fairly small, mostly less than 10 umhos/cm in Delta locations, and that is far less than 1 percent of tidal amplitude. This is about where the point convergence falls off. DSM2-QUAL, Version 8.1 and subsequent versions show qualitative convergence

with respect to time step and parcel size with the corrections to advection and dispersion formulation (Liu et al. 2011).

Table 4-1 Results for Convergence Test

	Grid size	L_1 (µmho/cm)	L_2 (µmho/cm)	L_{inf} (µmho/cm)	Ratio		
					L_1	L_2	L_{Inf}
Old River at Bacon Island	500 ft	1.2944	0.0029	8.5038	-	-	-
	1,000 ft	3.5950	0.0081	25.2857	2.7773	2.8072	2.9734
	2,000 ft	14.8277	0.0324	68.3060	4.1245	3.9829	2.7014
	P	**1.3872**	**1.3409**	**0.9119**	-		
Collinsville	500 ft	12.5143	0.0306	106.9648	-	-	-
	1,000 ft	44.2307	0.0967	445.3335	3.5344	3.1587	4.1634
	2,000 ft	170.8205	0.3356	666.7441	3.8620	3.4707	1.4972
	P	**1.0702**	**1.0820**	**0.2830**	-		
Emmaton	500 ft	3.5039	0.0117	64.4849	-	-	-
	1,000 ft	11.2394	0.0295	193.4102	3.2077	2.5219	2.9993
	2,000 ft	51.4593	0.1321	476.2666	4.5785	4.4810	2.4625
	P	**1.3053**	**1.6214**	**0.8204**	-		
Antioch	500 ft	9.4444	0.0242	109.6953	-	-	-
	1,000 ft	32.1238	0.0718	371.1885	3.4014	2.9608	3.3838
	2,000 ft	116.7253	0.2428	630.4229	3.6336	3.3838	1.6984
	P	**1.0540**	**1.1228**	**0.4345**	-		
Jersey Point	500 ft	4.3004	0.0123	55.9795	-	-	-
	1,000 ft	10.2797	0.0266	170.6326	2.3904	2.1535	3.0481
	2,000 ft	44.4614	0.1084	419.1099	4.3252	4.0811	2.4562
	P	**1.6805**	**1.8336**	**0.8063**	-		

Notes: *P* = order of convergence, *µmho/cm* = micromhos per centimeter

4.7 Summary

1. DSM2-GTM accomplishments so far include integrating GTM into DSM2, accommodating special features (boundaries, junctions, external flows, reservoirs and gates), and successfully simulating EC for the full Delta using a full cycle of DSM2-HYDRO and DSM2-GTM.
2. With the historical Delta EC simulation, January 1999—April 2012, and the calibrated dispersion coefficients from current DSM2-QUAL Version 8.1, DSM2-GTM shows consistent results compared with DSM2-QUAL. DSM2-GTM also matches historical EC data at key locations fairly well. Except for some discrepancies in the South Delta area, most locations are almost identical.
3. For advection only, the numerical diffusion of the new Eulerian scheme is minimal and has been confirmed at field scale. Results of the test case are close to the results from DSM2-QUAL.

4. The Eulerian scheme has been well-tested on a single channel problem with different scenarios by Ateljevich et al. (2011). We have also done field-scale tests with reasonable convergence results.
5. Sensitivity tests indicate the response from DSM2-GTM to hydrology is as anticipated and in a range that is consistent to the response of DSM2-QUAL.
6. DSM2-GTM is stable in convergence and during years of simulation. The performance is reasonable considering it has more precise grids and tracks of the grid at each time step. Currently, it takes DSM2-GTM about 30 minutes for a 10-year simulation while it takes DSM2-QUAL 15 minutes for the same period. There may be room to improve the performance, but both are fairly fast, so this is not considered as a critical issue early in development.
7. The fixed DSM2-GTM grid offers convenience and extensibility. Sediment, dissolved oxygen, and mercury modules will be released soon.
8. A fixed grid should make visualization tools easy to implement, which has been a difficulty with DSM2-QUAL for a long time.
9. Currently, DSM2-GTM only operates off-line of DSM2-HYDRO. There is interest to conduct salinity simulation in-line with DSM2-HYDRO, partially to incorporate density-induced setup in the model and partly to allow operation of hydraulic structures based on salinity.

