


Article

An Open-Source Cross-Section Tool for Hydrodynamic Model Geometric Input Development

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Abstract: Hydrodynamic models are widely used in simulating water dynamics in riverine and estuarine systems. A reasonably realistic representation of the geometry (e.g., channel length, junctions, cross-sections, etc.) of the study area is imperative for any successful hydrodynamic modeling application. Typically, hydrodynamic models do not digest these data directly but rely on pre-processing tools to convert the data to a readable format. This study presents a parsimonious open-source and user-friendly Java software tool, the Cross-Section Development Program (CSDP), that is developed by the authors to prepare geometric inputs for hydrodynamic models. The CSDP allows the user to select bathymetry data collected in different years by different agencies and create cross-sections and computational points in a channel automatically. This study further illustrates the application of this tool to the Delta Simulation Model II, which is the operational forecasting and planning hydrodynamic and water quality model developed for the Sacramento–San Joaquin Delta in California, United States. Model simulations on water levels and flow rates at key stations are evaluated against corresponding observations. The simulations mimic the patterns of the corresponding observations very well. The square of the correlation coefficient is generally over 0.95 during the calibration period and over 0.80 during the validation period. The absolute bias is generally less than 5% and 10% during the calibration and validation periods, respectively. The Kling–Gupta efficiency index is generally over 0.70 during both calibration and validation periods. The results illustrate that CSDP can be efficiently applied to generate geometric inputs for hydrodynamic models.



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1. Introduction

Hydrodynamic models are indispensable tools used to simulate the movement of water in different types of water bodies, and for various purposes. In oceans, hydrodynamic models can be used to help characterize the tides [1] and to simulate regional oceanic circulation [2]. In estuaries, hydrodynamic model results can be used to simulate shallow water wave motions [3,4], to simulate flooding [5], as input to water quality models, for purposes including water project operation [6], and as input to particle tracking models [7], for purposes including determining the effects of water project operations on fish survival rates [8–10]. In riverine systems, hydrodynamic modeling can be used to better understand flood risks [11] and to evaluate the effects of dredging [12].

Hydrodynamic models require an understanding of the shapes of the beds of river channels and other waterbodies in the systems they simulate. Geometry input datasets, created using bathymetry data, describe these shapes to the models. The geometry data requirements of a model depend in part upon its dimensionality. Hydrodynamic model dimensionality can be one-dimensional (1D) (DSM2 [13,14] and HEC-RAS [15]), two-dimensional (2D) (RMA2 [16,17], HEC-RAS [15]), or three-dimensional (3D) (Delft 3D [18], SCHISM [19,20], SUNTANS [21,22], UnTRIM [23,24]).

Multidimensional model geometry creation requires a continuous surface created from channel bathymetry data. Examples are a Digital Elevation Model (DEM) or Digital Terrain Model (DTM), such as a river terrain model [25]. Both types of surfaces can be created from datasets such as bathymetry data and cross-sections. Surfaces can be further refined using tools such as the GIS-based tool Waterscape Subbasin Identification (WASUBI), which identifies subbasins [26]. Tools used to create geometry for 1D models can also use a continuous surface, but they generally do not require it, since they can also work with bathymetry point data.

Three-dimensional model geometry, also known as a mesh, consists of 3D polygonal elements, which have a node at each vertex of the elements. Mesh development software displays a mesh as a set of points connected by lines. Each node has x, y, and z coordinates, which determine the shapes and sizes of the elements. A mesh can be structured or un-structured. An unstructured mesh allows grid size and shape to vary as needed to appropriate size for the resolution needed, given the variations in the bottom contours. Different 3D models have different constraints on element shape [27]. Tools to create 3D meshes include Aquaveo SMS, used for SCHISM and other multidimensional models, and RiverBox [28], which is an ArcGIS toolbox. Two-dimensional model geometry input is similar to a 3D model geometry input, consisting of a mesh of 2D polygons. The mesh is visualized as a flat surface, but each node has an elevation defined, which is typically determined using a continuous surface created from bathymetry data. HEC-RAS and RMA2 both can include 2D elements in their meshes, as well as 1D elements. Tools to create 2D meshes include Aquaveo SMS and the HEC-RAS 2D Flow Area editor [15].

Cross-sections for 1D models are created exactly or approximately perpendicular to the channel center lines of a river system. The shapes of the cross-sections are derived from bathymetry data, either as individual points, or as a surface created using GIS, such as a DEM. Coordinate systems are channel-based, with cross-section point coordinates measured in the longitudinal and transverse directions. Cross-sections are placed as needed to approximate the variations in the channel bathymetry that are most important for the accuracy of the flow simulation. Examples of 1D models using this approach include DSM2 [14] and HEC-RAS [15]. Tools used to create cross-sections for 1D models include HEC-RAS, the Advanced Spaceborne Thermal Emission and Reflection (ASTER) Radiometer Global Digital Elevation Model [29], and RiverBox [28]. HEC-RAS (USACE), ASTER [29], and RiverBox [28] all have the option to create cross-sections automatically, using DEM data. ASTER also has the ability to create synthetic cross-sections using a rating curve derived from observed data. Automatic cross-section creation may be less time-consuming than manual cross-section creation, but it requires a surface such as a DEM, created from high-quality bathymetry data, and in the case of ASTER, the automatically created cross-sections must be adjusted manually to exclude lower-quality data [29]. ASTER's method of creating synthetic cross-sections appears to be useful in areas lacking adequate bathymetry data, but their applicability of these cross-sections outside the range of hydrologic conditions used to develop them is not discussed [29]. HEC-RAS, in addition to creating cross-sections automatically, allows the user to create and edit cross-sections manually by entering and/or modifying station and elevation coordinates for each cross-section [15]. RiverBox is a tool for creating cross-sections automatically, using interpolation to create reasonable approximations in areas with relatively sparse bathymetry [28]. The method used by RiverBox is almost completely automated, and it appears to assume that all bathymetry data are of equal quality.

Automated approaches to cross-section creation can save time and yield more consistent results. However, they either assume that all data used to create them are of equal quality, or they include a method for making manual adjustments to cross-sections. The current study proposes a parsimonious cross-section development tool: the Cross-Section Development Program (CSDP). It is an open-source application written in Java. It is a standalone application, requiring no other software, such as GIS. It is easy to use, and is designed specifically to create input for DSM2 [14] but also can be applied to other

hydrodynamic models. The CSDP differs from the other tools described above in that the placement of channel centerlines, cross-section lines, and cross-section points are all conducted manually. This has the advantage of allowing the user full control over cross-section creation, allowing the user to place more emphasis on bathymetry data considered to be higher quality, and to easily incorporate proposed changes to channels, such as dredging. However, the manual cross-section development process can be time consuming, and results for a given set of input data will be more variable than results from automated tools.

The process of creating cross-sections with the CSDP involves clicking on a graph of bathymetry data and/or DEM data. The bathymetry points on the graph can be color-coded to identify attributes such as collection year or data source. The use of a DEM requires more pre-processing of bathymetry data, and can make variations in data quality less obvious to the user. The CSDP also includes a tool to display bathymetry data together with cross-sections in a 3D interactive plot [30], allowing the user to zoom, pan, and rotate the plot to determine qualitatively how the cross-sections compare to the bathymetry data. The 3D plot can also help the user identify features that the user may wish to exclude from model geometry, such as narrow deep holes.

This paper describes the application of the CSDP for developing geometry for DSM2, including descriptions of bathymetry data used by the CSDP, the DSM2 model grid, and DSM2 geometry input requirements. The usage of the CSDP graphical user interface (GUI) is then demonstrated, including creating channel centerlines, cross-section lines, and cross-sections. Recently added CSDP features for adjusting cross-sections to match bathymetry data are introduced, along with best practices for cross-section development, and adjusting cross-sections to match channel volumes calculated using GIS. The results of a recent DSM2 calibration using geometry updated with the CSDP are then presented.

2. Case Study Setup

2.1. Study Area: The Sacramento–San Joaquin Delta, California

The Sacramento–San Joaquin Delta (Delta; Figure 1a), the largest estuarine environment on the west coast of the United States, serves as the hub of the State of California's vast water supply system with significant water supply and environmental benefits to the State. It supplies water to over 25 million people, about two-thirds of California's population, via the State Water Project (SWP) and Central Valley Project (CVP). It also provides habitats for over 750 species, with some of that are at risk or endangered. The Delta is located at the confluence of Sacramento River (in the north) and San Joaquin River (in the South and East), two largest river systems in the State. It consists of a complex system of diked islands surrounded by channels, sloughs, marshes, and shallow lakes. A portion of the freshwater from those two river systems flows through the Delta to repel the intrusion of salty water from the Pacific Ocean (via the San Pablo Bay), maintaining desirable water quality in the Delta suitable for agricultural, municipal, and environmental usage. Another portion of the freshwater serves as a major source for Delta diversions (including SWP and CVP exports).

A set of State and federal regulatory standards (e.g., minimum flow rate, maximum level of salinity) have been set across the Delta to maintain a sustainable and healthy Delta ecosystem. Water operations in the Delta (e.g., when and how much the SWP and CVP can move water) must follow these regulations. The hydrodynamic and water quality conditions of the Delta are monitored via a number of flow, stage, and water quality (e.g., salinity) stations in the Delta to ensure compliance with those standards. Some of the key stations are illustrated in Figure 1. For forecasting operations and planning studies (e.g., proposed structural changes to the Delta) where real observations are not available, numerical models are typically used to simulate the hydrodynamics and water quality in the Delta to ensure compliance. The operational model applied for this purpose will be described in the following sub-section.

