Salinas River Critical Riffle Analysis

Development and Validation of Flow Thresholds for Steelhead Passage

Submitted To:
Monterey County Water Resources Agency

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Background

South–Central California Coast (SCCC) steelhead (*Oncorhynchus mykiss*, hereafter referred to as steelhead) are a threatened species (62 FR 43937) that occur in the Salinas Watershed and use the river primarily as a migratory corridor. As such, the species is affected by impoundments and flow releases from Nacimiento and San Antonio dams (hereafter collectively referred to as the dams), as well as discharge from the Arroyo Seco and other tributaries. Steelhead are also one of the primary species driving development of the Salinas River Operations Habitat Conservation Plan (SROHCP), which seeks to secure long-term regulatory coverage for flow releases from the dams, among other activities. Despite extensive fisheries and water quality monitoring conducted for the now withdrawn 2007 draft Biological Opinion issued by the National Marine Fisheries Service (NMFS) for the Salinas Valley Water Project (SVWP), there are still several critical information gaps that need to be addressed to develop effective conservation strategies for steelhead under the SROHCP.

Previous flow thresholds for steelhead passage were detailed in the Salinas Valley Water Project Flow Prescription for Steelhead Trout (Monterey County Water Resources Agency [MCWRA] 2005). This document outlined passage thresholds for adult and juvenile steelhead based on water year type, reservoir storage, and natural discharge in the Arroyo Seco. Notably, the Flow Prescription stated that "*Fish passage and count observations in the Carmel River indicate that a flow of 340 cubic feet per second (cfs) or greater at the Arroyo Seco near Soledad USGS gauge (11151700) during the months of January, February, and March may indicate that adult steelhead trout are ready to move up the Salinas River…*" Ultimately, a threshold of 260 cubic feet per second (cfs) as measured at the Chualar USGS gauge (11152300) was set as the threshold flow to facilitate steelhead passage in the system (MCWRA 2005). The reference to the Carmel River demonstrates that there was no data available from the Salinas Watershed for use in the development of passage criteria, and demonstrates the need for empirically-derived, watershed-specific thresholds. Watershed-specific, field-validated passage flow thresholds are critical for providing a more accurate picture of how steelhead migration opportunities are affected by changes in discharge, and for identification of any critical riffles or reaches that may be limiting connectivity in the watershed.

Previous efforts have attempted to determine the flows necessary to provide steelhead passage opportunities in the Salinas Watershed including a geomorphological evaluation led by NOAA Fisheries that provided data designed to enable development of a hydrograph that could facilitate successful steelhead migrations (Cluer and McKeon 2005). Although this study sought to establish hydrograph characteristics and minimum discharges required to facilitate steelhead migration, its main focus was on "*...the influence of the hydrograph on the geomorphic form of the low flow channel bed, and the resulting discharge relationships to riffle crest formation*." To address this, the authors conducted a single low flow geomorphological assessment over the course of four days with the majority of the six assessed transects being surveyed at only a single discharge. The report on the study is heavily focused on sediment transport and the dynamics of riffle crest formation, and only a single criterion for adult passage (≥1 foot of depth continuous across ≥10 feet of channel width) was considered. Ultimately, the authors determined that minimum flows to achieve their designated passage criteria ranged from 150-230 cfs across the transects that they assessed.

However, they note that lower flows may be expected to achieve passage thresholds "…*once the dune field has been incised and an unbroken thalweg has been formed in the low flow channel*."

The improved understanding of geomorphological processes provided by Cluer and McKeon (2005) is valuable, but it did not fulfill the need of a targeted assessment and modeling of flows to evaluate multiple potential passage criteria across varying flows and seasons. This study was primarily focused on the relationship between discharge and the geomorphic form of the low flow channel bed, and thus did not provide a comprehensive assessment of fish passage feasibility at spatially dispersed riffles across a range of flows. In addition, the riverbed is composed primarily of sandy substrates that shift annually, and although the fundamental processes governing riffle crest formation likely remain the same, the river topography has changed significantly since this assessment. As such, an updated assessment of discharge-depth relationships at key shallow riffles in the Salinas and Arroyo Seco rivers was necessary to update previous findings and inform hydrological models (e.g., Salinas Valley Integrated Hydrologic Model [SVIHM]; Salinas Valley Operations Model [SVOM]) for the development of an updated flow prescription for the SROHCP.

The critical riffle analysis (CRA) methods used for this effort were based largely on the California Department of Fish and Wildlife (CDFW) Standard Operating Procedure (CDFW 2017) but were modified to account for the sandy substrates in the Salinas Watershed. Methods were also informed by an extensive literature review to assess variability in CRA methodologies and variability in steelhead passage thresholds that have been used across the Pacific Northwest. In general, CRA is a method of identifying discharge levels necessary for the passage of salmonids through the shallowest locations within a river, referred to as "critical riffles." The standard operating procedure (SOP) for CRA in California involves locating a critical riffle, identifying a transect along the riffle's shallowest point from bank to bank, measuring water depth at set intervals along the transect, and repeating this measurement process over a range of flows (CDFW 2017). Field measurements of water depth are then compared to passage criteria for various life stages of steelhead, which are derived from existing literature (primarily Thompson 1972). After several sampling events have been completed along the transect across a wide range of flows, a graph of discharge versus the corresponding percent of the transect that exceeds the minimum depth criteria for the species and life stages can be used to determine stream flows necessary for passage. However, the SOP explicitly states that this method "*does not apply to river or stream channels that do not have riffles, such as those dominated by silt and sand substrates with particle sizes less than 0.1 inches*" (CDFW 2017).

The Salinas and lower Arroyo Seco rivers are dominated by sandy substrates, and therefore the effectiveness of this traditional methodology in these systems was unclear. As such, we developed an alternative approach to this SOP that used drone-derived digital elevation models (DEMs) to develop models of discharge-depth relationships at critical riffles and predict minimum flows to achieve passage criteria. This approach was proposed due to the limitations of the CDFW SOP in sandy river systems and was designed to minimize field effort, greatly expand spatial coverage, and improve the modeling flexibility of the CRA. The development and testing of these models also required the application of a field validation approach, which involved the recording of water depths along target transects at varying levels of flow for comparison with model-derived depth values.

Field work for this study was undertaken over the course of a year, between December 2022 and December 2023. This period also happened to be one of the wettest years on record in the Salinas River Watershed, with a peak flow of approximately 24,000 cfs in the Salinas River in March of 2023. These high flows substantially altered the channel configuration and geomorphological condition, in some cases quite significantly (Figure 1). While this created challenges for data collection, it also created a unique opportunity to test this methodology and analyze data under two vastly different channel conditions. Field-validated models leveraging data collected across varying channel conditions will allow for robust predictions of passage conditions for steelhead. These predictions are especially important for ensuring continued conditions suitable for steelhead passage in the context of increasingly variable hydrologic regimes in the region (Dettinger 2011).

Figure 1. Shifting channel position of the Salinas River near Chualar following unusually high discharge in March 2023. Flows during September 2023 field surveys occurred only in the new channel to the north of the old thalweg that contained the entire river flow during surveys.

A description of the methodology used, and the results of the analyses noted above are presented in this report. The main objectives of this report are to 1) demonstrate the feasibility of using drone-derived DEMs to predict the minimum flows necessary to facilitate upstream passage of adult steelhead in the Salinas River, 2) use model-derived data to propose a locally-informed, conservative flow threshold for adult steelhead passage in the Salinas River, and 3) present field data to assess and validate the proposed flow thresholds in each river reach. While this report is primarily focused on determining passage thresholds for migrating adult steelhead, analyses could be modified to develop passage thresholds for juvenile steelhead as well. However, since the threshold for adult steelhead is higher, and since post-spawn adult steelhead (kelts) have potential to migrate downstream at the same time as juveniles during the months of March-June, we believe the thresholds presented herein will provide adequate conditions for migration of all life history stages of steelhead in the Salinas River.

Results of our analyses suggest that the combination of drone elevation profiles and Manning's equation are able to provide realistic predictions of depths at assessed riffles in the Salinas River, and in turn, provide a predicted minimum flow threshold to achieve passage minima throughout the assessed reaches. The accuracy of model outputs is supported by field validation across varying flows, and the findings of both the hydrologic model and field collected measurements suggest that the minimum flow threshold to achieve passage criteria is considerably lower than the existing threshold established by the previous Flow Prescription (MCWRA 2005).

Methods

Pilot Surveys

A proposed methodology and work plan for conducting CRA in the Salinas and Arroyo Seco rivers was developed by FISHBIO and presented to MCWRA, SROHCP consultants, and regulatory agencies (NMFS and USFWS) in March of 2022. The proposed methodology involved the use of an Unmanned Aerial System (UAS; hereafter "drone") to create digital elevation models of the dry riverbed. These elevation data were then incorporated into a model that uses Manning's equation to predict water depth at critical riffles across various levels of discharge. Briefly, Manning's equation is an empirical equation that describes open channel flow as a function of the channel velocity, flow area, and slope, and is written as follows:

$$Q = VA = \left(\frac{1.49}{n}\right) AR^{2/3}\sqrt{S}$$

In which Q = flow rate (cfs), V = velocity (feet/second), A = flow area (square feet), n = Manning's roughness coefficient, R = hydraulic radius (feet), and S = channel slope (feet/feet). As the drone-generated DEMs are able to provide flow area and slope, and the Manning's n value for the substrate of the Salinas River (a roughness coefficient for sand) has been described by previous studies (Cluer and McKeon 2005), we were able to input these values into the equation to solve for water surface elevation across varying levels of flow. These predicted water surface elevations were, in turn, combined with channel profile data to estimate depths across the assessed transects at varying levels of flow, and we used these estimates to solve for the minimum flow at which depths were sufficient to achieve minimum passage criteria for steelhead. With support from MCWRA staff, FISHBIO conducted a pilot effort to test the methodology in June of 2022, which involved drone surveys in a reach of the Salinas River near Chualar.

