Two-Dimensional Modeling

When estimating flow-habitat relationships for fish and other aquatic species, the California Department of Fish and Wildlife Instream Flow Program (IFP) uses a series of methods to predict stream hydraulics over a range of flows. More and more, the IFP has relied upon two-dimensional (2D) models to predict hydraulics for site-specific studies. These models can estimate depths and velocities uniformly across a select site, even when that site includes hydraulically complex zones.

The IFP was not the first to use 2D modeling to estimate depths and velocities to quantity fish habitat. The U.S. Fish and Wildlife Service (USFWS) has used 2D modeling techniques in the Central Valley Project area to estimate fish habitat in several Sacramento River salmonid tributaries, notably to estimate adult spawning habitat for spring-run Chinook Salmon in Butte Creek (USFWS 2003 - see Figure 1) and fall-run Chinook Salmon and steelhead/rainbow trout in Clear Creek (USFWS 2011).

This fact sheet describes the overall structure of a 2D model, the field data needed to build a 2D model, and how those field data are used to calibrate and validate a 2D model.

1. 2D Model Overview

A 2D model is a digital representation of a selected portion of a stream. It is a valuable tool to calculate stream information (e.g., surface water depths, velocities, and flow direction) and analyze how the hydraulics of the stream behave. Understanding stream hydraulics is necessary to assess the relationship between instream flows and fish habitat needs, and ultimately develop instream flow criteria to support and maintain healthy aquatic resources.

Figure 1. Spring-run Chinook Salmon on Butte Creek.

Depth and velocity are two primary hydraulic parameters used to specify criteria for flow-fish habitat relationships (Bovee 1982). 2D models are used to predict depth and velocity within representative portions of rivers and streams (Holmes et. al. 2016). These models are especially adept at simulating complex stream hydraulics that often occur in areas of optimal fish habitat in a stream or river.

2. 2D Model Structure

In the basic structure of a 2D model, flows enter and exit through pre-defined boundaries that are single-thread channels (Figure 2). The stream channel within the boundaries can be mutli-thread.