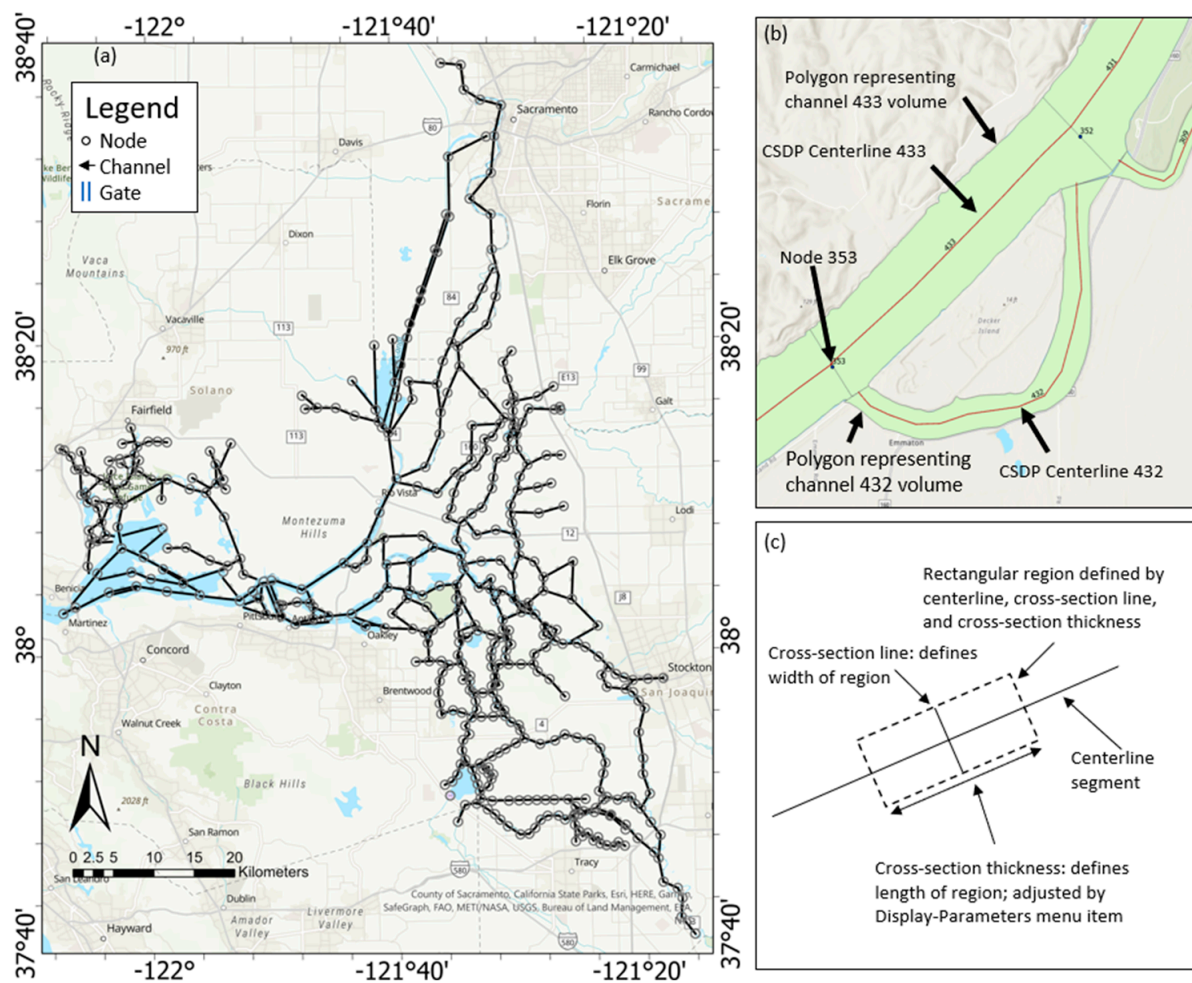


Figure 1. (a) An example CSDP grid network representing the waterways and water facilities in the Sacramento–San Joaquin Delta, California. (b) Polygons used to represent real-world channels and calculate channel volumes. Centerlines are not attached to nodes to prevent overlapping volume estimates. (c) The CSDP displays data in cross-section view for a rectangular region of data defined by a centerline segment, a cross-section line, and the cross-section thickness.

2.2. Study Model: The Delta Simulation Model II

This study exemplifies the application of the CSDP to the operational one-dimensional hydrodynamic and water quality model for the Delta, the Delta Simulation Model II (DSM2). DSM2 is developed and maintained by the California Department of Water Resources (CDWR). It has been widely used in environmental impact assessment and decision-making support in the Delta by the State, federal, and other stakeholders. Despite of the increasing availability of multi-dimensional models in the Delta, DSM2 is still the primary model applied in contemporary Delta studies due to its ubiquity, short runtime, and long-established and probably the best-understood performance among all Delta models [31,32]. The current version of DSM2 contains three modules: HYDRO, QUAL, and PTM. HYDRO calculates one-dimensional hydrodynamic variables (e.g., flow rate, stage) across the Delta. Based on the flow field generated by HYDRO, QUAL simulates the spatial and temporal variations of water quality variables (e.g., salinity, water temperature, dissolved oxygen) and PTM simulates the pseudo-3D transport of neutrally buoyant particles in the Delta. The demonstration in this study focuses on the hydrodynamic module HYDRO, as its output depends on the channel geometry directly.

The numerical algorithms adapted in HYDRO are based on the FourPt Program of the U.S. Geological Survey (USGS Reference). The program simulates one-dimensional

(1D) unsteady flow in open-flow channel networks. Using the four-point implicit finite-difference approach with Newton–Raphson iteration, the program converts the mass and momentum conservation governing equations of unsteady 1D open channel flows into a set of linearized equations. These equations are then solved via Gaussian elimination. HYDRO requires user-defined channel cross-sections. Initially, cross-section information is supplied to HYDRO manually, which is tedious and time-consuming, particularly for complex open-channel networks like the Delta. The CSDP program is developed to streamline and standardize the process of creating channel cross-sections and exporting them in a format that can be digested directly by DSM2 based on the latest available bathymetric data, which will be discussed in the following sub-section.

2.3. Bathymetry Data

Bathymetric surveys in various areas of the Delta have been ongoing ever since the 1930s by different state and federal agencies as well as the private sector. The surveying methods and the quality of the data collected have evolved over time. The previous version of DSM2 (Version 8.2) has adapted all survey data up to 2009. Since then, higher-resolution data, including the multi-beam and single-beam survey data in different portions of the Delta, have become available. Based on some of these recently available surveyed data, CDWR and the U.S. Geological Survey (USGS) created Digital Elevation Models (DEMs) with grid sizes of 10 m (m) and 2 m in part of the Delta [33].

In the current version of DSM2 (Version 8.3), the CSDP is applied to re-create cross-sections based on existing geometric data (adapted in Version 8.2) as well as the newer geometric data since 2009 (Figure 2). Specifically, for the newer data, the CSDP considers the 2 m DEM first. When the 2 m DEM data are not available, the data collected via single-beam instruments that were not used to create the 2 m DEM are used instead. For places where neither 2 m DEM nor single-beam data are available, 10 m DEM data are utilized. For areas without the newer data, the geometric data in version 8.2 are employed.

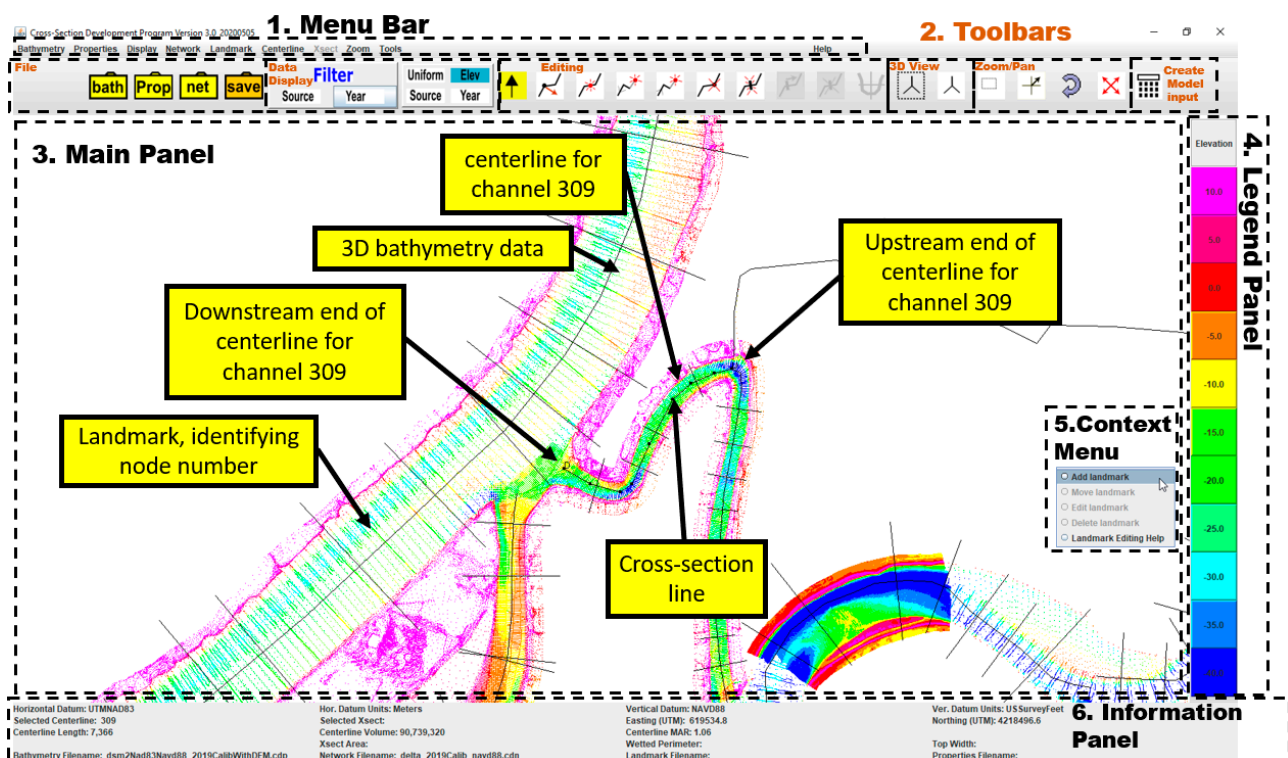


Figure 2. An example graphic user interface window of the CSDP.

3. The Cross-Section Development Program

This section presents the purpose and scope of the Cross-Section Development Program (CSDP), the graphic user interface (GUI) of the CSDP, and some of the CSDP main features. CSDP software availability is detailed in Appendix A. A nomenclature summarizing abbreviations used in this paper is provided in Appendix B.

3.1. Purpose and Scope of the CSDP

The CSDP is designed to create geometry inputs for hydrodynamic models. These inputs include a geo-referenced grid network of channels, nodes, reservoirs, and flow and water quality control facilities (e.g., gates) representing the real-world modeling domain (e.g., Figure 1a), cross-sections approximating the shape of each channel, and conveyance characteristics of each cross-section.

In hydrodynamic models, each channel is typically connected to other channels by nodes located at channel endpoints. The CSDP uses channel centerlines to represent channels (e.g., Figure 1b). The CSDP uses landmarks to represent features whose location can be described using a single set of geographic coordinates. Landmarks appear as points with text labels in the CSDP and are used to represent nodes and other features. Each channel can be divided to several polygonal regions, which are defined by the centerline, cross-section line, and cross-section thickness (Figure 1c). Each channel can have one or more cross-sections. Each cross-section's location is defined by channel number and the distance measured along the channel centerline from the upstream end toward the downstream end. Cross-section lines are always perpendicular to the centerline segment that they intersect. A cross-section represents a portion of the channel that extends either all the way to the node or half the distance to adjacent cross-sections. Ideally, the cross-section thickness should be sufficiently large to include the entire portion of the channel that it represents, but in practice, the thickness is often reduced depending mostly upon the curvature of the channel and the density of the bathymetry data. In the CSDP, the channel centerlines, cross-section lines, and cross-section drawings are referred to as the “network”.