For the initial effort, seven critical riffles within the reach, previously identified by MCWRA, were reassessed and four were confirmed to still exist through visual surveys and were selected for preliminary modeling. Attempts to identify some of the other riffles that were selected from the original aerial data proved difficult, which may be due to challenges associated with observing critical riffle areas from the ground when the channel is dry and/or changes to the riverbed that had occurred since the original aerial surveys were performed (in this case, 2019). However, the fact that at least four of these areas had retained similar structure that could be identified from the ground provides support for their selection as key areas for passage criteria monitoring. Ultimately, these four reaches were subjected to initial drone surveys in late June of 2022. Subsequent analysis of collected data was completed in early July of 2022, and initial results from this pilot effort were promising, although field validation of model results was not possible until later in the year following resumption of flows. Several lessons learned during the pilot effort were also applied during subsequent field work and analyses, and the drone-derived DEMs of these reaches were used to begin developing an initial model. In general, the following methods were deployed to conduct the modeling and field validation at critical riffles (Figure 2):

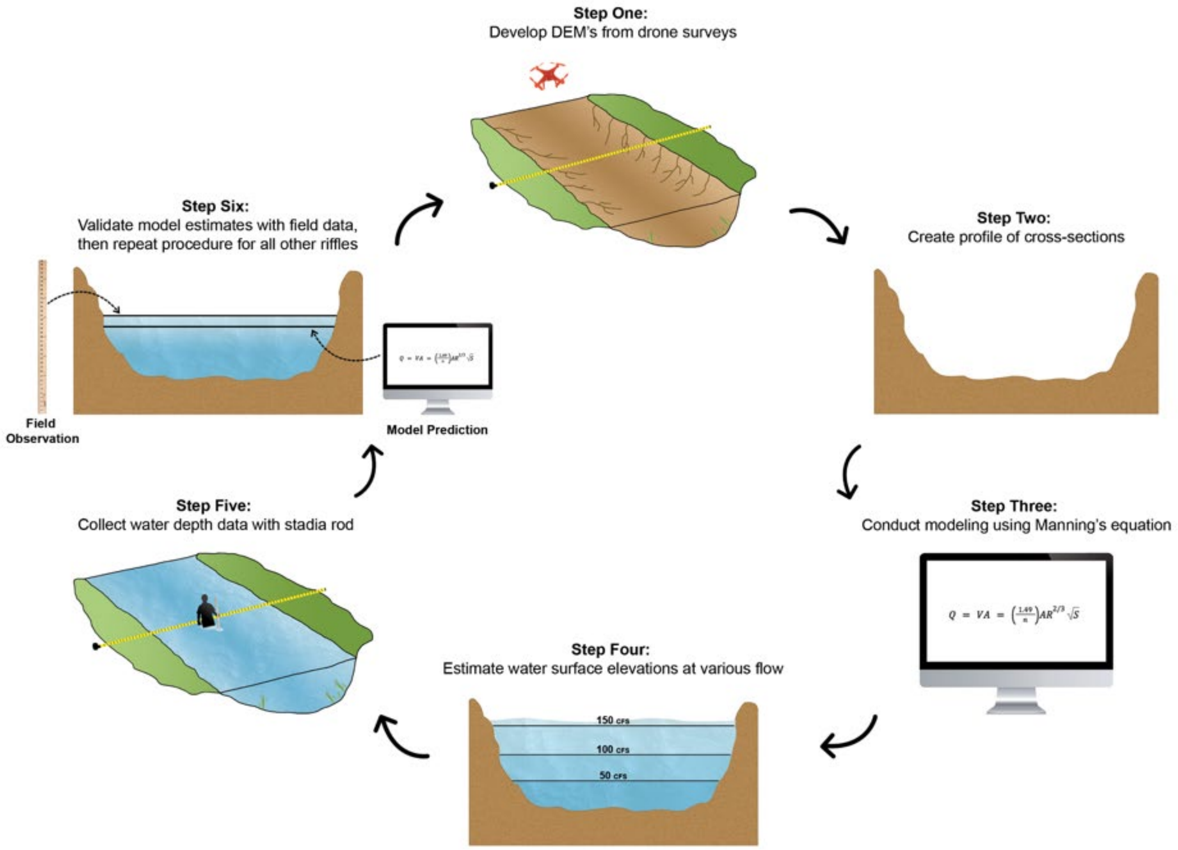
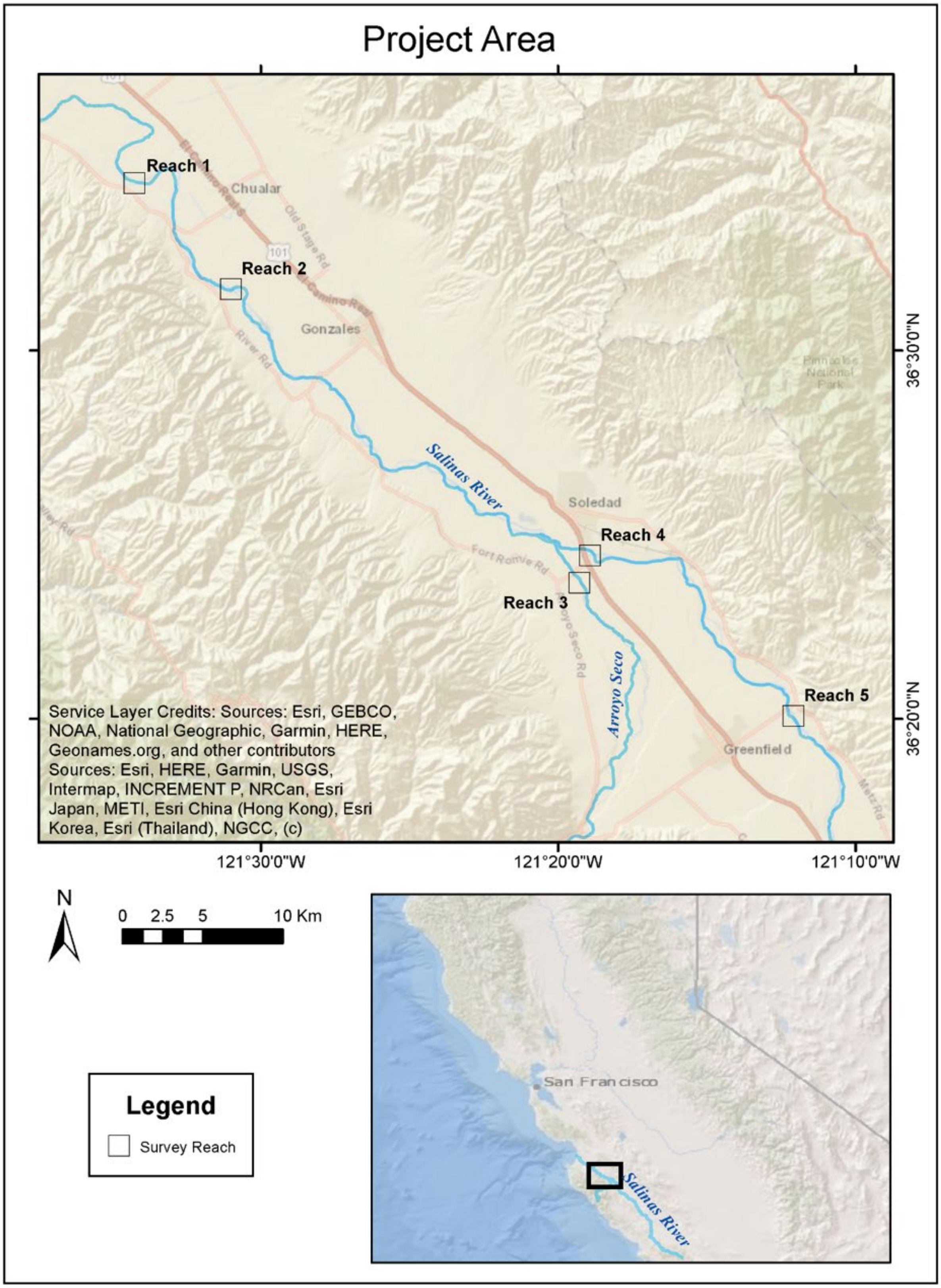


Figure 2. Depiction of methods used to predict and assess passage thresholds for critical riffles in the Salinas River.

Reach Selection

Based on the promising results of the pilot effort, staff from MCWRA worked to identify a series of river reaches for the CRA. Reaches were assessed through review of aerial flight data previously collected by MCWRA, available satellite imagery (Google Earth; latest imagery used at the time was from February 2021), and field verification. Final selection was determined based on location within the watershed and access considerations, as well as the existence of multiple potential critical riffles within each reach. Ultimately, five reaches were chosen for analyses: four on the mainstem Salinas River located near Chualar (reaches 1 and 2; downstream of the Arroyo Seco confluence) and Soledad (reaches 4 and 5; upstream of the Arroyo Seco confluence), as well as one reach in the lower Arroyo Seco River (reach 3, Figure 3). Reaches were spread from approximately river kilometers 36 through 86 on the Salinas, and river kilometers 1.6 through 6 on the Arroyo Seco. Reaches ranged between approximately 2.5 – 4 kilometers in length, although field-validated transects were generally concentrated within a smaller subset of each reach due to access considerations. The inclusion of larger reaches was intended to allow for evaluation of model accuracy at multiple riffle transects within each reach, as well as to allow for evaluation of riffle movement and riffle forming processes following flow events.



Service Layer Credits: Sources: Esri, GEBCO, NOAA, National Geographic, Garmin, HERE, Geonames.org, and other contributors Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri (Thailand), NGCC, (c)

Figure 3. Map of the five reaches selected for critical riffle analysis. More detailed reach maps depicting assessed transects are available in Appendix A (Figures A1-A5).

Drone Surveys

Following identification of target reaches, drone mapping software (DroneDeploy, San Francisco, California) was used to generate flight plans. On December 19-20, 2022, following a brief period of flow from the first precipitation event of the season that removed tire tracks and created a smoothed channel, a DJI Phantom 4 Quadcopter was deployed to collect imagery for map development. Collected images were used to generate DEMs of each identified critical passage reaches in the mainstem Salinas River (Reaches 1, 4, and 5) through photogrammetry. Drone surveys covered the entire length of each reach and included the deployment of ground control points to improve accuracy and precision of drone-derived DEMs. Reach 2 was mapped at that time (Figure 1), but difficulties with access arising due to flooding of fields surrounding that location precluded collection of field measured depth data for model validation (see below). Drone mapping was conducted during a period of no flow to ensure accuracy of the models, as photogrammetry is less accurate through water. Although some small pools persisted in the target reach, the riffles of interest were completely dry at the time of each survey. Drone surveys of the target reach in the Arroyo Seco River (Reach 3) were flown several months later on February 8 and 14, 2023. During both of these surveys, flow persisted in the riverbed. Discharge was 177 cfs on February 8, 2023, and 100 cfs on February 14, 2023, as measured at the USGS gauge below Reliz (gauge number 11152050). The presence of water in the channel likely reduced the accuracy and precision of the drone-derived elevation profiles generated for the riverbed, and along with other confounding factors ultimately precluded use of the model in that reach (see Arroyo Seco results below).