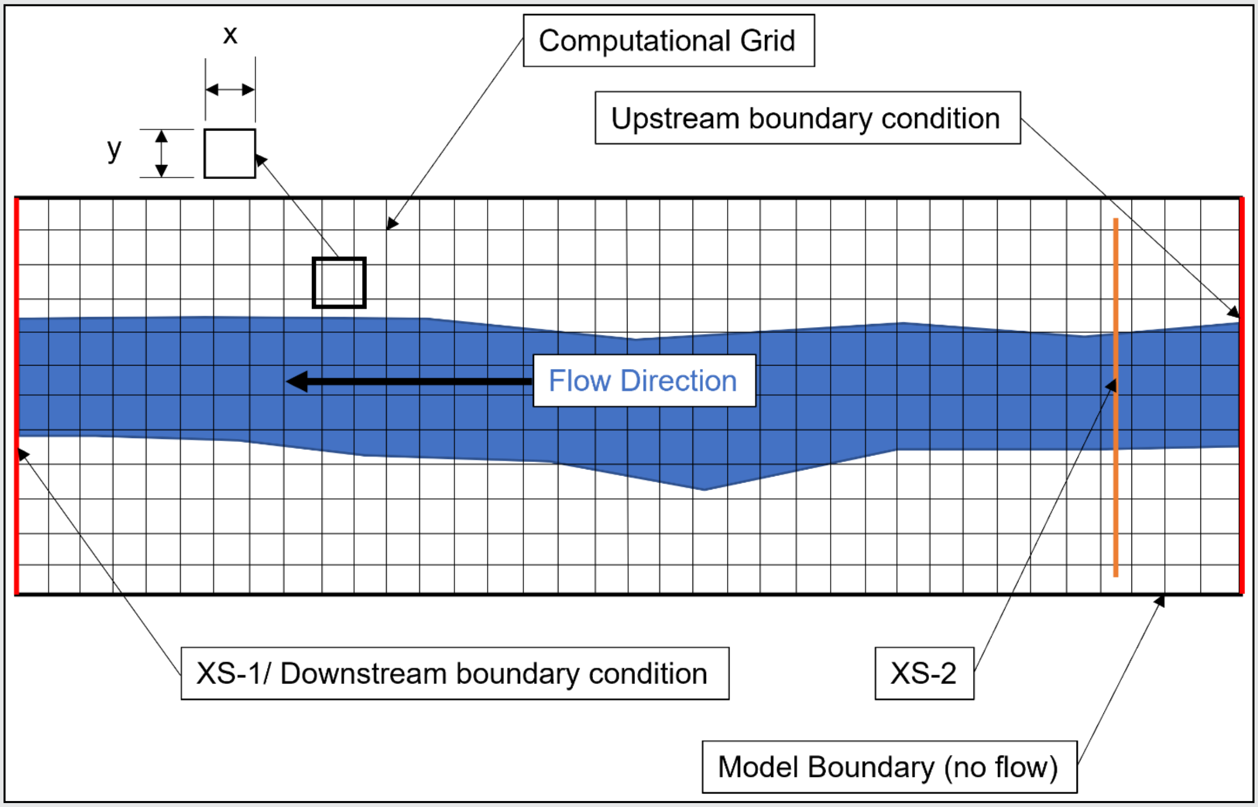

Figure 2. Basic schematic layout of a 2D model. Flow enters the defined upstream boundary and exits at the defined downstream boundary.

These models are governed by the conservation of mass principle (Brunner 2016), where the amount of water that enters the model space must be equal to the amount of water leaving the model area once equilibrium has been reached. 2D models can have multiple defined flow input and output boundaries, but the conservation of mass at equilibrium still applies. Model simulations produce an estimate of water depth and velocity within each cell of the computational grid. With detailed bathymetry data, the model scale is small enough to correspond to the scale of microhabitat use data with depths and velocities produced on a continuous basis, rather than in discrete cells. As such, high densities of bed topography data points are needed within complex substrate zones.

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To define and calibrate a 2D model, the relationship between the flow magnitude (amount of flow) moving through the site and the water level at both the upstream and downstream ends of the site must be known. A stream rating is a relationship developed from flow and water level measurements over time. The rating is used to predict the flow magnitude and water level at flow levels that are not sampled directly.

3. Field Data Collection

The data needed to build a 2D model consist of the flow/water level relationship used to calibrate the model, channel bed topography used to construct the digital terrain model (DTM), and substrate coding along with topography point density used to estimate bed roughness.
Data collection for a 2D model is performed in a sequence of steps to maximize the accuracy of the results. Large-scale storm events, referred to as channel-forming flows, can rearrange the stream bed and alter the relationship between flow and water level. For optimal 2D model development and calibration, water level data collection should precede any channel-forming flow events that can alter the stream bed structure. Ideally, the topographic survey is performed after flows have receded to a point when access to all areas of the study site is convenient and safe, typically during the low-flow summer period.

Based on the sequence structure described above, the flow and water level relationship data are collected first, prior to the topographic survey. Discharge and water surface elevation (WSEL) are recorded at a minimum of three flow levels (but preferably four or five distinct flow levels) with WSEL being measured at both XS-1 and XS-2 (see Figure 2).

3a. Discharge

Discharge is measured (Figure 3) at a location with stream characteristics that will give the most accurate estimate of flow.

Site selection and other procedural information may be found in the IFP's *Standard Operating Procedure for Discharge Measurements in Wadeable Streams in California* (CDFW 2020).

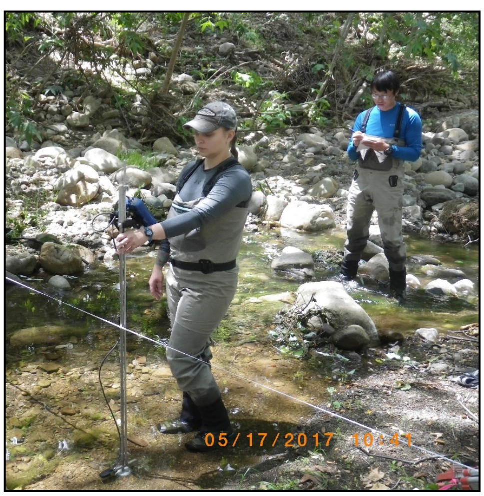

Figure 3. Measuring discharge across a transect using a current velocity meter.

3b. Water Surface Elevation

Water level is measured (Figure 4) using differential leveling techniques with an auto level and stadia rod (Harrelson et al. 1994). Each water level measurement is referenced to a fixed point established prior to the beginning of data collection. By referencing each water level measurement to a common benchmark, the water levels are transformed into WSELs.