The CSDP calculates the following conveyance characteristics for each cross-section: area, width, wetted perimeter, hydraulic radius, x centroid, and z centroid. Based on these metrics, the channel volume can be derived. The CSDP's functionality for viewing and calculating cross-sections can also be used to analyze bathymetry data for use in developing model inputs for reservoirs and gates that represent weirs.

3.2. The CSDP GUI

The main application window of the CSDP contains six main components: a menu bar, a set of toolbars, a main panel, a legend panel, an information panel, and a context menu for creating and editing landmarks (Figure 2). The menu bar includes ten menus, which provide access to most of the CSDP functionality. The “bathymetry” menu is for loading and saving bathymetry data files. The “properties” menu is for loading and saving files that contain various program options. The “display” menu is for adjusting program options, filtering the display of bathymetry data, changing the bathymetry data color scheme, and loading a file that displays channel outlines. The “network” menu is for loading and saving network (channels and cross-section) files, creating various types of bathymetry plots and network diagnostics, and creating DSM2 geometry input. The “landmark” menu is for loading and saving landmark (locations of nodes or other features) files. The “centerline” menu is for editing channel centerlines and cross-section lines, and for creating various types of bathymetry and cross-section plots. The “Xsect” menu is for viewing and editing cross-sections. Section 3.3 discusses cross-section editing in detail. The “zoom” menu is for zooming and panning the bathymetry display in the main panel. The “tools” menu is for accessing a number of functions for viewing and manipulating CSDP data. The “help” menu displays the CSDP license information.

The main function of the toolbars is to provide easy access to the most commonly used functions that are also accessible through the menu bar. The file toolbar is for loading

bathymetry, properties, and network files, and for saving the currently loaded network file. The data display toolbar includes a filter panel and a color scheme panel. The data display filter panel (on the left) is for toggling the display of bathymetry data for selected sources (data provider names) and/or years. The data display color scheme panel (on the right) is for setting the color scheme for the bathymetry points, which can have different colors based upon elevation, source, and year. The editing toolbar is for editing centerlines and cross-section lines and viewing cross-sections. The buttons in this toolbar are for activating the various centerline and cross-section line editing modes. When a mode is activated, the background of the button will change from white to yellow, and mouse click and drag events on the main panel will perform the corresponding operation. The button with the vertical arrow is for deactivating all centerline and cross-section line edit modes. The buttons that follow activate the following editing modes or perform the following functions: move centerline point, insert centerline point, add upstream centerline point, add downstream centerline point, delete centerline point, add cross-section line, move cross-section line, delete cross-section line, and view selected cross-section. The 3D view toolbar is for displaying three-dimensional cross-section plots for a region defined by clicking and dragging a window in the main panel, or for a region including specified channels. The zoom/pan toolbar is for zooming and panning in the main panel. The buttons perform the following functions: activate zoom mode, activate pan mode, undo last zoom, and zoom all the way out. The create model input panel contains one button that is for calculating the network, which exports geometric information to hydrodynamic models in a readable format.

The main panel displays bathymetry data, channel centerlines, cross-section lines, and landmark data (usually nodes) in plan view. The bathymetry data are surveyed bathymetry points or DEM data created from surveyed data. The data are colored according to a specified color scheme. Channel centerlines and cross-section lines come from a user-defined network data file, while grid nodes come from a user-defined landmark data file. The logical relationships between upstream and downstream nodes are defined in a channel connectivity file that can be imported to help ensure that channels are defined with the correct upstream to downstream orientation. Names of all currently loaded data files are displayed in the information panel.

The context menu is accessed by right-clicking on the main panel. Right-clicking on an existing landmark will enable landmark editing functions. Right-clicking on a location with no existing landmark will create a new landmark. The legend panel shows the range of bathymetry data characteristics in different colors. There are three characteristics considered in CSDP: the data source (i.e., the name of the agency that collected the data), collection time (i.e., the year when the data were collected), and the elevation of data points (e.g., Figure 2). The “Uniform” option will use the same color for all points. These characteristics can be selected in the toolbar.

The information panel provides users with the basic information of a selected feature in the main panel. For instance, if a centerline is selected, its name, length, and associated channel volume will be highlighted in the information panel; when a cross-section is selected, its length, top width, wetted perimeter, and other hydraulic information will be displayed. The information panel also provides geodetic datum information, geographic coordinates corresponding to the cursor position, and the names of all loaded data files.

3.3. CSDP Cross-Sections

This section describes the tools used to create, edit, and analyze cross-sections. Section 3.3.1 describes the cross-section window, which is used to create and edit cross-sections. Sections 3.3.2 and 3.3.3 describe some of the tools used to determine how well the cross-sections fit the bathymetry data, identify errors in cross-sections, and identify the potential impacts of a cross-section upon model convergence.

3.3.1. Cross-Section Window

A cross-section window displays bathymetry data in cross-section view, and allows the user to draw a line approximating the shape of the cross-section (Figure 3). The procedure for opening a cross-section window is as follows: (1) click on a channel centerline to select the centerline (the centerline will then have dots displayed at each centerline point (Figure 2), (2) click on a cross-section line to select the cross-section line (the cross-section line will then have dots displayed at each of the cross-section line endpoints), and (3) click the "view cross-section" button (Figure 2, rightmost button in the editing toolbar).

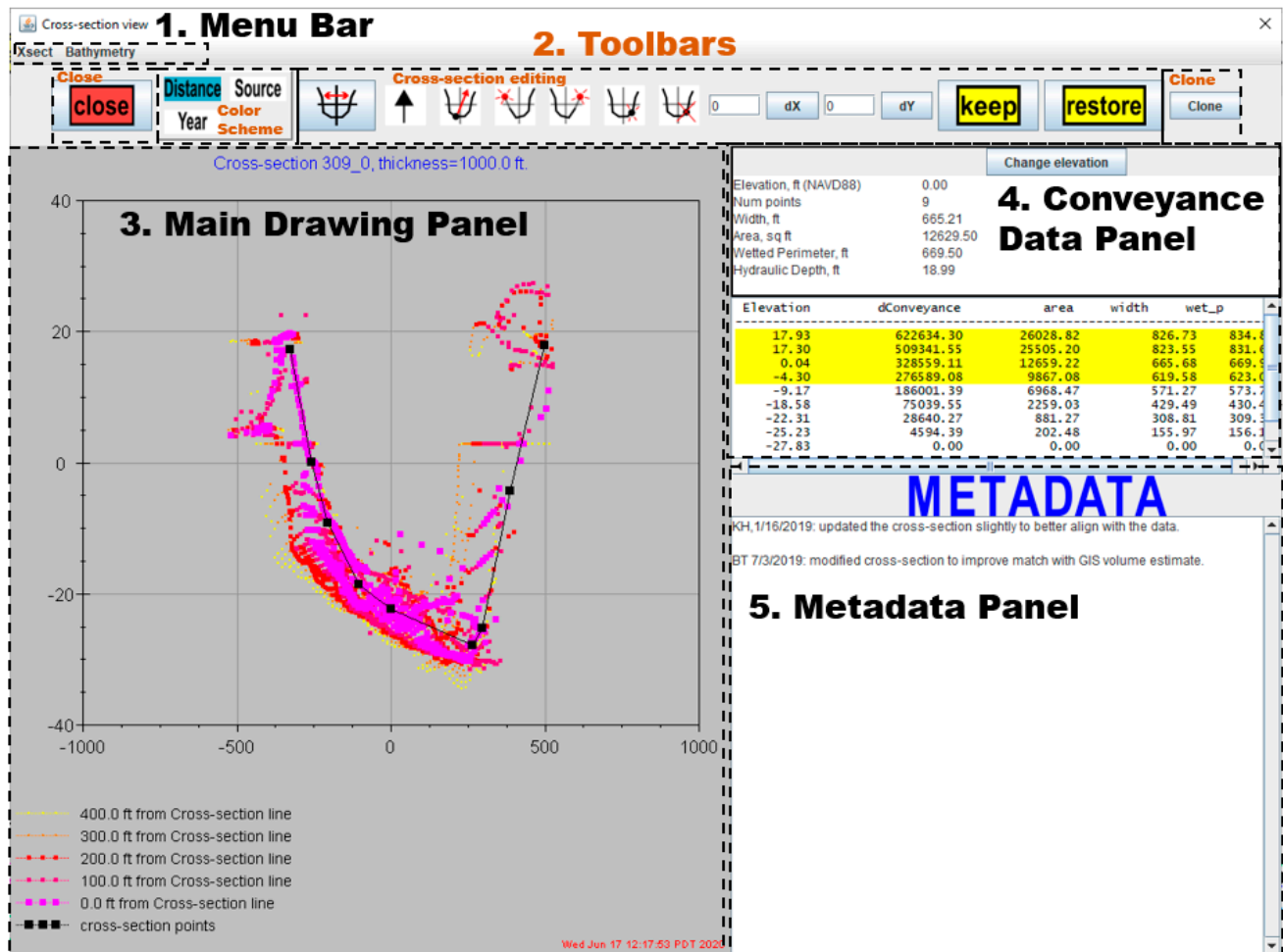


Figure 3. An example cross-section window of the CSDP.

The cross-section window of the CSDP contains five main components: a menu bar, a set of toolbars, a main drawing panel, a conveyance data panel, and a metadata panel. The menu bar contains two menus. The Xsect menu is for saving an image of the window to a file, and for exiting the window. Upon exiting, if there are any unsaved changes to the cross-section drawing, the user will be prompted to save or discard the changes. The bathymetry menu is for changing the size of bathymetry points and changing the color scheme of the bathymetry points.

The cross-section window includes four toolbars, which provide easy access to some of the functions accessible via the menu bar. The close toolbar includes a button for closing the cross-section window. The color scheme toolbar is for selecting a color scheme for the bathymetry data points. The cross-section editing toolbar is for creating and editing the cross-section drawing. The remaining buttons activate the various edit modes. When an edit mode is activated, the button's background will change from white to yellow, and mouse clicks or drag events on the main drawing panel will perform the corresponding

operation. The arrow button on the left hand side of the cross-section editing toolbar turns off edit modes. The remaining buttons from left to right activate the following editing modes: move cross-section point, add left-side cross-section point, add right-side cross-section point, insert cross-section point, and delete cross-section point. The cross-section editing toolbar also includes buttons labeled “dX” and “dY”, each with a text field. Entering a value into one of the text fields and clicking the corresponding button will add the value to each of the “x” or “y” coordinates on the graph. This function can help compare the cross-section drawing to datasets that may not be aligned well with each other, due to data inaccuracies or differences between datasets as a result of changes in the physical system over time. The cross-section editing toolbar also contains “keep” and “restore” buttons. The “keep” button will save the state of the cross-section in memory. The “restore” button will undo all changes since the last time the “keep” button was clicked.

The clone toolbar contains the “clone” button, which will remove all the points in the current cross-section window, replacing them with the points from another cross-section.