After a remarkably wet year, the Salinas River experienced flood flows that altered channel morphology and resulted in continuous flow in downstream reaches of the river through November 2023. Following cessation of flow near Chualar, drone flights were repeated in reaches 1 and 2 on November 7, 2023. These maps were created to evaluate changes in the river's morphology following the periods of very high flow that occurred between December 2022 and October 2023, and to serve as updated elevation profiles for model validation based on field data collected in June and September 2023. Notably, precise locations of the transects pulled from the November 2023 drone-derived DEMs were based on the locations where depth was measured during field surveys, which in some cases varied from the original transects measured during earlier surveys in December 2022 due to the movement and reformation of riffles throughout the target reaches. In reaches that were still inundated in November 2023 (reaches 4 and 5), alternate methods were used to obtain channel profiles at critical riffle sites (see *Obtaining Elevation Data at Critical Riffle Sites* section below).

It is important to note that the drone-derived elevation data is precise relative to itself and allows for calculation of riverbed morphology but is not accurate in absolute terms. In other words, the elevation as measured at any given point on the DEMs created by DroneDeploy is not an accurate representation of the real-world elevation above sea level at that location but does reflect the difference in elevation between it and neighboring points.

Obtaining Elevation Data at Critical Riffle Sites

The resulting maps from drone surveys were exported as Raw Elevation Values using the NAD83 (2011)/California zone 4 (ftUS) coordinate system at resolutions of 7.73 to 10.21 cm per pixel, and were imported into ArcMap (ESRI, Redlands, CA). In each reach, critical riffles were identified through a combination of drone DEMs, overhead imagery, and on-site reconnaissance. Generally, overhead imagery and DEMs were used to identify shallow areas, and the precise location of riffle crests were determined in the field using visual observations and stadia rod measurements. Attempts were made to identify the shallowest riffles in the vicinity with a secondary goal of identifying riffles that were relatively straight across the river (i.e., the riffle crest was not horseshoe shaped). At each selected riffle a virtual transect was constructed by digitizing a line feature near the area of interest running approximately perpendicular to the river channel but following along the riffle crest (and the field-validated transect) as closely as possible.

In each case, care was taken to align the elevation profile transect in the DEM with the transect that was measured in the field. Where vegetation obstructed bare earth and prevented continuous extension of the transects up the bank, digitized points were used to augment at locations that appeared to be roughly in-line with the transects and appeared to have bare earth (where feasible). The digitized line transect was then broken into five-centimeter (0.164-foot) sections and converted to a point feature with points at each node or break. Each point, including the augmented placed points, were assigned a distance measurement starting from river left in meters. This meant that the point farthest up the left bank (looking downstream) would be assigned a zero distance, the next point would be five centimeters to the right, and so on until all points along a transect had a unique position value. These points were then overlaid on the raster layer and elevations were transferred to a field within the point layer corresponding to their location (Figure 4). Each point was then assigned its respective latitude and longitude and the table was exported to a Microsoft Excel file for further analysis.

Using similar methods, a longitudinal profile along the river's thalweg was produced in 1-meter intervals to determine gradient. Slopes were obtained for each transect by tracing the thalweg from 10 meters upstream to 10 meters downstream of the riffle (Figure 5). In total, the December 2022 maps generated profiles for 10 unique transects: three in Reach 1, four in Reach 4, and two in Reach 5. The February 2023 surveys generated another two profiles for Reach 3.

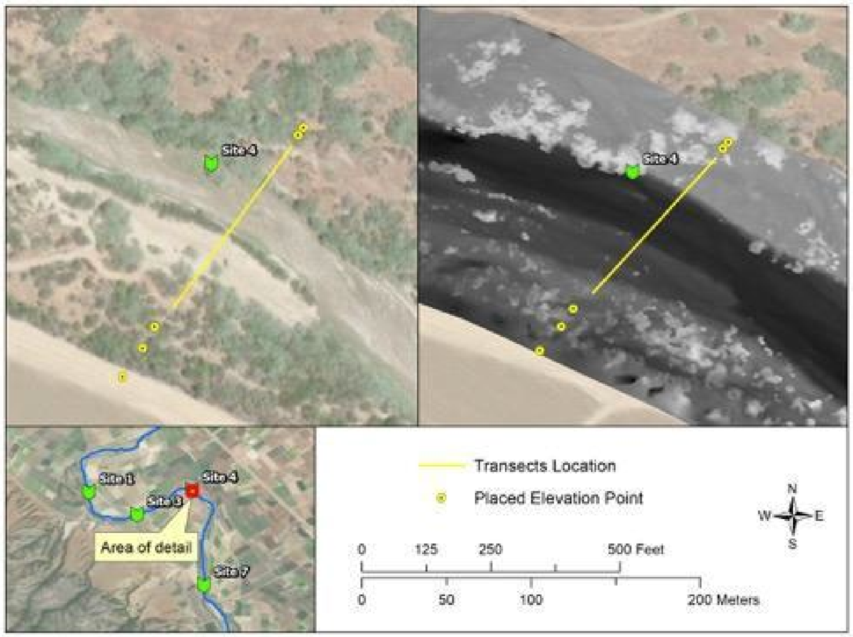


Figure 4. Example transect shown on overhead images and digital elevation models at Transect 4 in Reach 1 from the original drone surveys performed in June 2022.

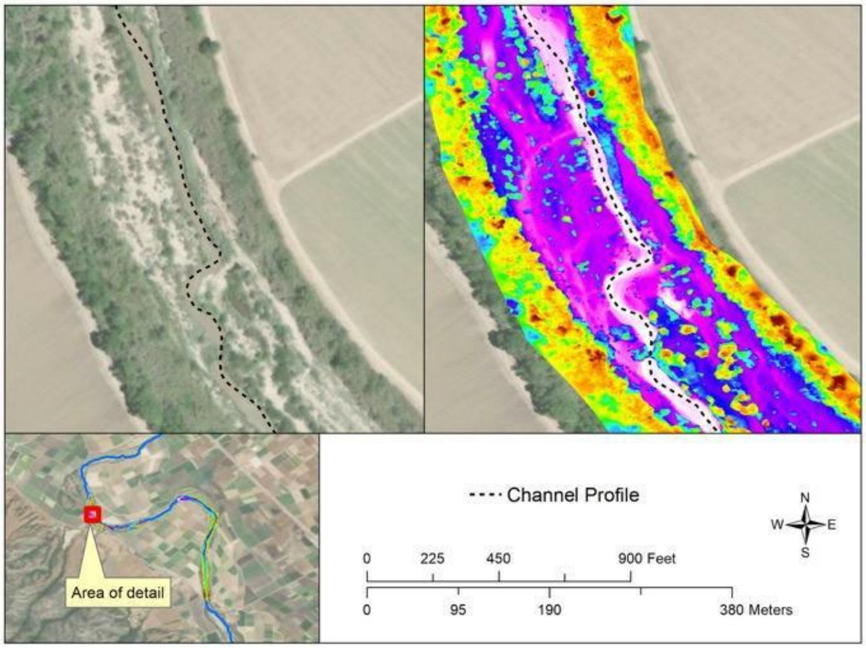


Figure 5. Depiction of the selection of the thalweg from DroneDeploy imagery. This approach was used to calculate average slope across a 20-m sub-reach centered on each individual transect. The left image shows the original drone imagery, and the right image depicts the elevation values generated through photogrammetry.

Table 1. Assessed transects and corresponding data collection methods and dates.

Site	Elevation Profile	Slope Measurement	Profile Survey Date	Depth Survey Dates
R1T1-A	Drone	Drone	12/19/22	12/13/22
R1T2-A	Drone	Drone	12/19/22	12/13/22
R1T3-A	Drone	Drone	12/19/22	12/13/22
R4T1-A	Drone	Drone	12/20/22	01/03/23
R4T2-A	Drone	Drone	12/20/22	01/03/23
R4T3-A	Drone	Drone	12/20/22	01/03/23
R4T4-A	Drone	Drone	12/20/22	01/03/23
R5T1-A	Drone	Drone	12/20/22	01/03/23
R5T2-A	Drone	Drone	12/20/22	01/03/23
R2T1-A	Drone	Drone	12/20/22	06/15/23
R2T2-A	Drone	Drone	12/20/22	06/15/23
R2T3-A	Drone	Drone	12/20/22	06/15/23
R1T1-B	Drone	Drone	11/07/23	09/13/23 and 09/25/23
R1T2-B	Drone	Drone	11/07/23	09/13/23 and 09/25/23
R1T3-B	Drone	Drone	11/07/23	09/13/23 and 09/25/23
R1T4-B	Drone	Drone	11/07/23	09/13/23 and 09/25/23
R2T1-B	Drone	Drone	11/07/23	09/13/23
R2T2-B	Drone	Drone	11/07/23	09/13/23
R2T3-B	Drone	Drone	11/07/23	09/13/23
R4T1-B	Laser Level	Laser Level	12/19/23	09/25/23 and 12/19/23
R4T2-B	Laser Level	Laser Level	12/19/23	09/25/23 and 12/19/23
R4T3-B	Laser Level	Laser Level	12/19/23	09/25/23 and 12/19/23
R5T1-B	Laser Level	Laser Level	12/18/23	12/18/23
R5T2-B	Laser Level	Laser Level	12/18/23	12/18/23
R5T3-B	Laser Level	Laser Level	12/18/23	12/18/23
R5T4-B	Laser Level	Laser Level	12/18/23	12/18/23
R3T1	NA	NA	NA	12/13/23, 02/08/23, 02/14/23, and 05/24/23
R3T2	NA	NA	NA	12/13/22, 02/08/23, 02/14/23, and 05/24/23

At some reaches, obtaining drone elevation data was not possible due to flows in the channel that precluded accurate drone measurements (e.g., reaches 4 and 5 in November 2023). At these locations, elevation profiles were obtained through physical measurement. Briefly, rebar stakes were placed high up on the bank on either side of the river to mark the location of the riffle for repeated measurements and to facilitate placement of a measuring tape to ensure accurate stadia rod measurements. Coordinates were collected at each stake using a handheld GPS. Once the measuring tape was set, elevation measurements were taken every foot using a laser level. At these locations, slope data was also obtained by collecting physical elevation measurements with the laser level in the channel thalweg 10 meters upstream and 10 meters downstream of the transect.

A total of 28 transects were assessed across all reaches throughout the duration of the study (Table 1; see Appendix A for bank margin coordinates of each transect). We originally aimed for 2-4 transects in each reach in order to facilitate field validation. However, new transects were selected following high flows in spring 2023 that completely altered channel configuration in most reaches. As such, analyses using profiles derived from the drone flights conducted in December of 2022 (denoted as period "A") were considered separately from analyses using profiles derived from drone flights and laser level profiles performed in November and December of 2023, respectively (period "B"; Table 1). In other words, the assessed reaches effectively underwent two rounds of critical riffle analyses based on channel conditions before and after spring flood flows.