Later, the WSELs are associated with the georeferenced DTM bed elevations along XS-1 and XS-2. Also, measurements of discharge and WSEL in the study site are used to calibrate flow simulations in 2D models.

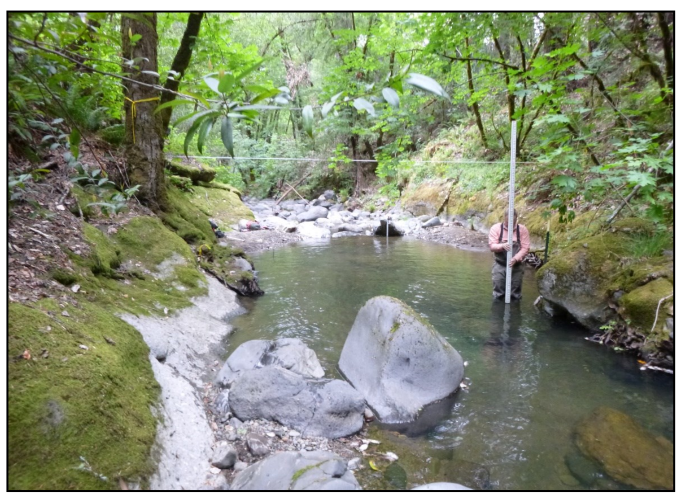

Figure 4. Measuring water level along a transect using an auto level and stadia rod.

3c. Digital Terrain Model

Figure 5. RTK-GPS topographic survey point collection.

A DTM is the digital representation of the study site in the 2D model. The topographic survey points are imported into the 2D model to create the DTM. The accuracy threshold of the topographic survey must be finer than the criteria being applied. For instance, if the criteria are specified in tenths of a foot, the survey variance threshold must be in hundredths of a foot or finer. This allows depths and velocities for fish habitat to be accurately predicted. Generally, the higher the density of survey data, the better the results of the hydraulic simulations, particularly in areas with complex topography (Ghanem et al. 1996). It is important to also survey high enough on the stream banks to get above the water's edge at the highest flow to be simulated.

The topographic survey for wadable streams can be performed using a high-resolution light detection and ranging (LIDAR) flight, survey-grade real-time kinematic global positioning system (RTK-GPS) point collection (Figure 5), or total station (TS) survey (Figure 6). The Department has used all three techniques to generate DTMs in the past. The use of LIDAR is dependent upon whether a recent high-resolution flight has occurred in the area. Both LIDAR and RTK-GPS reception are limited by dense canopy cover. In addition, traditional LIDAR does not capture topography within wetted portions of the stream channel. Green LIDAR can collect topographic survey data in wetted portions of the stream channel but may still need to be supplemented by other methods in deep water (USGS 2022). When dense canopy cover blocks LIDAR or RTK-GPS reception, TS surveying is employed.

Figure 6. Total station topographic survey point collection. *Left*: the total station reads the elevation and a distance to the rod held by a staff member at a survey point. *Right*: the handheld unit shows collected survey points.

3d. Substrate/Cover

In conjunction with the topographic survey (see 3c), substrate size and cover codes are assigned to each surveyed point. For LIDAR data, substrate size and cover can be mapped using high-resolution aerial photography or by mapping substrate and cover polygons with RTK-GPS. The substrate size code (e.g., sand/silt, small cobble, boulder) is a visual observation meant to approximately quantify the average substrate size at and around the surveyed point. The area represented by an average substrate size depends upon the point density being surveyed in that area. In zones with complex structure and variable substrate size, a higher point density is required. The area observed for one point in a complex zone may be a few square inches, while it may be up to several yards in areas with uniform substrate size and slope.

In conjunction with the topographic survey, substrate size and cover codes are assigned to each surveyed point.

Substrate coding is used by the IFP to estimate bed roughness, a required hydraulic parameter to execute and calibrate flow simulations. Cover codes (e.g., overhead cover, undercut bank, aquatic vegetation) are also recorded at each point, but the use of cover coding is dependent upon the fish life stage being considered in the study.

3e. Stage of Zero Flow

One final hydraulic parameter needed for model construction is stage of zero flow (SZF). The SZF is used to improve accuracy in the development of the discharge/WSEL relationship. Ideally, transects XS-1 and XS-2 are located in pools where WSEL across the transect is flat and calm. Model calibration is aided when the flow entering and exiting the model boundaries is laminar (i.e., smooth, not turbulent). While pools provide the best hydraulic characteristics for 2D model calibration, the gradient of the WSEL is governed by a downstream hydraulic control point.