The main drawing panel displays selected bathymetry data viewed from the upstream end of the centerline segment to the downstream end, so that data on the left bank appear on the left-hand side of the graph, and data on the right bank appear on the right-hand side of the graph. The cross-section drawing consists of the line segments connected by points in black, which are created by the user by clicking on the graph. Editing (adding, deleting, moving) points can be achieved via checking on the corresponding icons in the toolbar of the cross-section window and then clicking the desirable places in the main drawing panel.

The upper portion of the conveyance data panel displays conveyance characteristics values for a specified elevation. Clicking the “Change elevation” button will allow the user to change this elevation. The lower portion of the panel displays a table of conveyance characteristics for every elevation in the cross-section. Rows in the table that intersect a user-specified range of water levels, intended to represent the intertidal zone, are colored yellow.

The metadata panel in the cross-section window allows the user to enter metadata. Metadata document why a cross-section was drawn the way it was, in order to prevent a future user from making changes without understanding the previous user’s goals in creating the cross-section. Users are encouraged to create or update metadata every time a cross-section is created, reviewed, or edited, including the following information regarding the creation, review, or edit: (1) date, (2) user name or initials, (3) datasets that were prioritized in creating/editing the cross-section drawing, and (4) an explanation of any deviations in the cross-section drawing from the bathymetry data. Metadata are especially important when creating a cross-section that does not align with bathymetry data. There are a number of reasons for creating a cross-section that does not align with bathymetry data, including: (1) to simulate proposed changes in channel geometry, such as dredging, (2) to exclude abrupt changes in geometry that would impact the convergence of the model, and (3) to adjust channel volume to match a GIS volume estimate.

All cross-section drawings in a given channel (centerline) can be viewed together in a multiple cross-section graph (Figure 4). The graph is created by first selecting a centerline in the CSDP main panel, then selecting the menu item “Centerline–Multiple Cross-Section Graph”. In the graph, all cross-section drawings are centered horizontally by the cross-section X centroids. This multiple cross-section graph can help the user to: (1) understand how shape and cross-sectional area vary along the channel; (2) identify sudden changes in geometry, such as narrow deep holes; and (3) locate errors in cross-section drawings.

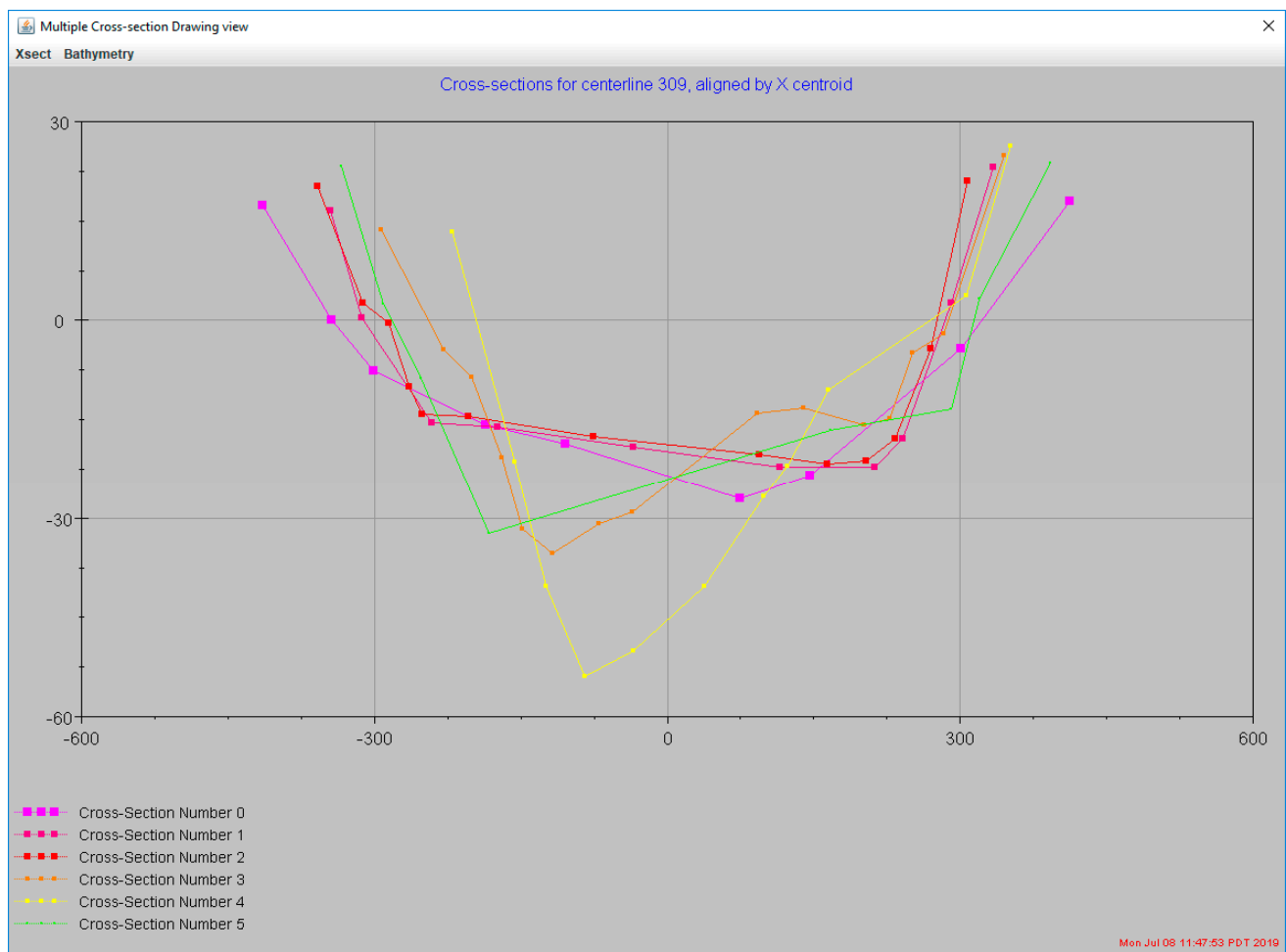


Figure 4. An example multiple cross-section graph, showing all user-defined CSDP cross-sections, aligned by X centroids, for Channel 309 (Three Mile Slough).

3.3.2. Three-Dimensional Cross-Section Plot

Bathymetry data and cross-sections for a specified channel, reach, or geographical region can also be displayed in three-dimensional (3D) view. The plot can be created by selecting the menu items “Network-3D Plots”, “Centerline-Centerline 3D View” or by clicking one of the buttons in the 3D View toolbar (Section 3.2). Figure 5 shows an example 3D plot of bathymetry data (in colorful points) and cross-sections (in white lines). The user can rotate, pan, and zoom the plot in three dimensions to gain a better understanding of the variations in the shape of the channel. This plot can help the user verify that the cross-sections are including/excluding all the physical features (represented by bathymetry data), which should be included/excluded. The user can also determine if cross-sections are likely to accurately approximate the channel volume and identify deep narrow holes that the user may wish to exclude from the cross-sections.

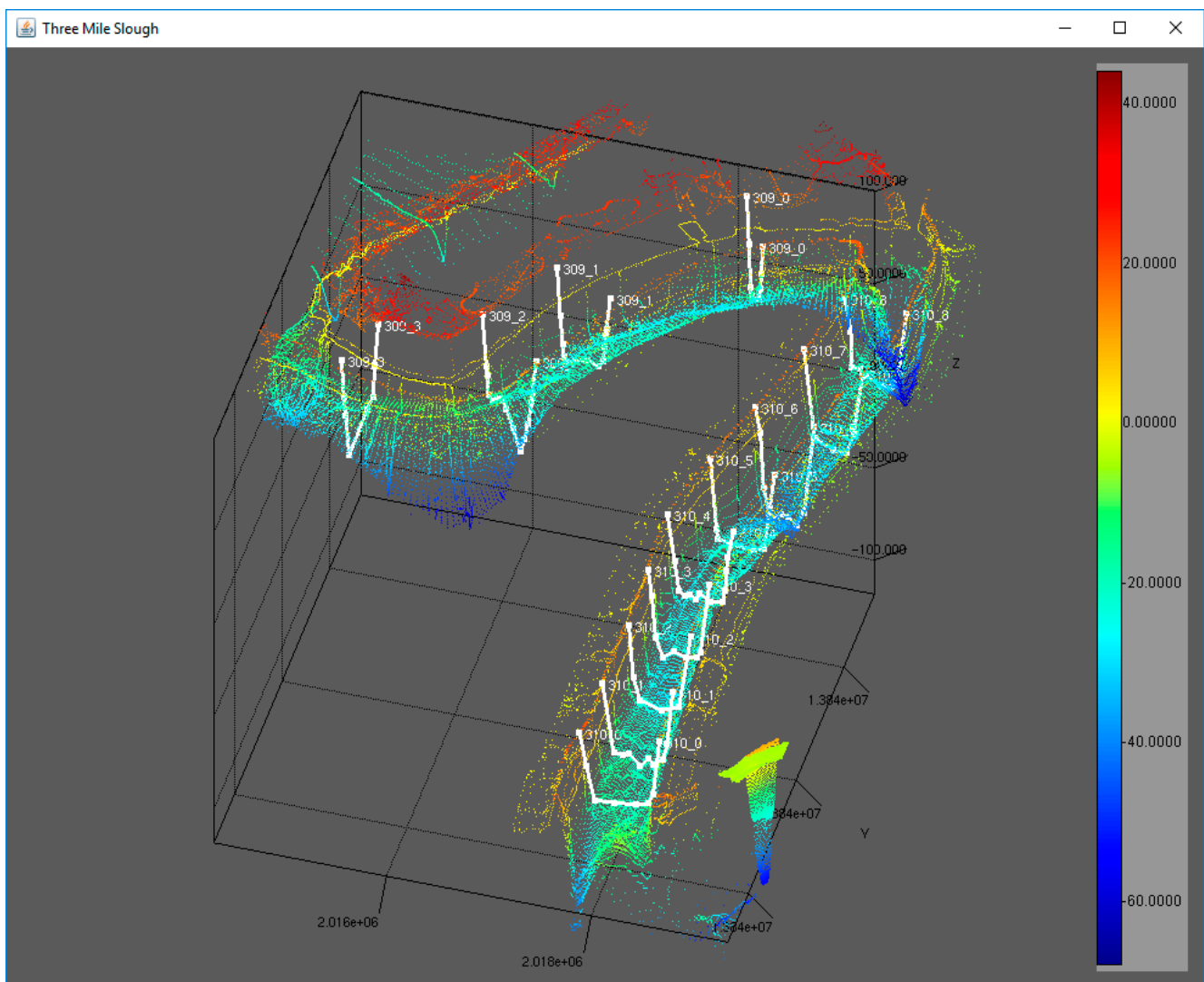


Figure 5. An example 3D bathymetry and cross-section interactive plot showing the Three Mile Slough bathymetry and user-defined cross-sections. The legend shows the elevation variations of the bathymetry data.