Applying the Model to each Transect

Based on the model created during the pilot study in June of 2022, a revised and improved model was developed in R version 3.5.3 (R Core Team, 2019) to implement Manning's equation to estimate water depths at the critical riffle across various levels of discharge. Manning's equation is an empirical equation that applies to uniform flow in open channels and is a function of the channel velocity (i.e., Manning's n, in this case a roughness coefficient for sand), cross-sectional area, and channel slope. The cross-sectional area and slope were derived from the DEM files (see above), and a roughness coefficient of n = 0.0223 for the sandy substrate characteristic of the Salinas was obtained from Cluer and McKeon (2005).

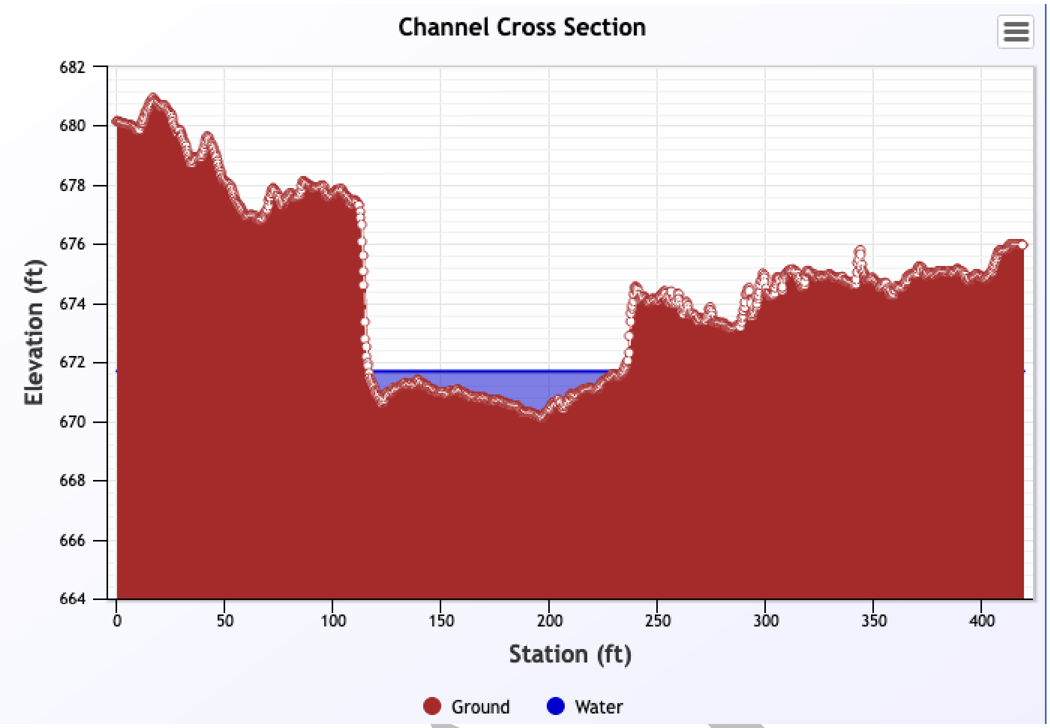


Figure 6. Example of a channel cross section for Reach 5 Transect 1, which was created in the NOAA calculator using elevation values obtained from the drone-generated DEM. Note that elevation values depicted are precise relative to one another but do not reflect real-world elevation values, and the varying scale of the x- and y-axes make the bank margins appear to have greater relief than they do in reality.

By incorporating the channel morphology derived from the DEMs or elevation profiles into the publicly-available NOAA normal depth calculator (Figure 6; calculator available at https://www.weather.gov/aprfc/NormalDepthCalc), a lookup table of corresponding discharge and water surface elevations was constructed for each of the critical riffle sites. This lookup table included predicted water surface elevation values for discharges ranging from 0 to 350 cfs at intervals of 10 cfs. This range was selected to slightly surpass the 260 cfs recommended by NMFS as providing sufficient flow to meet minimum passage criteria at Chualar (NMFS 2005).

The R script then performed a loop function to develop depth profiles for the transects across varying levels of discharge based on projected water surface elevations. These profiles were then used to evaluate the thresholds at which various potential passage criteria for steelhead were achieved. The primary passage criteria considered in this modeling effort are those recommended CDFW (2017) for steelhead (Model A). However, the same approach was implemented to calculate thresholds for a total of four different sets of passage criteria (hereafter "models") based on review of existing literature on steelhead passage (see Appendix D), and included the following:

Model A – 25% of the wetted width is ≥0.7 feet in depth, with ≥10% of this depth contiguous
Model B – 25% of the wetted width is ≥0.6 feet in depth, with ≥10% of this depth contiguous
Model C – 10 feet of the wetted width is ≥1 foot in depth
Model D – 2 feet of the wetted width is ≥0.7 feet in depth

While all of these models were analyzed for comparative purposes, we primarily focused on Model A for our results, as this is the most commonly used criteria for salmonid passage based on our literature review (see SWRCB 2010; Booth et al., 2014; Holmes et al., 2015). This threshold of 25% of wetted width ≥ 0.7 feet in depth and ≥10% of this depth being contiguous was derived from Thompson (1972), which in our review of available literature was found to be the most commonly cited threshold related to steelhead passage criteria (Appendix D). Further, this is the threshold that has been most broadly applied for steelhead passage minimums in the state of California. Notably, a near complete lack of empirical data related to steelhead passage capabilities became evident in our review of the literature, and as a result management plans and studies have generally relied on the theoretical thresholds established in documents such as that created by Thompson (1972). Given a lack of physical evidence of steelhead passage capabilities, selecting a threshold value that falls towards the upper end of estimated depth minima (which ranged from 0.35 to 1 foot; Appendix D) seemed a reasonable choice. Note that although discussions of passage criteria in the body of this report reflect the Model A threshold, minimum discharge estimates for alternative models are provided in Appendix B.

Field Validation

To evaluate the validity of model calculations, comparisons were made between the depths measured at the transects in the field using either an acoustic doppler current profiler (ADCP) or stadia rod and the model-derived depth profile at the same discharge. Because the ADCP was also used to calculate discharge, precise estimates of flow at the specific transect locations were used as inputs in the models when available, although comparison between USGS gauge-derived discharge and ADCP-derived discharge showed very good agreement (i.e., within 1-2 cfs). Following model-based generation of depth profiles at the ADCP- or gauge-derived discharge value, comparisons were made between the average and maximum depths estimated by the model and measured by the ADCP and/or stadia rod. Notably, the ADCP is not able to measure very shallow depths (i.e., less than a few inches), and uses interpolation to estimate depths near the shore. In addition, the ADCP could not be used at locations which included in-channel islands. As such, model-derived depth profiles were trimmed to include only depths above the minimum threshold for ADCP measurement to ensure that model results would not be negatively biased by the inclusion of the very shallow depths near the margin of the channel. Depth profile data was also supplemented with stadia rod measurements to gather accurate data at shallow depths.

Multiple field measurements were taken from December 2022 through September 2023 with the intention of generating data for comparison with and validation of model outputs. Comparisons of field data with model outputs were performed for nine transects across Reaches 1, 4, and 5 using a model based on DEMs from the December 19-20, 2022, drone flights and depth data from December 13, 2022 (Reach 1) and January 3, 2023 (reaches 4 and 5) field validation efforts. A second round of comparisons was made for the four transects in Reach 1, three transects in Reach 2, three transects in Reach 4, and four transects in Reach 5 using a model based on DEMs from the November 7, 2023, drone flights and December 18-19, 2023, laser level profile measurements combined with depth data from June 15, September 13, September 25, December 18, and December 19 field validation efforts.

At identified riffles, rebar stakes were placed on either side of the river to mark the location of the riffle for repeated measurements and to facilitate placement of a measuring tape to ensure accurate stadia rod measurements. Once the measuring tape was set, measurements of water depth were taken every foot starting at the edge of the wetted channel, and GPS points were collected to mark each edge of the river. Alternatively, if the ADCP was used to measure depths, then the unit was ferried across the channel directly underneath the measuring tape.

A total of 10 days were spent collecting field validation data across a range of flows between approximately 30 and 230 cfs (Figures 7-8). Notably, all field measurements in June 2023 and September 2023 were collected after the major channel-altering flows that occurred in March of 2023, and data collected during these surveys were then compared to models developed from the November 2023 drone data (reaches 1 and 2) and December 2023 laser level data (reaches 4 and 5). Many of these measurements occurred at flows <100 cfs, after initial model runs suggested that lower flows may be suitable for passage. By collecting empirical depth data across these declining flows and performing repeated drone mapping following cessation of flows and laser level profile measurement in reaches where flow persisted, it was possible to evaluate model performance at lower discharges, and more precisely evaluate minimum passage criteria.

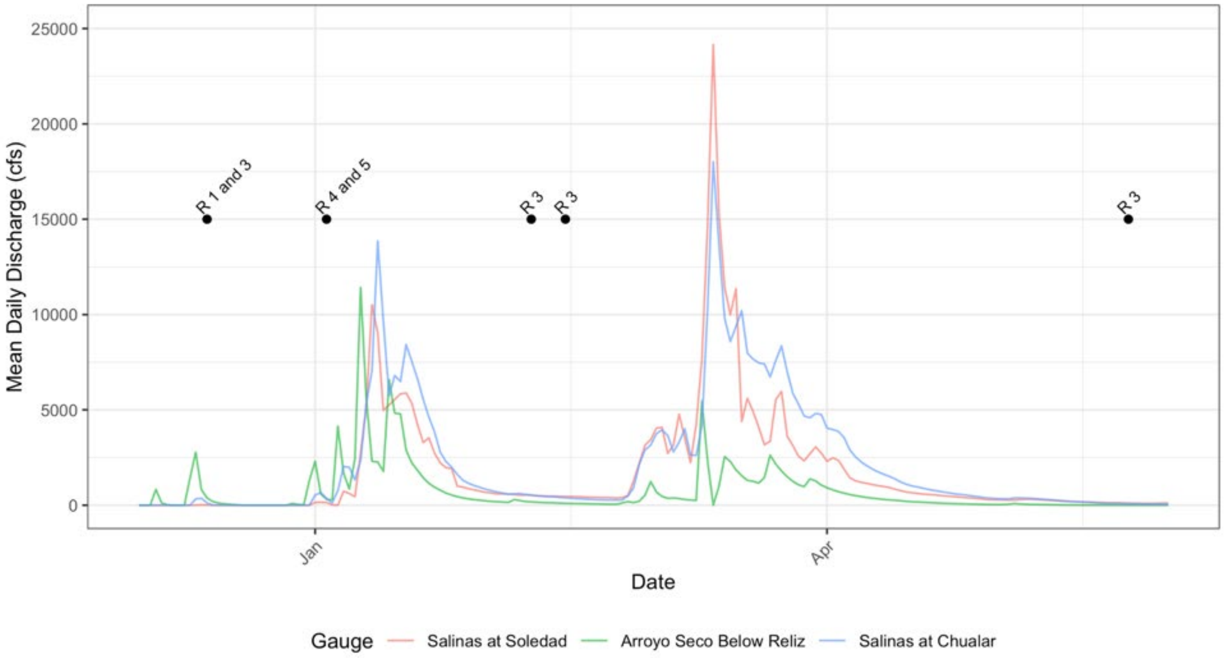


Figure 7. Dates of field validation surveys and corresponding flows in the Salinas and Arroyo Seco Rivers for the first round of modeling (December 2022 through May 2023).