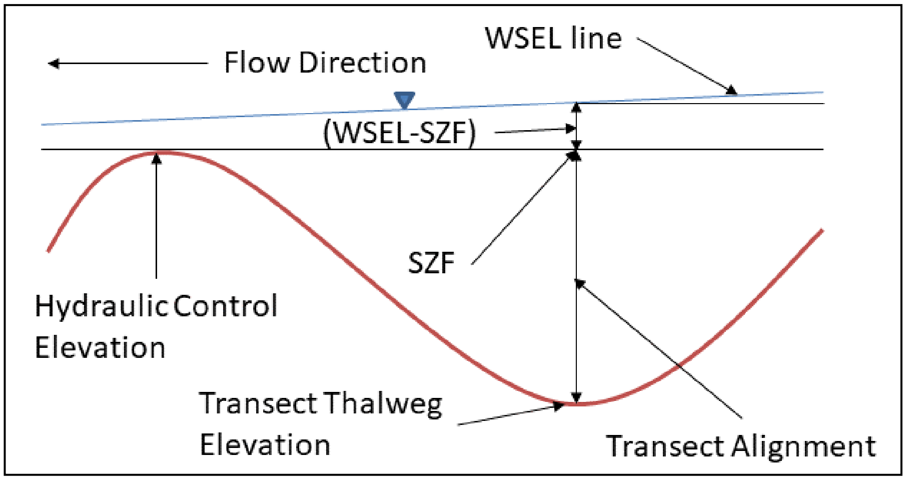

Figure 7. SZF diagram.

The SZF is used to improve accuracy in the development of the discharge/ WSEL relationship.

The SZF is the bed elevation at the downstream end of the pool where the last flow exits the pool once flow stops in the stream (Figure 7). The resultant WSEL at the point when the flow first stops is the SZF. The ratio of change in the WSEL portion of the rating relationship is optimized once this dead pool elevation is subtracted from each WSEL measured in the pool unit during data collection.

4. Model Validation

Another key step in 2D model development is model validation (Figure 8), which is the process of comparing model outputs with data collected at randomly selected locations within the study area. Staff conduct validation data collection independent of model calibration data collection.

For validation data collection events, staff go to the study site, measure the discharge, and randomly select locations in the wetted area of the stream. At each random location, staff survey the position with TS or RTK-GPS, measure the depth using a stadia rod, and measure the velocity at that point using the same velocity meter used for discharge data collection.

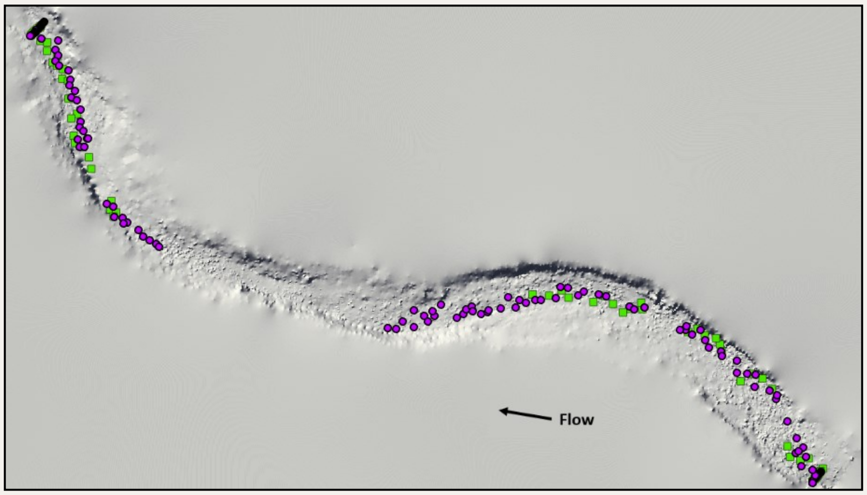

Figure 8. Validation data points collected at random locations from a study site in Mark West Creek. Depth and velocity were measured at 10.5 cfs (green squares) and at 2.4 and 2.2 cfs (purple squares).

5. Stream Rating Development

Prior to building the model using hydraulic analysis software, the predictive rating relationships must be defined because they are required to calibrate flow simulations. The IFP uses logarithmic (Log) scales to develop linear best-fit predictive trend lines to develop stream ratings. This method plots the Log of the discharge (Log(Q)) on the x-axis and the Log of the WSEL minus the SZF (Log(WSEL-SZF)) on the y-axis (Figure 9) to predict WSEL at XS-1 and XS-2 for a chosen discharge magnitude.