3.3.3. Cross-Section Slideshow

The CSDP cross-section slideshow (Figure 6) displays windows with two cross-section plots side by side. The two plots display user-created cross-sections from two different network files, and bathymetry from either two different bathymetry files or from the currently loaded bathymetry file. This tool can show how cross-sections differ between two network file versions. Cross-sections are matched by proximity, determined by comparing the locations of the intersections of the centerline segments with the cross-section lines. The window is opened by selecting the “Tools-Cross-Section Slideshow” menu item.

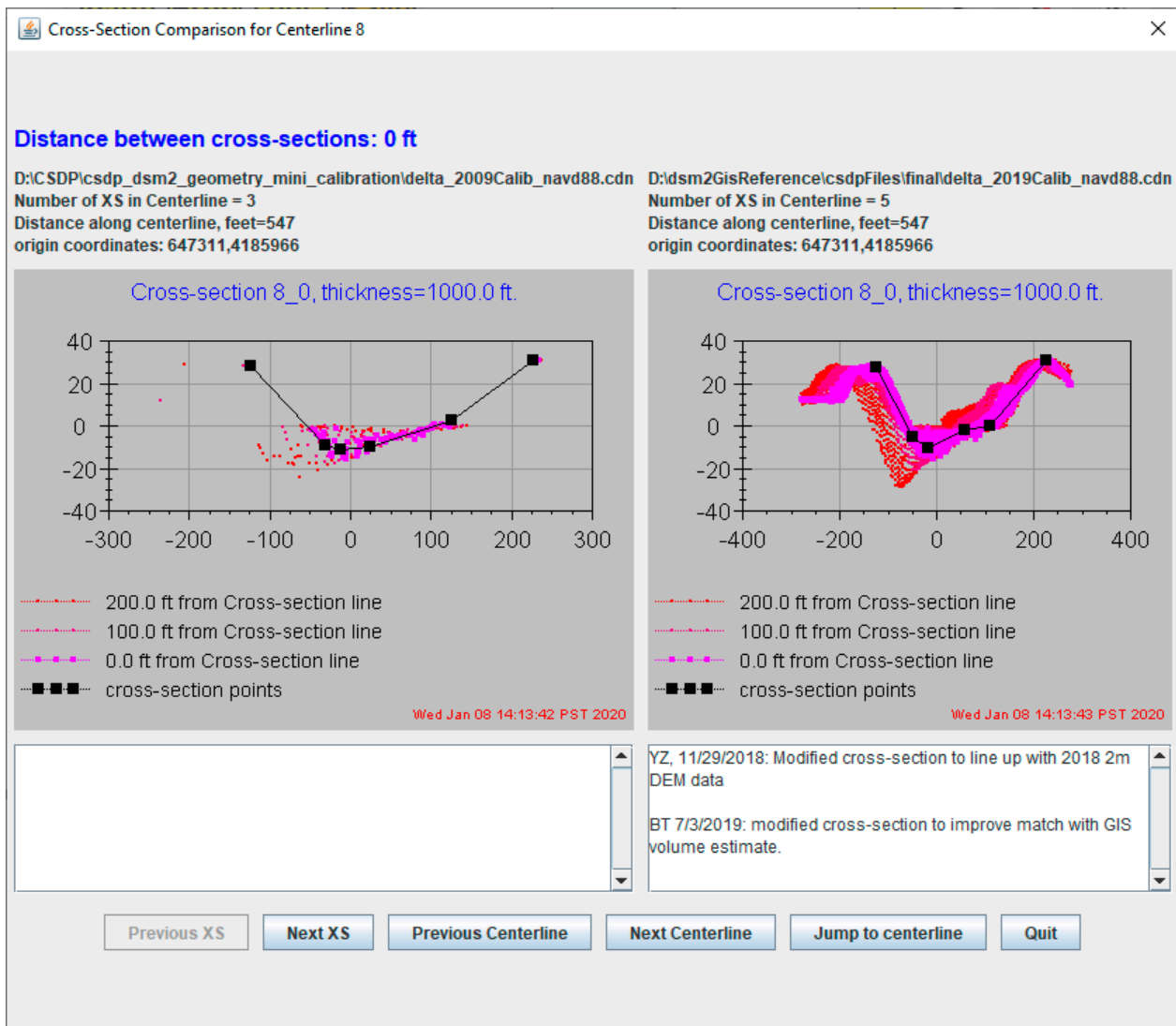


Figure 6. An example cross-section slideshow comparing cross-sections in the same location from two different network files.

3.4. Geometry Fine-Tuning

Once the geometry (i.e., centerlines and cross-sections) is roughly determined via the aforementioned CSDP functions, it can be imported into the target hydrodynamic models. To make the model run successfully and meaningfully, however, the geometry may need to be fine-tuned for several practical reasons. Firstly, geometry-related convergence issues in hydrodynamic models can arise when a channel has large variations in a cross-sectional area. Secondly, some hydrodynamic models are not designed to simulate channels drying up. The potential causes include: (1) convergence failures can be sufficient to cause oscillations in calculated stage values of increasing amplitude (also known as “blowing up”), (2) an initial stage value that is too high can cause model solvers to overcompensate, calculating a stage value near the beginning of a simulation that is below the bottom of a cross-section, (3) errors in model inputs can result in the model removing all water from a channel, and (4) the model is not designed to simulate conditions that would result in a channel drying up or almost drying up in reality (if a channel comes close to drying up in the model, the model may dry up while iterating to find a solution). Thirdly, the channel volumes determined from CSDP cross-sections need to mimic the actual channel reasonably well. This is typically achieved by matching CDSP channel volumes with channel volumes determined from other techniques. Among all existing software, ArcGIS is probably the most popular one

applied widely in calculating channel volumes for hydraulic and hydrodynamic models. The CSDP uses ArcGIS-derived (via Cut Fill calculation) channel volumes as the benchmark and tried to match it as much as possible. The CSDP includes functions to support the user in adjusting geometry to eliminate any potential geometry-related model convergence issues, prevent channels from drying up, and match GIS channel volume estimates. Some of the critical functions include: (1) a network summary report that contains diagnostical metrics that can guide users in geometry fine-tuning; (2) a centerline summary showing the variations of area, width, wetted perimeter, and bottom elevation along a specific CSDP centerline; and (3) the 3D bathymetry and cross-section plot (Section 3.3.3).

Geometry-related model convergence issues can be avoided if the areas of cross-sections in a specific channel do not vary dramatically. The CSDP calculates a metric (and exports it to the network summary report) to represent the variability in cross-section areas: maximum area ratio. It is defined as the ratio of the largest to the smallest cross-sectional area. Empirically, maintaining this value to below 2.0 has been found to be sufficient to ensure geometry-related numerical stability.

Channel drying up normally occurs when cross-section bottom elevations are above any calculated minimum stage value in a model run. The CSDP adopts a simple strategy to prevent drying up by creating pseudo-cross-section bottom elevations. The following geometry adjustment procedure can help prevent channels from drying up:

1. Determine a historical minimum stage value for each channel, using historical data or output from a long-term historical hydrodynamics simulation.
2. Use the CSDP Network Summary Report to compare this value to the lowest CSDP bottom elevation for each channel.
3. Lower cross-section bottom elevations that are less than about 0.6 m (2 feet) below the historical minimum stage value. For channels that dry up or come close to drying up, these adjustments may involve adding a narrow “V” shape (Figure 7) to the bottoms of the cross-sections. The “V” shape added in this example is defined by 3 points; the lower point has an elevation of approximately −2 feet, and the upper two points have an elevation of approximately 1.3 feet. There is very little distance between the upper two points, and on the graph, they appear to be plotted almost right on top of each other. The narrow “V” shape lowers the bottom elevation of the cross-section to help prevent drying up, while adding very little cross-sectional area.

Adjusting cross-sections to match GIS volume is an iterative process, which involves modifying cross-sections, re-creating the Network Summary Report, comparing CSDP and GIS volumes tabulated in the report, and repeating the steps as needed. A cross-section represents not a single location, but a portion of the channel between model computational points. Therefore, to match channel volume, a cross-section drawing should not necessarily align perfectly with the bathymetry data that are closest to their location longitudinally. To keep cross-sections as realistic as possible while matching the channel volume, recommended cross-section adjustments may involve either: (1) moving cross-section points within the cloud of bathymetry points (Figure 8a,b), or, if necessary, (2) moving cross-section points outside the boundary of the cloud of bathymetry points while maintaining a similar shape (Figure 8c,d). Increasing the cross-section thickness in straighter channels can enlarge the cloud of points, making it easier to create a representative cross-section.

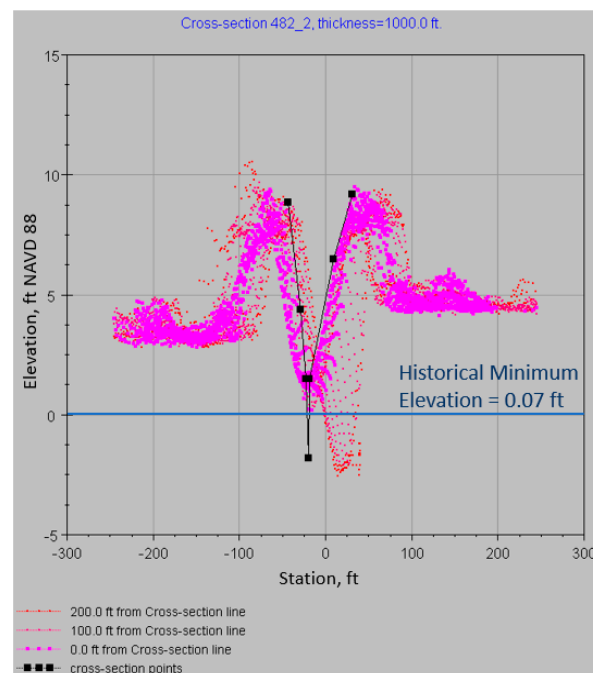


Figure 7. Example cross-section adjustment (deep “V” shape added to cross-section bottom) to prevent drying up.