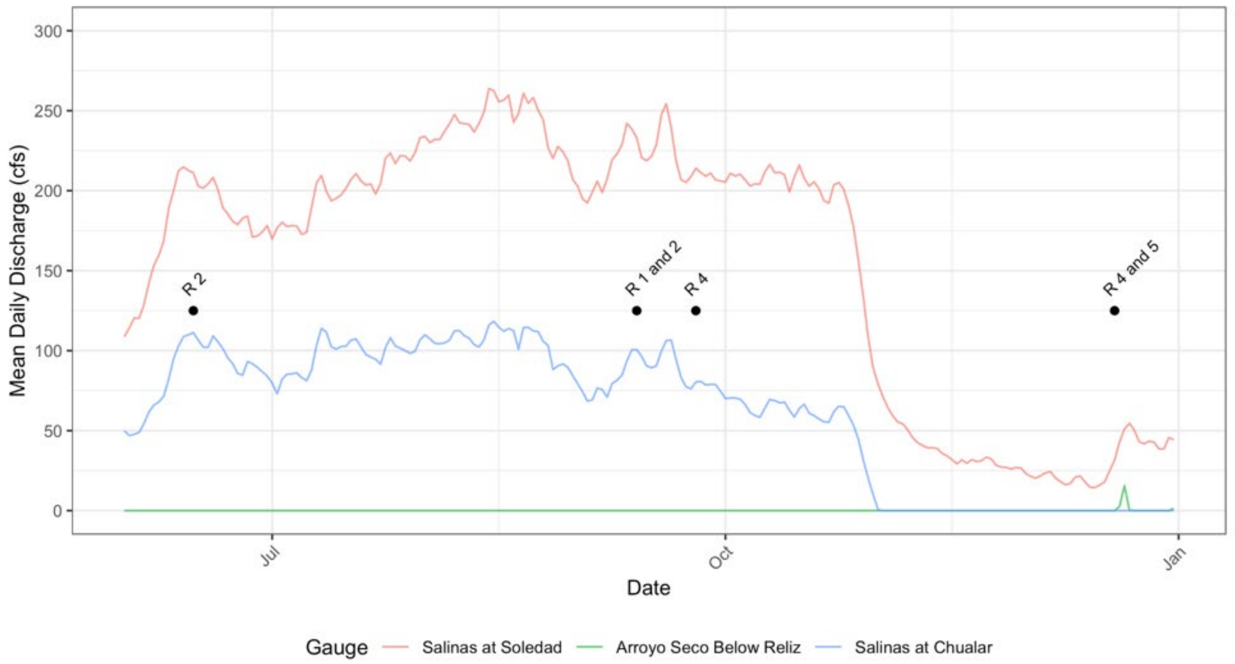


Figure 8. Dates of field validation surveys and corresponding flows in the Salinas and Arroyo Seco Rivers for the second round of modeling (June 2023 through December 2023).

Arroyo Seco Passage Assessment

Although the Arroyo Seco is undammed and therefore beyond the control of water managers to facilitate passage conditions, there was still interest in obtaining estimates of minimum passage flows for this system in order to more accurately evaluate the number of passage days that occur in each migratory season. However, the presence of flow in the channel contributed to imprecision in drone-derived elevation profiles, and this combined with the differences in substrate composition in the Arroyo Seco compared to the mainstem Salinas (i.e., a greater proportion of cobble intermixed with sand as opposed to the predominantly sandy substrates of the Salinas) and the associated difference in Manning's n value led to challenges in applying the hydrologic model to these transects.

Field measurements were collected at Reach 3 transects during the first field validation trip on December 13, 2022 – at which time flows in Reach 3 were measured at 458 cfs using the ADCP. Several months later, two drone surveys were performed one week apart on February 8 and February 14, 2023, in the target reach on the lower Arroyo Seco River. During these drone surveys, there was still flow in the river – 176 cfs on February 8 and 99 cfs on February 14 – as measured using the ADCP. As such, a more traditional riffle assessment was implemented, and stadia rod and ADCP measurements were collected at riffles within the Arroyo Seco reach during these surveys. These data allowed for plotting of average transect depth across the range of assessed flows to provide some insight into the level of discharge that may be necessary to achieve minimum passage criteria (i.e., depths ≥ 0.7 feet). However, of the two transects that were repeatedly assessed across these four sampling events, only one of them (the more downstream of the two) met passage criteria for more than one field sampling event, and therefore the regression only applies to that transect. The upper transect was passable during the very high flows in

December of 2022, but failed to meet the criteria of 25% of channel width ≥0.7 feet in depth. See the *Results* section for further discussion of these findings.

Sensitivity Analysis

A sensitivity analysis was used to assess how estimated passage thresholds varied in response to changes in channel slope and Manning's n value. This was performed as a means of understanding how sensitive the model was to variations in the input parameters, and thereby provide insight into how slight error in field and drone-based measurements may impact model outputs. To perform this analysis, a single transect for which field values had been shown to align with model outputs very closely was selected as an example. Using this transect profile, the model was run multiple times while manipulating the slope and Manning's n input values. Four model runs maintained the standard Manning's n for the Salinas of 0.0223 (Cluer and McKeon 2005) and varied only the slope by doubling it, increasing it by an order of magnitude, halving it, and decreasing it by an order of magnitude, respectively. Another six model runs were performed using the actual drone-derived slope measurement while manipulating the Manning's n value using a range of values for varying substrates from a reference table available at https://www.fsl.orst.edu/geowater/FX3/help/8_Hydraulic_Reference/Mannings_n_Tables.htm. All of these variations were employed to evaluate the potential impacts on model estimation of water surface elevation, and therefore on the expected depth at a transect.

Results

Model Runs

Minimum flow thresholds calculated for each of the assessed transects ranged from 20 to 260 cfs, depending on the location and the model being applied (Table 2). The standard passage criteria established by CDFW (Model A) generated an average threshold flow that fell between these two extremes at 71.07 cfs (Table 2). As mentioned above, results presented below are representative of Model A, but additional details on estimates of other model thresholds can be found in Appendix B.

Reach-specific model thresholds reveal critical differences between passage thresholds at each studied reach, as expected. In general, average passage thresholds were much lower in the downstream reaches near Chualar (1 and 2) than they were in upstream reaches near Soledad (4 and 5), with average threshold flows of 42 cfs in Reach 1, 47 cfs in Reach 2, 82 cfs in Reach 4, and 106 cfs in Reach 5. These average passage thresholds represent the average of all the predicted passage thresholds at each individual transect in each reach.

Period A (December 2022) and Period B (November-December 2023)

Differences in reach-specific passage thresholds were largely consistent across both analysis periods, with the exception of Reach 4, where the average passage threshold increased substantially between the two analyzed time periods (Table 2). These differences likely had more to do with alteration of channel geometry following spring flood flows, which was evident during field surveys (see *Discussion* below). At the other reaches, average passage thresholds were more similar across the two analyzed time periods. Maximum thresholds represent the highest predicted passage threshold among all the transects within each reach, and range between approximately 55-70% higher than the average passage thresholds. The maxima also follow a similar pattern as the average thresholds in that they increase from the downstream to the upstream reaches (Table 2). Additional details on all predicted threshold maxima can be found in Appendix B.

Table 2. Average model-derived flow thresholds for each reach and survey period. Thresholds presented are those necessary to achieve at least 25% of wetted width ≥0.7 feet deep and ≥10% of this depth being contiguous. Refer to Table 1 for precise dates of elevation profile surveys.

Profile Survey Period	Profile Survey Method	Gauge	Reach	Number of Transects Assessed	Average Passage Threshold (cfs)	Standard Deviation of Passage Threshold (cfs)	Maximum Threshold
December, 2022	Drone	Chualar	1	3	46.67	11.55	80.00
November, 2023	Drone	Chualar	1	4	37.50	17.08	60.00
November, 2023	Drone	Chualar	2	3	46.67	11.55	60.00
December, 2022	Drone	Soledad	4	4	47.50	23.63	80.00
December, 2023	Laser Level	Soledad	4	3	116.67	55.08	180.00
December, 2022	Drone	Soledad	5	2	75.00	42.43	110.00
December, 2023	Laser Level	Soledad	5	4	127.50	93.59	220.00
				Chualar Average	**43.61 cfs**	**Chualar Maximum**	**80.00 cfs**
				Soledad Average	**91.67 cfs**	**Soledad Maximum**	**220.00 cfs**

Model Validation with Field Measurements

Based on the model outputs and field data from December 2022, the mean depths predicted by the model were -1.15 inches shallower than the mean depths observed in the field (Table 3). This suggests that the model is slightly underestimating the actual depths, at least at the flows that have been assessed to date. However, it is worth noting that there is some variance in these averages, and model predictions of mean depths for certain sites (e.g., Reach 1 Transect 4) were off by a greater degree, as were model predictions of maximum depths (e.g., Reach 4 Transect 3; Table 2). However, only three model predicted means and three predicted maxima showed disagreement of more than two inches with depth observations in the field (Appendix C).