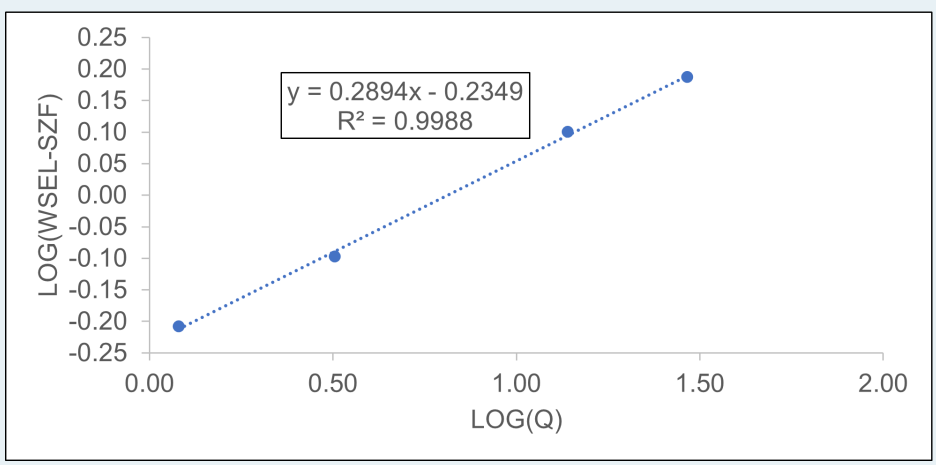

Figure 9. Log-Log discharge (Q)/WSEL-SZF rating best-fit linear trend line.

6. 2D Model Construction

The 2D model construction process consists of importing the site topography into the model to create the DTM, defining the computational grid size interval, and adding the inflow/outflow boundary conditions (Figure 2). Figure 10 is an example DTM created in the program HEC-RAS (2018) using topographic survey points collected using TS as depicted in Figure 6.

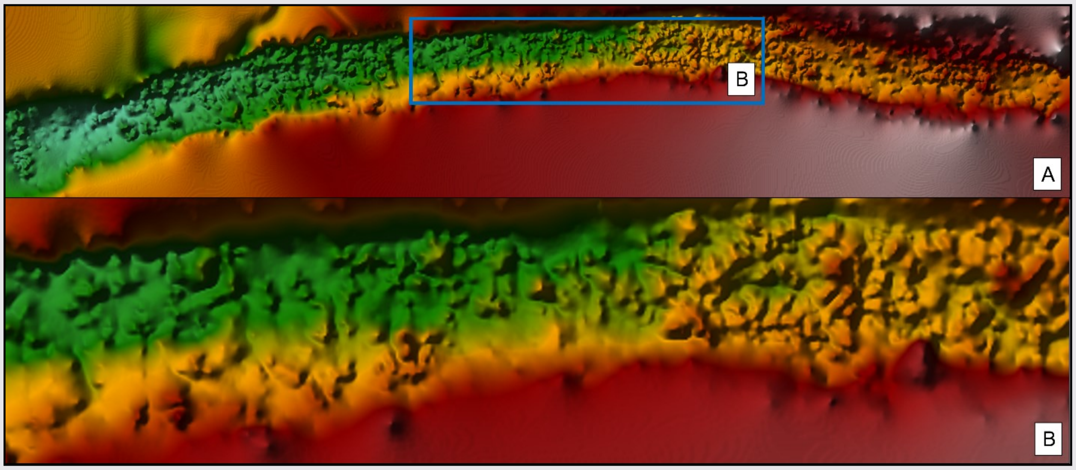

Figure 10. (A) 2D model DTM from site in Mark West Creek and (B) detailed topography of the site.

Once the DTM is established in the model, a model boundary is added (Figure 11(A)) that defines where flow will move through the site. The black line boundary in Figure 10(A) is a no-flow boundary and is digitized in elevation above where the highest simulated flows will advance in the site. Flows enter through the red upstream boundary condition line (Figure 11(B)) and exit through the red downstream boundary condition line (Figure 11(C)).