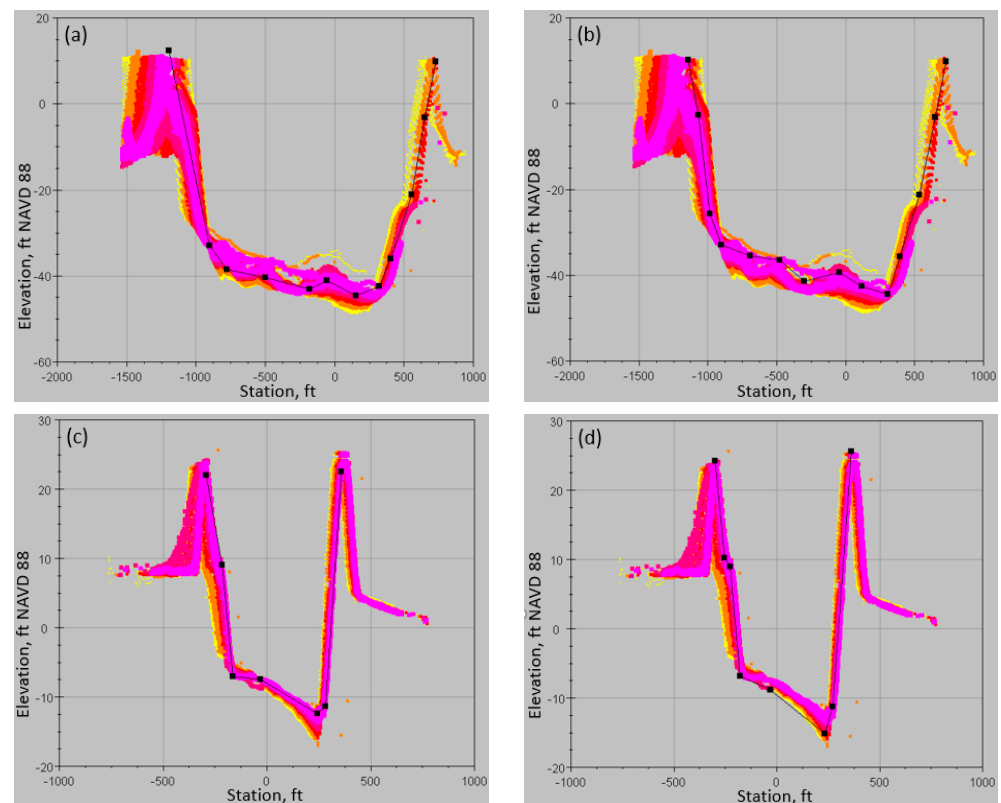


Figure 8. Example cross-section adjustments, including (a) cross-section 47_3 before adjustment; (b) cross-section 47_3 after adjustment; (c) cross-section near upstream end of channel 427 before adjustment; and (d) cross-section near upstream end of channel 427 after adjustment. Different colors indicate data from different sources.

4. Results

Channel volume can largely affect hydrodynamics by affecting residence time [34] and circulation patterns [35]. This section first compared channel volumes in two versions of DSM2: version 8.2, where geometric was not updated, and version 8.3, where geometric was updated using CDSP. The GIS-derived channel volume values are used as the benchmark. The section presents the calibration results of DSM2 (version 8.3) against observed flow and stage data in terms of both statistical metrics and visual inspection at calibration locations.

4.1. Volume Comparison

We used the following equation when comparing DSM2 channel volumes to GIS volume estimates:

$$\% \text{ volume difference} = 100 \times \left[\frac{\text{DSM2 volume} - \text{GIS volume}}{\text{GIS volume}} \right] \quad (1)$$

The maps in Figure 9 show how the % difference changed in the DSM2 model grid channels as a result of the volume adjustments. Before adjusting (DSM2 version 8.2), there were many channels where volume percent differences were 10% or greater (Figure 9a). After the adjustments (DSM2 version 8.3), almost all of the channels' volume percent differences were 2% or less (Figure 9b).

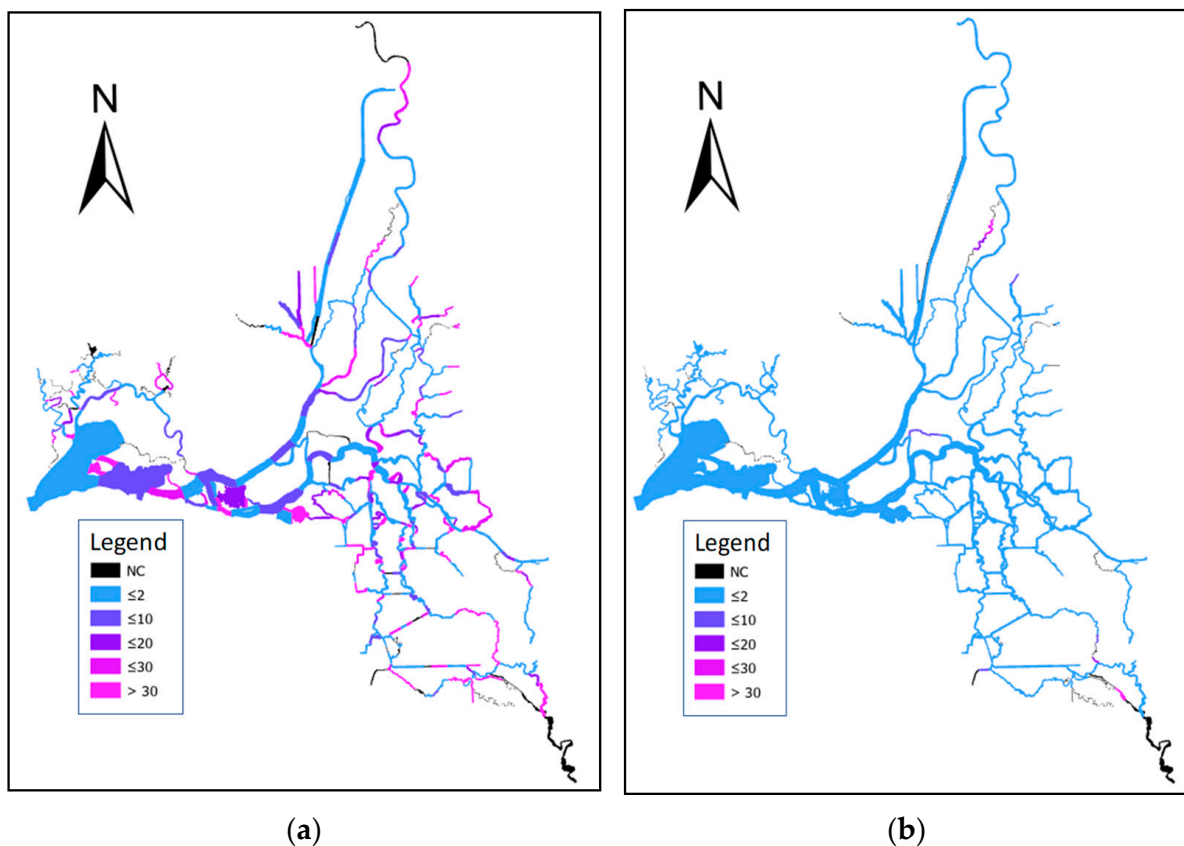


Figure 9. (a) DSM2 vs. GIS channel volume percent difference, before geometry adjustments (DSM2 version 8.2). (b) DSM2 vs. GIS channel volume percent difference, after geometry adjustments (DSM2 version 8.3).

The effects of the adjustments are also summarized in Figure 10, which shows that the percent volume difference between DSM2 (version 8.3) and GIS was at or below 2% for most of the channels. Channels with percent volume differences that were outside of this range are either: (1) labeled “NC”, which means channel volumes were not calculated,

either because the bottom of the channel was above the elevation used to calculate volume, or because the width of the channel was small, relative to the grid size of available DEM data, or (2) labeled with a high percent difference range ($>30\%$), these were channels with bottom elevations not far below the elevation used to calculate channel volume; in these channels, the elevation used to calculate volume is well below the average water level in the channel, and a large percentage difference is not as significant.

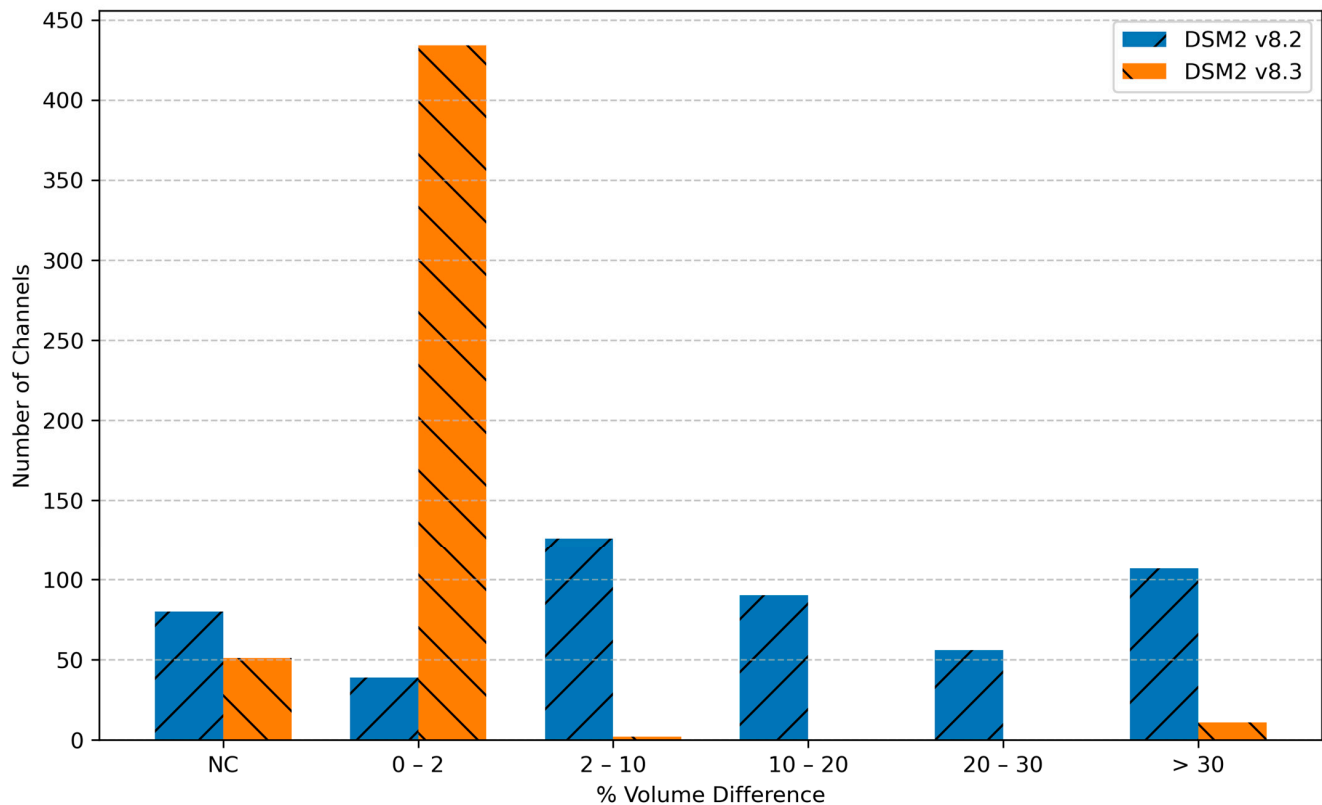


Figure 10. DSM2 vs. GIS channel volume percent difference histogram, before and after geometry adjustments.