Repeating these comparisons using the model outputs based on the drone-derived DEMs from November 7, 2023, and field-derived elevation profiles from December 18-19, 2023, mean depths predicted by the model were -1.52 inches shallower on average than the mean depths observed in the field (Table 3). Once again, there was variation between reaches with model predictions for some reaches appearing to be remarkably close to observed values (e.g., Reach 4) while other reaches were less accurate (e.g., Reach 2). It was expected that field validation during this time period would be more variable and potentially less accurate, given the shifts in the channel that likely occurred between June and September (when field observations were made) and November and December (when the model was developed). Further details on shifts in the channel geometry across the sampling season are discussed below and all validation data on all assessed transects during each field visit are available in Appendix C. Model predictions from all reaches, however, were still negative, indicating that model predictions underestimated the depths observed in the field at a given location. Therefore, passage flow thresholds established based on model outputs could, in all cases, be considered conservative (i.e., conditions experienced by migrating fish would be more favorable than the conditions predicted by the model).

Table 3. Differences between model-generated average depths and field measured averaged depths across all assessed reaches and survey periods.

Field Survey Date	Reach	Number of Transects Assessed	Average Difference between Model and Field Values (inches)	Standard Deviations of Differences between Model and Field Values (inches)
12/13/22	1	3	-1.52	3.36
01/03/23	4	4	-0.87	1.57
01/03/23	5	2	-1.08	1.70
09/13/23	1	4	-1.17	1.34
09/13/23	2	3	-3.08	0.77
09/25/23	1	4	-0.45	1.11
12/18/23	5	4	-0.78	2.00
12/19/23	4	4	-0.06	1.41
06/15/23	2	3	-3.6	0.48
		Overall Average	**-1.13**	

Importantly, outputs from models that utilized profile and slope data collected in close temporal proximity to the measurement of depths in the field demonstrated the best agreement with the field collected depth data (Table 4). When circumstances prevented the collection of profile data for extended periods of time, agreement was poorer. In particular, differences of more than 50 days between profile and field data collection dates led to average disagreements of over an inch, whereas the collection of profile and field validation data within 43 days of each other all resulted in differences of less than an inch (Table 4).

Table 4. Average disagreement between model outputs and field collected depth data based on the difference in days between profile data collection and field depth measurement. Note that a negative difference indicates the profiled data was collected prior to field depth measurement.

Site	Mean Difference Between Model Outputs and Field Measured Depths (in)	Standard Deviation of Difference (in)	Profile Measurement Method	Field Depth Measurement Method	Days Between Profile and Field Depth Measurement
Reach 1	0.42	3.36	Drone	ADCP/Stadia	7
Reaches 4 and 5	-0.94	1.43	Drone	ADCP	-14
Reach 2	-3.60	0.48	Drone	Stadia	145
Reaches 1 and 2	-1.66	1.46	Drone	Stadia	55
Reach 1	-0.45	1.11	Drone	Stadia	43
Reach 4	-3.72	3.17	Laser Level	Stadia	85
Reaches 4 and 5	-0.57	1.70	Laser Level	Stadia	0

Arroyo Seco Passage Estimates

Average transect depths were plotted against discharge to gain insight into the flow thresholds that may be necessary to achieve minimum passage requirements in the lower Arroyo Seco (Figure 9). Although passage criteria were met at Reach 3 Transect 1 during two of the field data collection efforts (December 13, 2022, and February 8, 2023), the data collected for Reach 3 Transect 2 showed that it met passage criteria at only one of the assessed flows (December 13, 2022). Assessment of the percentage of the transect exceeding the depth minimum of 0.7 feet suggests that a minimum discharge of approximately 90 cfs would achieve passage criteria at the Reach 3 Transect 1. However, the fact that Reach 3 Transect 2 did not meet passage criteria at discharges greater than this would suggest the true minimum to allow passage would be somewhat higher. Additional explanation and analysis of passage threshold results in the Arroyo Seco River are available in the *Discussion* section below.

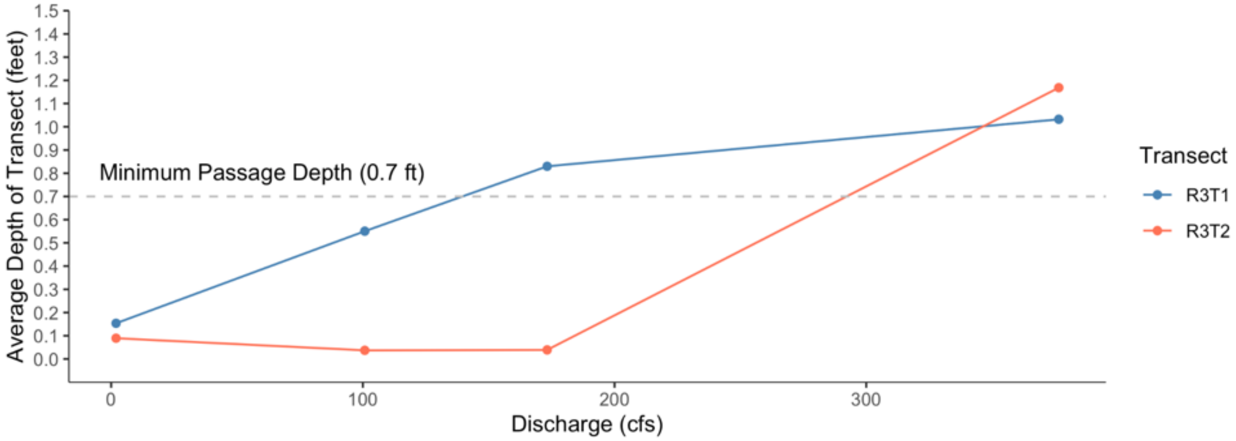


Figure 9. Average transect depths gathered from multiple measurements made at transects 1 and 2 in Reach 3 (Arroyo Seco) on December 13, 2022; February 8, 2023; February 14, 2023; and May 24, 2023.

Sensitivity Analysis

The ten model runs to assess model sensitivity to slope and Manning's n input values demonstrated that using slope values lower than the true slope of the reach or using Manning's n values greater than the true n of the substrate present at the assessed location result in an inflation of predicted depths and would therefore lead to underestimation of minimum passage flows. Conversely, use of slopes steeper than the true value of the reach lead to a reduction in the predicted depth, and therefore would lead to overestimation of minimum passage flows (Figure 10). Though lower Manning's n values were not assessed specifically – namely because n values lower than that assigned to the sandy substrates of the Salinas are not realistic for river channels – it could be presumed that use of a Manning's n less than the true n of the substrate present at the assessed location would also lead to artificially reduced estimations of depth and therefore overestimation of minimum passage flows. The average depths measured during the field surveys in September show good agreement with the model that relied on the Manning's n of 0.0223 provided by Cluer and McKeon (2005) and slope values derived from the drone-generated DEM (Figure 10). Although the manipulations of slope and Manning's n here are perhaps far more significant than the error that might be expected to occur from imprecision in field measurements, understanding the potential direction of bias is important for the accurate interpretation of model outputs.

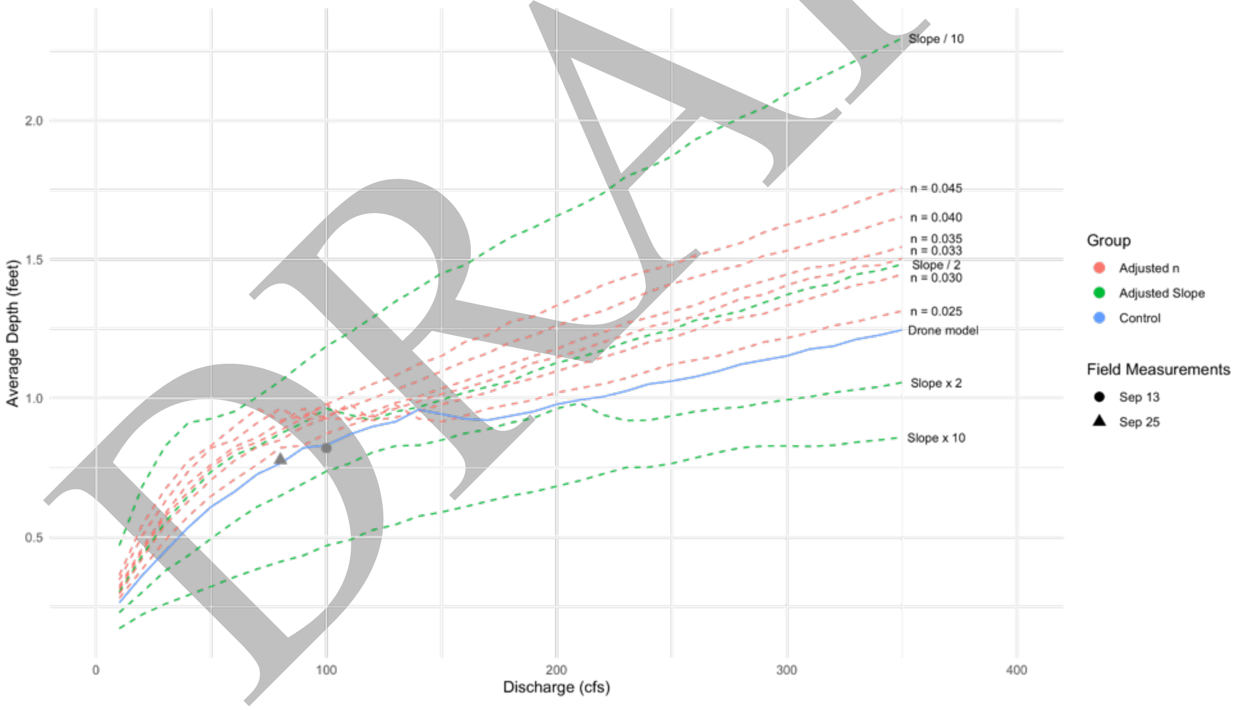


Figure 10. Model sensitivity testing using data from site R1T3-B. Four slope adjustments (doubled, increased by an order of magnitude, halved, and decreased by an order of magnitude) and six alternative values for the Manning's n were used in the model. The depicted "Control" line represents model outputs using the drone-derived slope in conjunction with a Manning's n of 0.0223 (obtained from Cluer and McKeon, 2005). Average transect depths obtained during the two field surveys of site R1T3-B conducted in September of 2023 are overlaid as points.

Discussion

Using drone-derived remote sensing data to model passage depths at various river flows is a novel approach in the Salinas Watershed and for SCCC steelhead as a whole. Remote sensing data has previously been used to assess multiple attributes of salmon behavior and habitat including spawning activity, habitat connectivity, and habitat characteristics (e.g., Harrison et al., 2020; Giroux et al., 2022; Arsenault et al., 2023), but to our knowledge very few studies have employed methods similar to this study to predict what flows will provide passage for adult steelhead. A recent study from the Sacramento River assessed the feasibility of using remotely sensed bathymetry data to develop hydrodynamic models of salmon spawning and rearing habitat. The authors of that study found that bathymetric data collected from piloted/uncrewed aircraft can be used to map bathymetry in clear-flowing and relatively shallow rivers (Harrison et al., 2022).