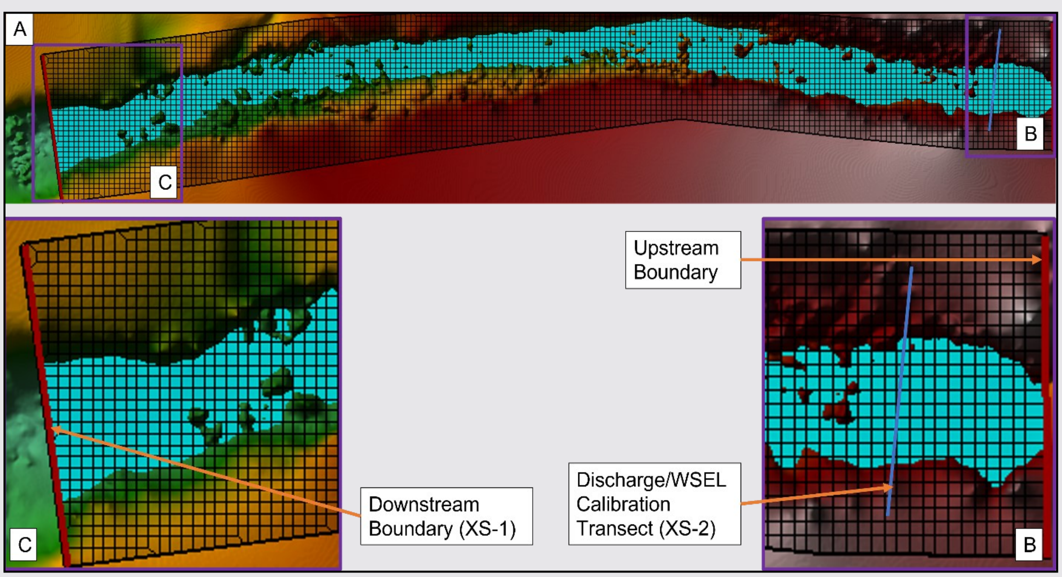

Figure 11. (A) 2D model geometry/computational grid (black) and boundary condition lines (red) applied to the DTM; (B) the upstream flow boundary and the discharge/WSEL calibration transect (XS-2) in the same pool unit where flow enters the model; (C) close-up of downstream boundary transect (XS-1).

7. Flow Simulation Output Data

Once the 2D model has been developed, flow simulations can be executed. The simulations produce the fields of hydraulic data that can be used to estimate depths for fish passage or depths and velocities to compute fish habitat. Flow simulations are typically completed over a range of flows to identify the flow needed to allow unimpeded fish passage or optimize fish habitat.

Figure 12 shows a depth-sensitive riffle with a marked transect line located in a California stream that supports salmonids. This riffle was simulated using 2D modeling; Figure 13 shows the fish passage transect digitized onto a 2D flow simulation of the riffle. The water depths from the transect in Figure 12 can be extracted from a 2D model and used to identify the amount of contiguous depth needed for a particular fish species to allow unimpeded fish passage (Figure 14).

Figure 12. Wide transverse riffle in Mill Creek near the confluence with the Sacramento River.

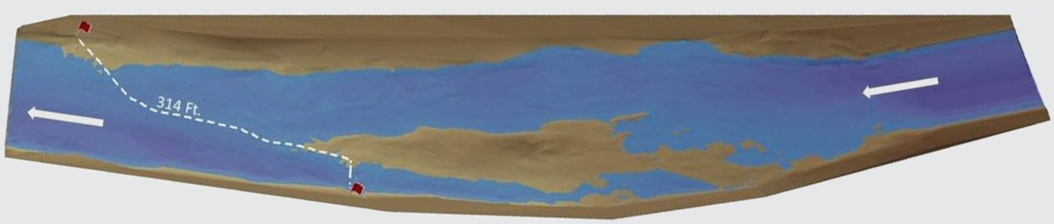

Figure 13. Shallowest course across a critical riffle digitized across the GIS depiction of a 2D model DTM and overlying flow simulation.

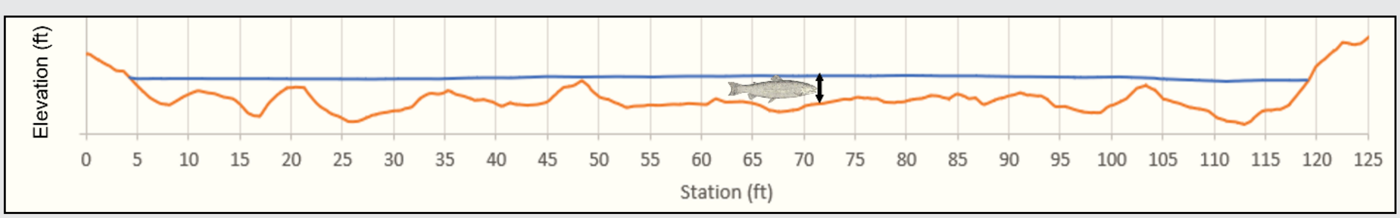

Figure 14. A transect following the shallowest course over a critical riffle, extracted from a 2D model to assess fish passage through the site.