4.2. Calibration Results

Model calibration involves evaluating model performance by comparing model results to observed data at key locations in the model domain, for a time period called the “calibration period”. For this calibration of the DSM2, we used a calibration period of 1 October 2010–1 October 2012, which includes a wet year and two below-normal years. Based on the results of each comparison, model input parameters (in this case, Manning’s n value for each channel) are adjusted, and model performance is re-evaluated. When adjustments are complete, the results are validated by again comparing model results to observed data, for a different time period, called the “validation period”. In the current study, we used a validation period of 1 October 2000–1 October 2021. This period includes four wet years, three above-normal years, five below-normal years, six dry years, and four critical years.

The locations in the model domain used for calibration correspond to the locations of existing monitoring stations. The locations used during the calibration are shown in Figure 11.

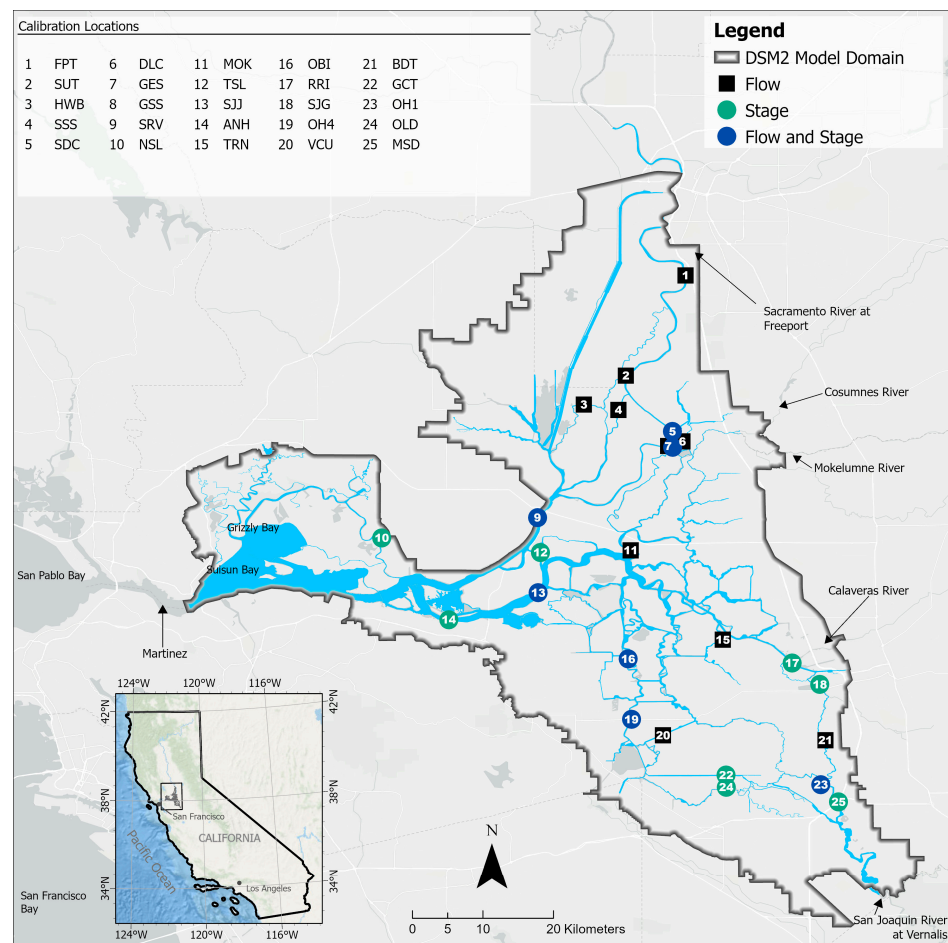


Figure 11. Map showing locations monitoring stations used for DSM2 calibration.

Figure 12 summarizes the flow calibration results for the Sacramento River at Rio Vista. Figure 12a compares the instantaneous 15 min model flow output with observed data for the calibration period. Figure 12b compares model output to observed data, both tidally filtered, for the calibration period. Figure 12c, similar to Figure 12b, compares model output to observed data, both tidally filtered, for the validation period. DSM2 performed well at Rio Vista (Figure 12), slightly overpredicting the peak instantaneous flows, and matching tidally averaged observed data well, but not as well for higher flows, where observed data are known to be less accurate.

Table 1 summarizes model performance based on a comparison of flow results for selected locations in the model domain, using four common metrics consisting of the square of the correlation coefficient (R^2), percent bias, normalized root-mean-squared error (RSR), and the Kling–Gupta efficiency (KGE) score [36] for the calibration and validation periods. The DSM2 well-simulated flows in most of the North Delta locations (Table 1, stations BDT–MOK), with R^2 values close to 1.0 for all locations, PBIAS values below 1.0 for most locations, RSR values below 0.2 for most locations, and KGE values above 0.90 for most locations. The exceptions were the SRV, SDC, and GES stations. Station SRV (Sacramento River at Rio Vista) has PBIAS values of 6.61% and 7.65% for the calibration and validation periods, respectively. Station SDC (Sacramento R above Delta Cross-Channel) has PBIAS values of 2.84% and 1.07% for the calibration and validation periods, respectively. Station GES (Sacramento River blw Georgiana Slough) has PBIAS values of 7.12% and 4.16%, respectively. Station SRV (Sacramento River at Rio Vista) has KGE values of 0.76 and 0.90, respectively. In the next phase of calibration, we hope to improve these results.

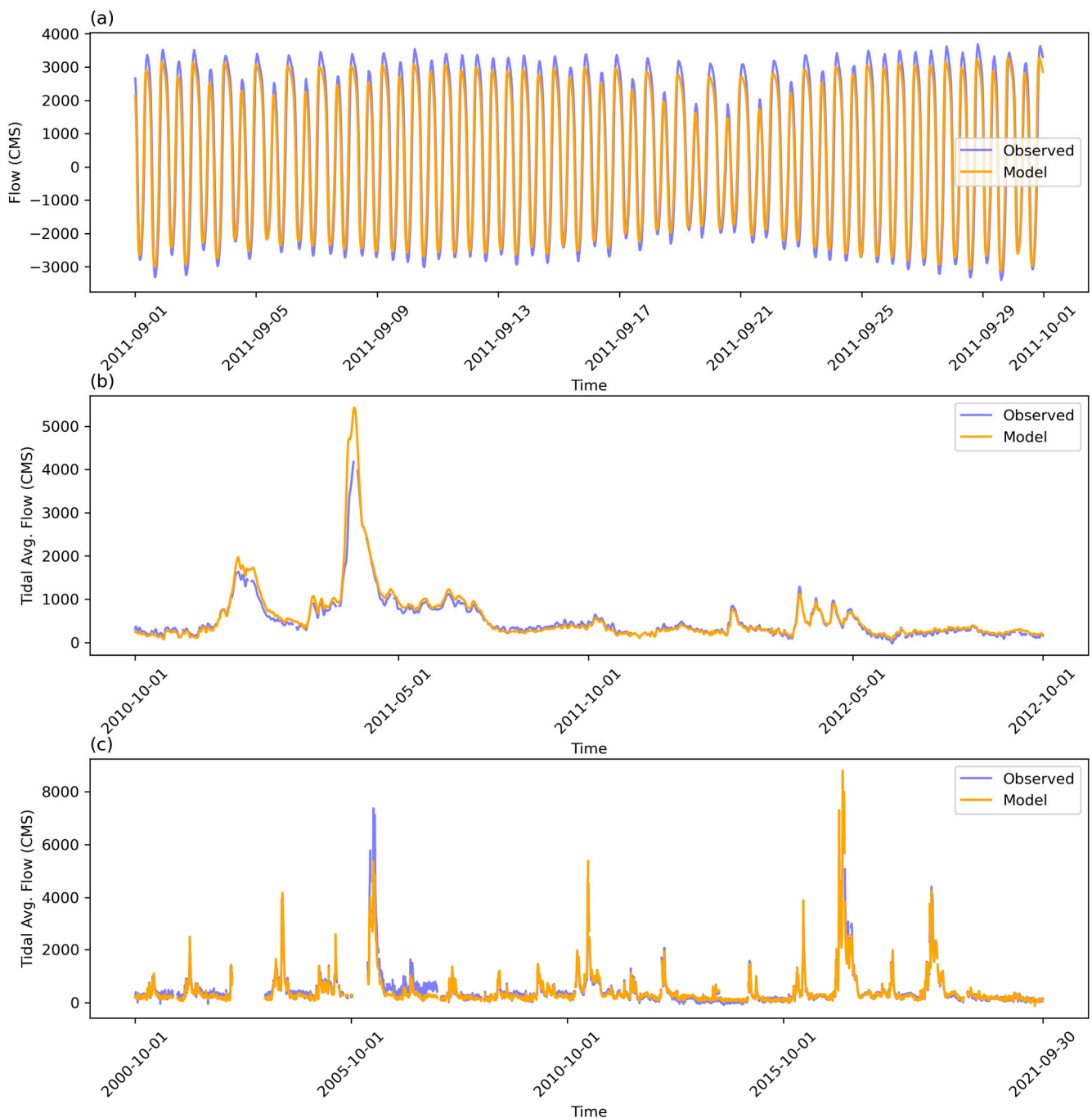


Figure 12. Calibration results for flow at Sacramento River at Rio Vista, 15 min (a), tidally averaged for the calibration period (b), and tidally averaged for the validation period (c).

DSM2 did not simulate flow as well in the Central Delta and South Delta (Table 1, stations MOK-VCU). R^2 values are still mostly above 0.9, but PBIAS is around 10% for stations SJJ, OBI, and OH1 for the calibration period, and ranges from 2.24 to 7.35% for the validation period. Results look better for stations MOK, TRN, and VCU, with R^2 values of 0.94, 0.90, and 0.97 for the calibration period, and 0.94, 0.78, and 0.96 for the validation period; and PBIAS values of 1.55%, 0.64%, and 1.56% for the calibration period, and 2.93%, 1.85%, and 4.44% for the validation period; and RSR values of 0.30, 0.35, and 0.18 for the calibration period, and 0.28, 0.49, and 0.21 for the validation period. KGE values in the Central Delta and South Delta are mostly above 0.80. Station TRN had slightly lower KGE values of 0.78 for the calibration period and 0.73 for the validation period. In the South

Delta, flows are lower than the North Delta and Central Delta. When flows are lower, consumptive use estimates are a more significant portion of the total flow in a channel. The Delta Modeling Section is working on improving consumptive use estimates, which should improve flow results in the South Delta.

Table 1. DSM2 flow simulation performance metrics for calibration and validation time periods.