Our study, although similar, relied on alternative methods to ameliorate challenges associated with the persistently high turbidity in the Salinas River, and the efficacy of our approach has been demonstrated and validated through multiple rounds of field data collection. Given that this field validation data was collected over a long time period and across a wide range of flows, it represents perhaps the most substantial body of evidence related to passage conditions in the basin. The field-collected depth data clearly demonstrates that passage conditions (as defined by CDFW) were possible at much lower flows than had previously been estimated for the Salinas River (Appendix E).

Based on the results of the models and field data collection efforts, we think a minimum flow of 80 cfs as measured at Chualar would provide sufficient depth to exceed the passage criteria set by CDFW (2017) at all evaluated riffles. This provides an approximately 80% buffer above the average flow threshold of 44.38 cfs at all assessed transects near Chualar (reaches 1 and 2) and exceeds the maximum passage threshold for any transect in those reaches. Given the buffer and the apparent tendency for the models to slightly overestimate the flow required to achieve a certain depth, we think this threshold would be a conservative means of ensuring passage is possible throughout the assessed reaches. While this passage threshold is lower than previous estimates in the basin, the results of this study match general observations in the field and have been verified through multiple rounds of field validation (Appendix C).

Passage thresholds in upstream reaches were substantially higher than the reaches assessed near Chualar, primarily due to differences in channel geometry in the upstream reaches (i.e., wider and flatter) compared to downstream reaches. However, it appears that a passage threshold of 80 cfs at Chualar would result in adequate depths to achieve estimated passage thresholds near Soledad. The Chualar gauge (near reaches 1 and 2), is located approximately 30 km downstream from the gauge at Soledad (near reaches 4 and 5). During the study period, the upstream gauge at Soledad experienced approximately 1.5 times the amount of flow observed at the downstream gauge at Chualar following resumption of flows after an extended period of no flow (as measured on December 13, 2022), and that value rose to 1.9-2.6 times the amount of flow after many months of continuous flow (as measured on June 15 and September 25, 2023, respectively). Therefore, achieving a flow threshold of 80 cfs in Reach 1 or Reach 2 would likely result in a simultaneous flow of between 152 and 208 cfs occurring at Reach 4 or Reach 5 during the time periods when the passage thresholds may be implemented following resumption of natural flows. Given this understanding, the recommended passage threshold of 80 cfs for Reach 1 and Reach 2 would likely result in adequate passage depths and much higher flows in Reach 4 and Reach 5.

The Arroyo Seco is not under the control of water managers, as it remains undammed. However, identifying a passage threshold in that system would help to better understand the flow conditions required to allow steelhead access to critical spawning and rearing habitat in the upper watershed. Unfortunately, challenges in applying the drone-based model precluded a precise estimation of a passage threshold for the lower Arroyo Seco. Although all manually assessed transects appeared to be passable during high flows (458 cfs), all other field measurements took place at discharges at or below 176 cfs. One of the assessed riffles appeared passable at flows as low as approximately 90 cfs but one of the transects did not achieve minimum passage criteria of 25% of channel width ≥0.7 feet in depth at any of these lower discharge levels. The dynamics of the lower Arroyo Seco are somewhat different than those observed in the mainstem Salinas, as the riverbed contains far more rocky substrates and the river is typified by a very flashy hydrograph. It is likely that these factors lead to different processes of channel formation and shifting during periods of high flow, and a more targeted study of the characteristics of that system may shed light on how these influence passability. We were unable to precisely determine what discharge would be necessary to achieve steelhead passage criteria in the Arroyo Seco because the model was ineffectual in that location given a lack of drone-generated profile data and uncertainty surrounding appropriate Manning's n selection, and because no field data were collected on the descending limb of the hydrograph between 458 and 176 cfs. However, we can be reasonably confident the value lies somewhere between those two discharges. However, given the ephemeral nature of the river, it is probable that it rapidly drops from passable to impassable water depths, and likely does not experience extended periods with a discharge that would result in water surface elevations near the margin of passability. Development of a data-informed passage threshold for the lower Arroyo Seco would require additional field sampling across a wider range of flows, particularly on the descending limb of the hydrograph.

The flow passage thresholds developed through this effort are substantially lower than previous investigations in the watershed, including those conducted by MCWRA (2005) and Cluer and McKeon (2005). The passage thresholds recommended by MCWRA were not based on field-derived or basin-specific data, so it is not surprising that those thresholds were different than those developed by this study. While the passage thresholds recommended by Cluer and McKeon (2005) were based on limited field sampling, their study was not as comprehensive as this passage depth assessment, and it had a fundamentally different focus. However, the work that Cluer and McKeon did to establish the relationship between discharge and the geomorphic form of the low flow channel bed was helpful in developing the design of this study to assess riffle development across an entire water year. Encouragingly, there was agreement among the studies, as Cluer and McKeon (2005) ultimately determined that minimum flows to achieve their designated passage criteria ranged from 150-230 cfs across the transects that they assessed near Soledad. These flow thresholds agree well with the predicted flows at Soledad (150-208 cfs) with the recommended passage threshold of 80 cfs at Chualar. In addition, Cluer and McKeon noted that lower flows may be expected to achieve passage thresholds "*...once the dune field has been incised and an unbroken thalweg has been formed in the low flow channel*."

This type of incision within the dune field was obvious during repeated field visits, as was evidence of bed movement even at low flows. During field visits in December 2023, when flows near Soledad were approximately 30 cfs, there was obvious bed movement across the entire channel, with several deeper areas being filled in along the channel margins and clear movement of substrate that could be observed while standing in the channel (Figure 11). However, a thalweg was still evident, as it was during all previous surveys, which suggest that once the channel has been incised, a thalweg will remain as long as there is flow in the channel. This propensity for the river to rapidly carve a thalweg through the sand when flows are present suggests that model flow threshold estimates are likely conservative and exceed the true discharge necessary to achieve passage criteria. This thalweg may fill in and the bed may appear flatter following cessation of flow (i.e., when the elevation profiles were obtained through drone surveys), which would in turn lead the model to predict somewhat shallower average depths than were truly present in the transect when flow was present. This hypothesis is supported by our observations in the field, when we witnessed the river actively moving sediment and sculpting a deeper thalweg even at very low flows (approximately 30 cfs), resulting in the maintenance of deeper pockets across the riverbed at the assessed transects.

Figure 11. Bed movement of sand into deeper areas of the channel (previously covered in silt) at flows of ~30 cfs in Reach 4 of the Salinas River near Soledad on December 19, 2023.

The highly mobile sandy substrates of the Salinas River make it a very dynamic system that is subject to significant changes in its channel morphology following periods of high flow. Dramatic shifts in channel shape and location were observed over the course of this study (Figure 1, Figure 12) following the very high flows that occurred in the spring of 2023. These significant shifts mean that the location and morphology of critical riffles may vary dramatically from season to season, or even month to month. However, the drone-based approach employed by this study allowed for rapid reassessment following such geomorphic changes and obtaining multiple profiles and associated model outputs across these shifts bolsters confidence that the passage criteria presented here are robust to large changes in hydrology. This was due in part to the approach that sought to measure individual riffle characteristics (channel shape, substrate, slope, etc.) across many reaches. Notably, though assessed riffles shifted in location and shape (Figure 12, Appendix A), the principles governing their formation and continued presence through the target reaches appeared to remain consistent across major flow events, and in most cases estimated flow thresholds remained relatively unchanged by their movement.

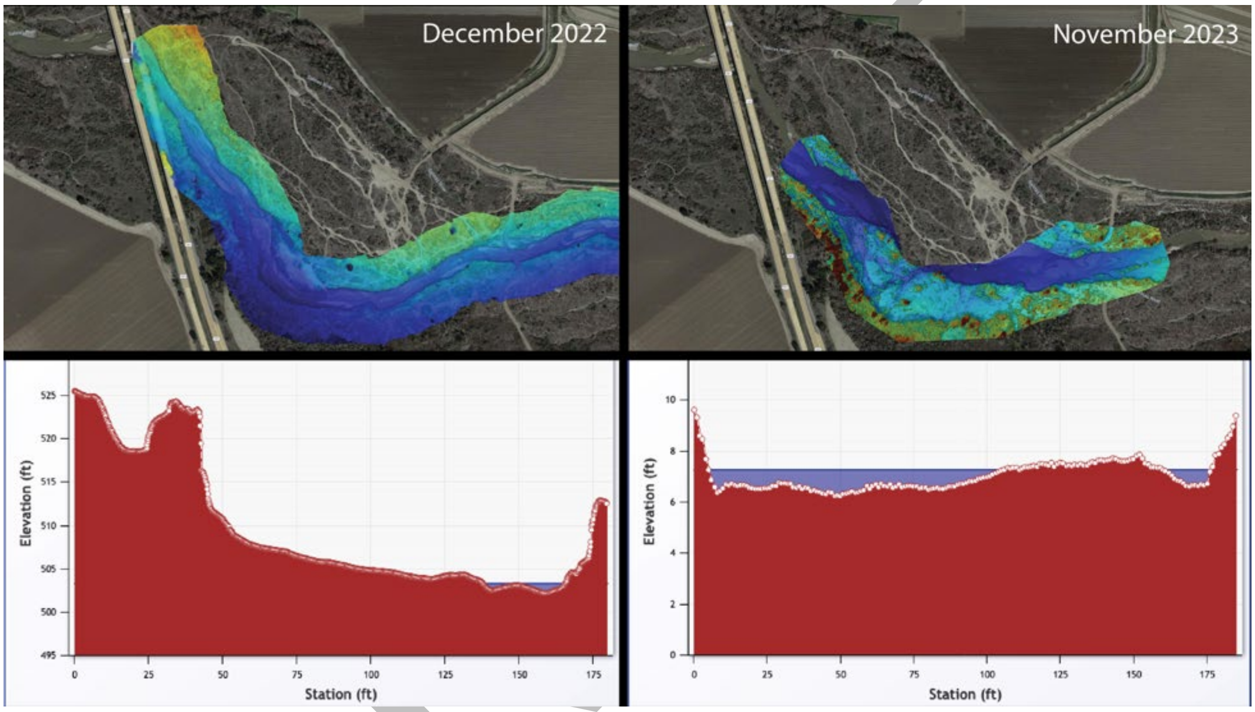


Figure 12. Apparent shifts in channel configuration and geometry at Reach 4 in the Salinas River. Clockwise from top left: DEM derived from December 2022 drone flights; DEM derived from November 2023 drone flights; channel profile derived from December 2022 drone flight depicting water surface elevation at a flow of 100 cfs; channel profile derived from December 2023 laser level surveys depicting water surface elevation at a flow of 100 cfs. Elevation values in the profiles are only accurate relative to one another and do not reflect real-world elevation, thus the disparity in values between the two. By November 2023 the channel had flattened and widened to the extent that building a flight path to cover the channel using Google Earth imagery in DroneDeploy failed to capture the entire width of the river.