2D modeling results are also used to estimate habitat for spawning adult and rearing juvenile fish. The habitat suitability criteria (HSC) for salmonids considers both depth and velocity. Models can be used to simulate depth (Figure 15) and velocity (Figure 16) over a range of flows.

Each 2D model simulation estimates depth and velocity in all wetted areas across the entire model boundary. Those outputs are then weighed by their associated HSC values to compute fish habitat by area weighted suitability (AWS, Figure 17). Defined simply, AWS is a scoring index that describes the amount of suitable habitat per unit of length at a specified flow for a given species and life stage (Payne and Jowett 2013).

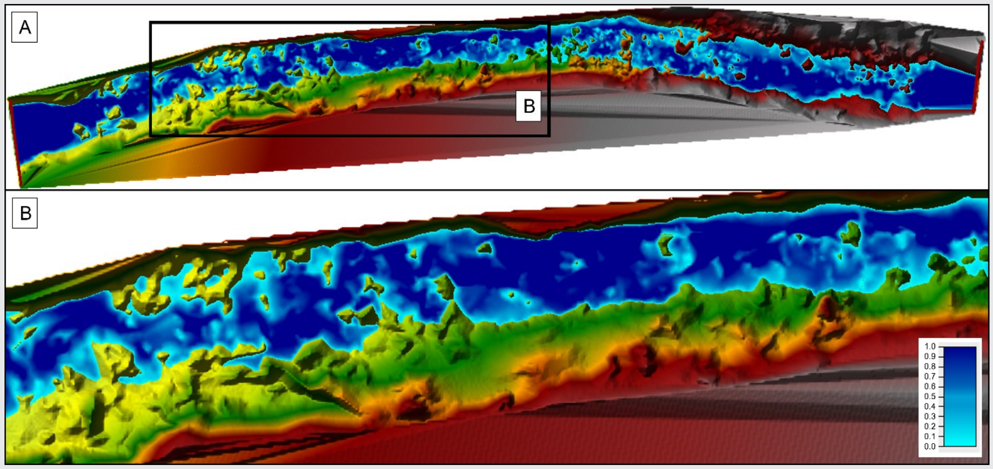

Figure 15. (A) Depth output in Mark West Creek 2D model. (B) Zoomed-in with depth scale in feet. Darker blue colors indicate greater depths.

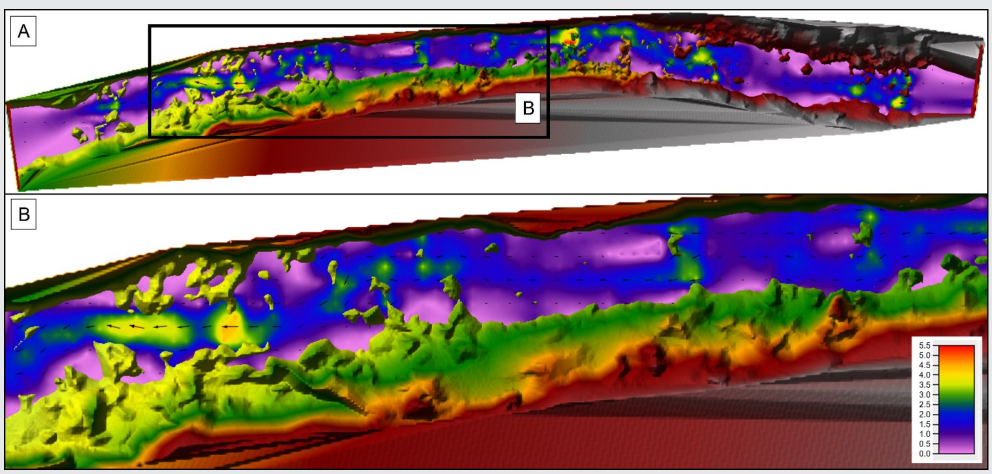

Figure 16. (A) Velocity output in Mark West Creek 2D model. (B) Zoomed-in with velocity scale in feet per second; black arrows indicate velocity vector direction and magnitude. Red, orange, and yellow colors in the stream indicate greater velocities.