Station ID	Station Name	Calibration Period				Validation Period			
		R ²	PBIAS	RSR	KGE	R ²	PBIAS	RSR	KGE
FPT	Sacramento River at Freeport	1.00	−0.17	0.04	0.99	1.00	−0.25	0.06	1.00
SSS	Steamboat Slough btw Sac R and Sutter Slough	0.99	0.08	0.15	0.89	0.99	1.24	0.13	0.94
SUT	Sutter Slough at Courtland	0.99	1.61	0.13	0.92	0.99	−0.14	0.15	0.92
HWB	Miner Slough at Hwy 84 Bridge	0.99	0.21	0.13	0.92	0.99	−2.58	0.17	0.88
SDC	Sacramento River above Delta Cross-Channel	1.00	−2.84	0.10	0.94	0.99	−1.07	0.12	0.98
DLC	Delta Cross-Channel	0.99	0.71	0.10	0.96	0.99	−4.04	0.13	0.95
SRV	Sacramento River at Rio Vista	0.96	6.61	0.33	0.76	0.94	−7.65	0.26	0.90
GES	Sacramento River blw Georgiana Slough	1.00	−7.12	0.13	0.90	0.99	−4.16	0.10	0.93
GSS	Georgiana Slough at Sacramento River	0.99	−0.21	0.11	0.99	0.98	−3.27	0.15	0.97
MOK	Mokelumne River at San Joaquin River	0.94	−1.55	0.30	0.80	0.94	2.93	0.28	0.84
SJJ	San Joaquin River at Jersey Point	0.92	10.39	0.32	0.80	0.91	−7.08	0.30	0.91
BDT	San Joaquin River at Brandt Bridge	0.99	0.78	0.10	0.98	0.99	2.50	0.11	0.97
OBI	Old River at Bacon Island	0.97	−10.25	0.23	0.87	0.79	2.24	0.48	0.88
OH1	Old River at Head	0.99	10.02	0.23	0.80	0.96	2.39	0.21	0.93
OH4	Old River at Highway 4	0.99	−6.71	0.14	0.93	0.97	−7.35	0.20	0.92
TRN	Turner Cut near Holt	0.90	0.64	0.35	0.80	0.78	−1.85	0.49	0.73
VCU	Victoria Canal Near Byron	0.97	−1.56	0.18	0.94	0.96	4.44	0.21	0.94

Table 2 summarizes model performance based on a comparison of stage results for selected locations in the model domain, using the metrics R², percent bias, RSR, and KGE for the calibration and validation periods. DSM2 stage simulations were not quite as good as flow simulations in most of the North Delta locations (Table 2, stations SDC–SRV), with R² values of 0.99, 0.99, and 0.93 for the calibration period, and 0.99, 0.99, and 0.83 for the validation period. PBIAS values were 10.77%, 8.8%, and 10.87% for the calibration period, and 11.16%, 9.13%, and 12.12% for the validation period. RSR values were 0.41, 0.36, and 1.07 for the calibration period, and 0.40, 0.36, and 1.17 for the validation period. KGE values were 0.80, 0.83, and 0.89 for the calibration period, and 0.79, 0.83, and 0.85 for the validation period. Overall, DSM2's stage simulation results are encouraging, given that stage results were not weighted as heavily as flow results in calibration. DSM2 simulated stages well in the Central and South Delta locations (Table 2, stations TSL–SJG), with R² values ranging from 0.88 to 0.99 for most stations for both the calibration and validation periods; PBIAS results ranging from 1.09 to 7.42 for both the calibration and validation periods; RSR values ranging from 0.12 to 0.79 for both the calibration and validation periods; and KGE values ranging from 0.60 to 0.96 for both the calibration and validation periods. The best performing station was station MSD (San Joaquin River at Mossdale Bridge), with R² values of 0.99 and 0.96 for the calibration and validation periods, respectively; PBIAS values of 1.67% and 1.09% for the calibration and validation periods, respectively; and KGE values of 0.96 and 0.94 for the calibration and validation periods, respectively. As the calibration enters its next phase, we expect that improvements in model input will reduce the model error at these locations.

Table 2. DSM2 stage simulation performance metrics for calibration and validation time periods.

Station ID	Station Name	Calibration Period				Validation Period			
		R ²	PBIAS	RSR	KGE	R ²	PBIAS	RSR	KGE
SDC	Sacramento River above Delta Cross-Channel	0.99	−10.77	0.41	0.80	0.99	−11.16	0.40	0.79
GSS	Georgiana Slough at Sacramento River	0.99	−8.80	0.36	0.83	0.99	−9.13	0.36	0.82
SRV	Sacramento River at Rio Vista	0.93	−10.87	1.07	0.89	0.83	−12.12	1.17	0.85
TSL	Three Mile Slough at San Joaquin River	0.94	−5.81	0.62	0.93	0.88	−5.92	0.65	0.91
SJJ	San Joaquin River at Jersey Point	0.94	−2.40	0.34	0.96	0.87	−2.33	0.42	0.92
ANH	San Joaquin River at Antioch	0.96	−5.99	0.67	0.93	0.90	−5.79	0.68	0.92
MSD	San Joaquin River at Mossdale Bridge	0.99	1.67	0.12	0.96	0.96	1.09	0.21	0.94
NSL	National Steel	0.97	−6.30	0.70	0.91	0.71	−3.79	0.68	0.83
OBI	Old River at Bacon Island	0.90	−6.98	0.70	0.89	0.87	−7.42	0.78	0.90
OH1	Old River at Head	0.99	−2.71	0.11	0.95	0.96	−5.44	0.25	0.92
OH4	Old River at Highway 4	0.93	−6.97	0.67	0.88	0.90	−7.08	0.66	0.91
OLD	Old River near Tracy	0.88	5.46	0.60	0.64	0.85	−1.34	0.50	0.75
RRI	Stockton Ship Channel @ Burns Cutoff	0.93	−7.74	0.79	0.91	0.88	−7.86	0.80	0.90
GCT	Grant Line Canal at Tracy Road Bridge	0.94	1.95	0.61	0.47	0.88	−4.45	0.62	0.60
SJG	San Joaquin River at Garwood Bridge	0.97	−6.84	0.50	0.87	0.93	−6.76	0.54	0.85

5. Conclusions and Future Work

Geometry for some hydrodynamic models consists of cross-sections that are defined at discrete locations in each channel in the model grid. The current study described a parsimonious modular tool, the Cross-Section Development Tool (CSDP), that prepares geometry inputs for hydrodynamic models that use cross-section input. It provides the user with full control over the placement of channel centerlines, cross-section lines, and cross-section points, optionally automating parts of the process. This enables the user, when creating cross-sections, to place more emphasis on datasets considered to be of higher quality, to design cross-sections to evaluate the effects of proposed changes, such as dredging, and to adjust cross-sections as needed to adjust channel volumes. The CSDP also includes tools to help the user identify cross-sections that could potentially cause model convergence issues. The study further demonstrated the application of CSDP in an operational hydrodynamic model (DSM2). We illustrated that the channel volumes derived from CSDP was able to match GIS-based channel volumes and that the model performed well with the updated geometry. Flow and stage simulations from DSM2 configured with updated geometry from CSDP at study locations are compared to the corresponding field observations. Overall, these simulations mimic the patterns of the observations very well. The square of the correlation coefficient between simulations and observations is generally over 0.95 during the calibration period and over 0.80 during the validation period. The absolute bias is generally less than 5% and 10% during the calibration and validation periods, respectively.

By virtue of the modular design, the CSDP could be used to create geometry input for any hydrodynamic model using similar input in any region, provided there are bathymetry data, for example, surveyed DEM or remote sensing data, available for the region of interest. The general procedure would be the same: (a) format the bathymetry data for the CSDP, (b) load the bathymetry data into the CSDP, (c) create cross-sections using the CSDP, and (d) calculate cross-section conveyance characteristics. We plan to continue enhancing CSDP in future releases. Planned enhancements include: (a) more GIS-like GUI; (b) base map display; (c) improving zooming in plan view; and (d) improving interface for centerline and cross-section editing, including undo and redo.

Automated approaches to cross-section development are very efficient, but they require high quality data. Automated approaches are not applicable to the entire California Bay-Delta system, due to the variability in bathymetry data quality. To the best of our knowledge, no other tools have been successful in creating model geometry for the entire California Bay-Delta System. CSDP takes more time than the automatic approach, but it

is more efficient than the manual approach to developing cross-sections used by DSM2's predecessor. The approach used by the CSDP also allows the user, when developing geometry, to use their personal knowledge of the system, improve the numerical stability of hydrodynamic models that use the geometry, and include effects of proposed changes in geometry.

Author Contributions: Conceptualization, B.T. and P.S.; methodology, B.T.; software, B.T.; validation, P.S. and M.H.; formal analysis, B.T. and M.H.; investigation, B.T. and M.H.; resources, P.S.; data curation, B.T.; writing—original draft preparation, B.T. and M.H.; writing—review and editing, M.H. and P.S.; visualization, B.T.; supervision, P.S.; project administration, P.S.; funding acquisition, P.S. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: All the data used in the study are available at: <https://data.cnra.ca.gov/dataset/dsm2-fc-2023-01> (accessed on 17 August 2023).

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Software Availability

Name: The Cross-Section Development Program.

Lead developer: Bradley Tom: Bradley.Tom@water.ca.gov.

Availability: The executable binary, user's manual, example data, and source code are freely available and can be downloaded using the following links:

Executable and user's manual: <https://data.cnra.ca.gov/dataset/cross-section-development-program-version-3> (accessed on 17 August 2023).

Example data: <https://data.cnra.ca.gov/dataset/cross-section-development-program-navd88-update> (accessed on 17 August 2023).

Source code: <https://github.com/CADWRDeltaModeling/csdp/tree/master> (accessed on 17 August 2023).

Training materials: The CSDP Training Video is available at <https://youtu.be/7utAIvLVpKU> (accessed on 17 August 2023).

Software required: Java Runtime Environment (JRE) Version 10.0 or above.

Operating system: Windows.

User interface: Graphic user interface.

Appendix B. Glossary

Term	Definition
Aquaveo SMS	Aquaveo Surface-water Modeling System
ArcGIS	Geographic Information System Software by ESRI
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
CADWR	California Department of Water Resources
CSDP	DSM2 Cross-Section Development Program
CVP	Central Valley Project
Delft 3D	A Hydrodynamic Model Developed by Delft University of Technology
DEM	Digital Elevation Model
DSM2	Delta Simulation Model II
ESRI	Environmental Systems Research Institute
GIS	Geographic Information System

Term	Definition
GUI	Graphical User Interface
HEC-RAS	Hydrologic Engineering Center's River Analysis System
HYDRO	The DSM2 Hydrodynamics Model
QUAL	A DSM2 Water Quality Model
RiverBox	An ArcGIS Toolbox for River Bathymetry Reconstruction
RMA2	A Two-Dimensional Hydrodynamic Model from Resource Management Associates
SCHISM	Bay-Delta SCHISM, A 3D Model of The California Bay-Delta System
SUNTANS	Stanford Unstructured Nonhydrostatic Terrain-following Adaptive Navier–Stokes Simulator
SWP	State Water Project of California
UnTRIM	Unstructured Tidal, Residual, and Intertidal Mudflat Model
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey

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