4.8 Acknowledgements

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

37th Annual Progress Report
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Chapter 5
Estimating Net Delta Outflow, Summary of March 2016 Report to the State Water Resources Control Board

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DEPARTMENT OF WATER RESOURCES

STATE OF CALIFORNIA

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5 Estimating Net Delta Outflow, Summary of March 2016 Report to the State Water Resources Control Board

5.1 Introduction

In fall 2015, the State Water Resources Control Board (SWRCB) requested that the California Department of Water Resources (DWR) provide technical guidance on the best available consumptive use models and, more broadly, on the subject of Net Delta Outflow calculations. DWR produced a report, titled *On Estimating Net Delta Outflow (NDO), Approaches to Estimating NDO in the Sacramento-San Joaquin Delta* (California Department of Water Resources 2016) and submitted it to the SWRCB in March 2016. This chapter is a brief outline and a summary of the report.

5.2 Summary

The first section of the report defines Net Delta Outflow (NDO) and the Net Delta Outflow Index (NDOI). The second section of the report describes various consumptive-use estimates including DAYFLOW, Delta Island Consumptive Use (DICU), and Delta Evapotranspiration of Applied Water (DETAW). DAYFLOW is a computer program designed to estimate the daily average NDOI. In order to determine NDOI, calculations of channel depletions are necessary for the estmate (see http://www.water.ca.gov/dayflow/). This consumptive-use section also addresses possible effects of groundwater and channel depletions and presents land-use data. The third section of the report addresses the difficulties and progress in measuring direct flows at various stations for determining outflow. The fourth section discusses using salinity at Martinez to determine outflow, which is a salinity inversion method. The fifth section describes recent activities in gathering data and information on consumptive use and suggests areas for additional data collection and modeling of groundwater interaction. This section also discusses the addition of increased instrumentation to measure flows to aid in quantifying net channel depletions.

5.3 Recommendations

The following are the report's key recommendations

- At this point in time, an NDOI-like water balance remains the best choice as an indicator of Net Delta Outflow, but should be updated to incorporate improvements in consumptive-use estimates and to correct a few known accounting errors, such as the inflow from Yolo Bypass during summer.
- The monthly DICU model represents our most mature consumptive-use estimate. It was the in-progress effort mentioned in the SWRCB Water Right Decision 16411 and has been established in planning and modeling practice throughout the Bay-Delta modeling community for many years. Much work has been done in recent years to replace DICU with a daily model, which is DETAW. DETAW includes shorter time scales and better soil moisture accounting. DETAW, a consumptive-use model, is now completed. Still, to estimate net channel depletions, which have a more direct impact on outflow estimates for factors, such as groundwater use, these factors must be incorporated in the calculations along with DETAW amounts. As a result, this model and its post-processed net channel depletions have not been officially released, in part, because of some uncertainties over the contributions of seepage from channels and groundwater uptake. Input, development, and acceptance of certain groundwater assumptions are needed from a wider group of groundwater experts before this model can be officially released.

- The 4-station (Rio Vista, Jersey Point, Dutch Slough, Threemile Slough) direct measurement approach to outflow is inaccurate and should not be used to calculate NDO or to corroborate NDOI. This recommendation is based on the lack of accuracy in the results and the nature of the approach.
- DWR and other institutions should continue to perform more measurements, field studies, and investigations to refine estimates.

5.4 References

California Department of Water Resources. 2016. *On Estimating Net Delta Outflow (NDO), Approaches to Estimating NDO in the Sacramento-San Joaquin Delta*. Sacramento (CA): Delta Modeling Section. Bay-Delta Office. California Department of Water Resources.