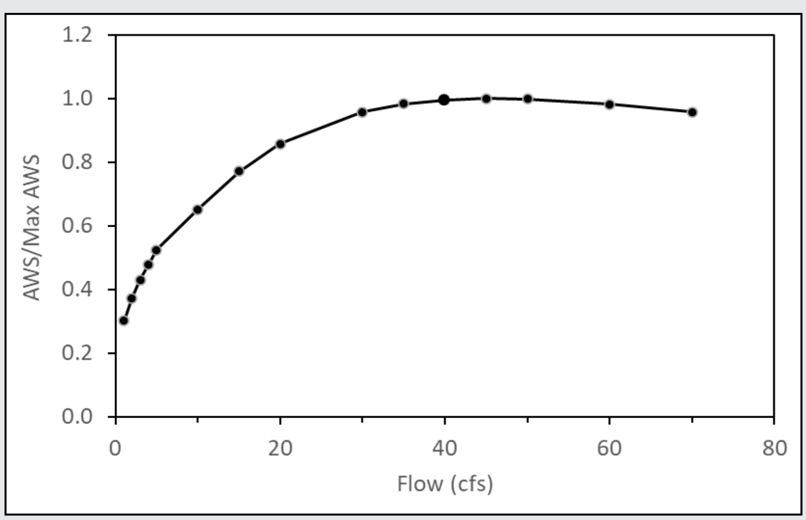

Figure 17. Example AWS curve.

8. 2D Models and the Instream Flow Program

The Department has used 2D modeling in site-specific studies throughout California. 2D models were used to estimate water depths and widths needed for salmonid passage through depth-sensitive areas of the Big Sur River in Monterey County (Holmes et al. 2016) and Butte Creek in Butte County (Cowan et al. 2016). On Butte Creek, the Department used 2D modeling to assess fish passage through a complicated bedrock exposure that was known to cause delays in upstream passage and stranding downstream. Output displays from *River2D* software, like the one in Figure 18, were used by staff to determine the amount of stream width and water depth available to spring-run Chinook salmon over a range of flows through the most depth-sensitive portion of the bedrock exposure.

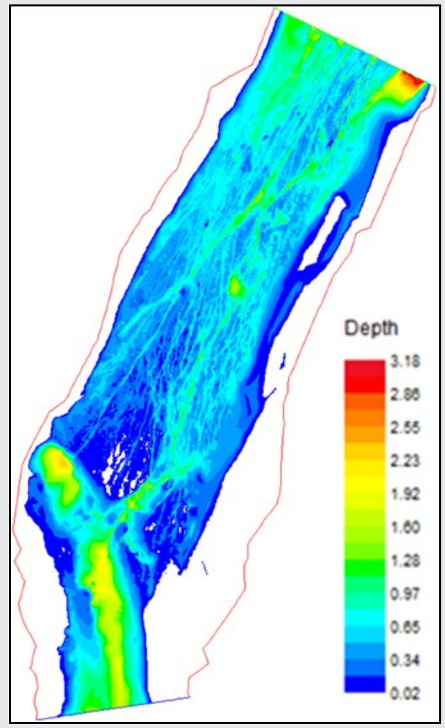

Figure 18. Depiction of depth in meters of the most depth-sensitive portion of Butte Creek for fish passage at a discharge level of 630 cfs.

More recently, the Department has employed 2D modeling to simulate flows that can enhance conditions for salmonid passage and juvenile rearing in three California Water Action Plan streams: Mill Creek, tributary to the Sacramento River in Tehama County (see Figures 12, 13, and 14); Ventura River in Ventura County; and Mark West Creek, tributary to the Russian River in Sonoma County (see Figures 10, 11, 15, and 16). For more information on each of these studies, please visit https://wildlife.ca.gov/Conservation/Watersheds/Instream-Flow/Action-Plan.

In the future, the IFP expects that more 2D hydraulic habitat studies will leverage remote sensing technologies. This would establish DTMs for large riverine areas and/or remote or restricted-access areas. The U.S. Geological Survey published a study in 2022 evaluating the ability to develop DTMs using a combination of airborne topographic bathymetry LIDAR with boat-based sonar in a large portion of the Oregon Willamette River basin (White and Wallick 2022).

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