Comparison of model outputs and field collected depth data in the context of the time elapsed between the collection of profile and slope data and field measured depth data suggest that the rapid collection of profile data using a drone following the cessation of flow is critical to ensuring the precision of model estimates. In some cases, results of field validation showed substantial differences between model predictions of water depths and field observations (Appendix C). Nearly all of these cases were due to presumed changes in channel geometry after significant time has elapsed between model development and field validation (Table 4). However, in all cases, the model predicted passage thresholds underestimated actual water depths observed in the field, which implies that the model predictions are sufficiently conservative to be resilient to the remarkable fluctuations in geomorphology (and hydrology) typical of this system.

In considering the establishment of passage thresholds, it is also important to acknowledge that little empirical data exist on the actual physical ability of steelhead to pass through varying depths of water. Although a substantial amount of literature has been published on steelhead passage criteria and critical riffle analysis methods (Appendix D), much of the underlying methodology and critical riffle criteria (water depths and widths) are based on a recommended methodology developed in Oregon, and the passage criteria established in this methodology are acknowledged to be somewhat arbitrary (Thompson 1972). These criteria have been relied on for years and are a useful guideline for understanding passage ability, but they have not been validated with empirical data on fish passage, and it remains unclear whether fish passage may be possible at lower thresholds. Thompson (1972) even warned that the methods had never been biologically validated, stating "*I might caution that the relationship between flow conditions on the transect and the relative ability of fish to pass has not been evaluated.*" Given this understanding, the thresholds set using these criteria may be regarded as suitable for facilitating steelhead passage, though they may indeed exceed the true minimum required by steelhead.

We attempted to determine whether the current criteria for adult steelhead (depths of ≥0.7 feet or greater for at least 25% of the total wetted width, with at least 10% contiguous; Model A) may be excessive for wide rivers such as the Salinas. Although our literature review did find examples of studies that found that passage corridors that were a few feet wide (and greater than 0.7 feet in depth) may provide sufficient passage, we did not find sufficient evidence to recommend alternative passage thresholds in this case. In general, there seems to be a lack of empirical data related to steelhead passage capabilities, and management plans and studies have relied on the theoretical thresholds established in documents such as Thompson (1972; additional studies available in Appendix D). Because of the lack of physical evidence, selecting a threshold value that falls towards the upper end of predicted depth minima seems the prudent choice, and the standard CDFW criteria of 0.7 feet across 25% of the wetted width appears to achieve this approach.

The results of this assessment could be strengthened through additional studies and future monitoring. Although we are confident that the passage thresholds recommended by this study will remain relevant and accurate into the future, it would be prudent to verify the continued accuracy of these thresholds at regular intervals to ensure their continued validity across changing conditions in the river. Remote sensing data can be collected with minimal field time, and models could be rerun at any point in the future given that the accuracy of these methods has been verified across a variety of conditions. If flows persist for extended periods of time, as was the case in 2023, alternative approaches may be necessary. In particular, the collection of profile data and depth data simultaneously with a laser level if flows are likely to continue for extended periods of time (as was performed in reaches 4 and 5 in December 2023) is a viable option for improving the accuracy of model outputs. Because the Salinas River is subject to intense off-road vehicle traffic following cessation of flows, and because extended periods of even low discharges have the potential to substantially reshape the channel profile, the collection of elevation and slope profiles as rapidly as possible following field depth measurement is critical. Therefore, any future efforts to apply the model in the future should involve specific plans for appropriate timing of profile data collection.

In addition, further data collection in the Arroyo Seco would facilitate watershed-specific passage thresholds to facilitate migration into the most important spawning and rearing habitat in the Salinas Basin. The Arroyo Seco is a unique watershed that can experience both extremely high levels of discharge following winter storms and high levels of percolation in the lower river that can confine approximately 50% of the river's annual flow (Staal, Gardner & Dunne 1994). As such, flows in the river often dissipate rapidly in the lower river, limiting passage opportunities for steelhead. However, the rate of dissipation is highly variable and dependent on levels of groundwater saturation. This adds additional challenges to the development of a flow prescription for the Salinas River that can maximize steelhead access to the Arroyo Seco watershed. Future monitoring of steelhead movement in the Salinas River and tributaries through the use of PIT tag systems or similar technology may help provide data that could be used to inform the development of passage criteria that are more relevant to the specific characteristics of the basin and of SCCC steelhead. This sort of empirical monitoring data is perhaps the most relevant and valuable tool that could be used to assess the recommended passage thresholds from this study. Further, long-term monitoring of fish passage through the use of PIT tags could provide the added benefit of data on escapement, as well as migration patterns of steelhead in the basin, which may help to further refine passage flow schedules to account for timing and duration of migration.

Literature Cited

Allen, M. A. (2015). Steelhead population and habitat assessment in the Ventura River/Matilija Creek Basin 2006-2012.

Arsenault, M., O'Sullivan, A. M., Ogilvie, J., Gillis, C. A., Linnansaari, T., & Curry, R. A. (2023). Remote sensing framework details riverscape connectivity fragmentation and fish passability in a forested landscape. *Journal of Ecohydraulics*, *8*(2), 121-132.

Booth, D. B., Cui, Y., Diggory, Z., Pedersen, D., Kear, J., and Bowen, M. (2014). Determining appropriate instream flows for anadromous fish passage on an intermittent mainstem river, coastal southern California, USA. *Ecohydrology*. 7: 745-759.

[CDFW] California Department of Fish and Wildlife. 2017. Standard Operating Procedure for Discharge Measurements in Wadeable Streams in California. California Department of Fish and Wildlife Instream Flow Program Standard Operating Procedure CDFW-IFP-001, 25 pp.

Cluer, B. and McKeon, J. 2005. The Problem of Repetitive Sand Dunes in the Salinas River: with Recommended Flows to Create Fish Passage Through the Sand-Dune Field. NOAA Fisheries Service Southwest Region, Santa Rosa, CA. 29 pp.

Dettinger, Michael, 2011. Climate Change, Atmospheric Rivers, and Floods in California – A Multimodel Analysis of Storm Frequency and Magnitude Changes. Journal of the American Water Resources Association (JAWRA) 47(3):514-523. DOI: 10.1111/j.1752-1688.2011.00546.x

DeVries, P., Reiser, D., Huang, C., Beck, S., Ramey, M., Olson, A., Hendrix, N., Oliver, K., and Nightengale, T. (2007). North Coast Instream Flow Policy: Scientific basis and development of alternatives protecting anadromous salmonids. R2 Resource Consultants.

Endangered and Threatened Species: Listing of Several Evolutionary Significant Units (ESUs) of West Coast Steelhead, 62 F.R. 43937. https://www.federalregister.gov/documents/1997/08/18/97-21661/endangered-and-threatened-species-listing-of-several-evolutionary-significant-units-esus-of-west

Giroux, C., Grant, J., Brown, C. J., & Barrell, J. (2022). Remote sensing of river habitat for salmon restoration. *Frontiers in Remote Sensing*, *3*, 993575.

Grantham, T. E. (2013). Use of hydraulic modeling to assess passage flow connectivity for salmon in streams. *River Research and Applications*, *29*(2), 250-267.

Harrison, L. R., Keller, E. A., & Mertes, L. A. K. (2006). Minimum Flow Requirements for Southern Steelhead Passage on the Lower Santa Clara River.

Harrison, L. R., Legleiter, C. J., Overstreet, B. T., Bell, T. W., & Hannon, J. (2020). Assessing the potential for spectrally based remote sensing of salmon spawning locations. *River Research and Applications*, *36*(8), 1618-1632.

Harrison, L. R., Legleiter, C. J., Sridharan, V. K., Dudley, P. N., & Daniels, M. E. (2022). Evaluating the Sensitivity of Multi-Dimensional Model Predictions of Salmon Habitat to the Source of Remotely Sensed River Bathymetry. *Water Resources Research*, *58*(12), e2022WR033097.

Holmes, R. W., Rankin, D. E., Ballard, E., & Gard, M. (2015). Evaluation of Steelhead passage flows using hydraulic modeling on an unregulated coastal California River. *River Research and Applications*, *32*(4), 697-710.

Hwan, J. L., & Holmes, R. W. (2020). Flow regimes in coastal California steelhead trout streams: Spatiotemporal patterns in magnitude, duration and timing. *River Research and Applications*, *36*(2), 247-258.

[MCWRA] Monterey County Water Resources Agency . 2005. Salinas Valley Water Project Flow Prescription for Steelhead Trout in the Salinas River. Salinas, CA. pp. 140.

Mosley, M. P. (1982). Critical depths for passage in braided rivers, Canterbury, New Zealand. *New Zealand Journal of Marine and Freshwater Research*, *16*(3-4), 351-357.

[NMFS] National Marine Fisheries Service. 2011. Anadromous Salmonid Passage Facility Design. NMFS, Northwest Region, Portland, Oregon.

[NMFS] National Marine Fisheries Service. 2005. Salinas Valley Water Project Flow Proposal for the Biological Needs of Steelhead in the Salinas River.

Powers, P.D., and Orsborn, J.F. (1985). New Concepts in Fish Ladder Design: Analysis of Barriers to Upstream Fish Migration, Volume IV of IV, Investigation of the Physical and Biological Conditions Affecting Fish Passage Success at Culverts and Waterfalls, 1982-1984 Final Report. United States: N. p., 1985. Web. doi:10.2172/917018.

Ryan, E. R., Bledsoe, B., & Stephens, T. (2016). Modeling: Effects of Hydraulic Structures on Fish Passage: An Evaluation of 2D vs 3D Hydraulic Analysis Methods.

Staal, Gardner & Dunne. 1994. Hydrogeologic Investigation: Arroyo Seco Cone. Report prepared for Monterey County Water Resources Agency. 39 pp.

[SWRCB] State Water Resources Control Board. (2010). Policy for maintaining instream flows in Northern California coastal streams.

Thompson, K.E. 1972. Determining Streamflows for Fish Life. pp. 31-50 in Proceedings of the Instream Flow Requirement Workshop. Pacific N.W. River Basins Commission. Portland, OR.

Appendix A – Maps of Assessed Transects by River Reach

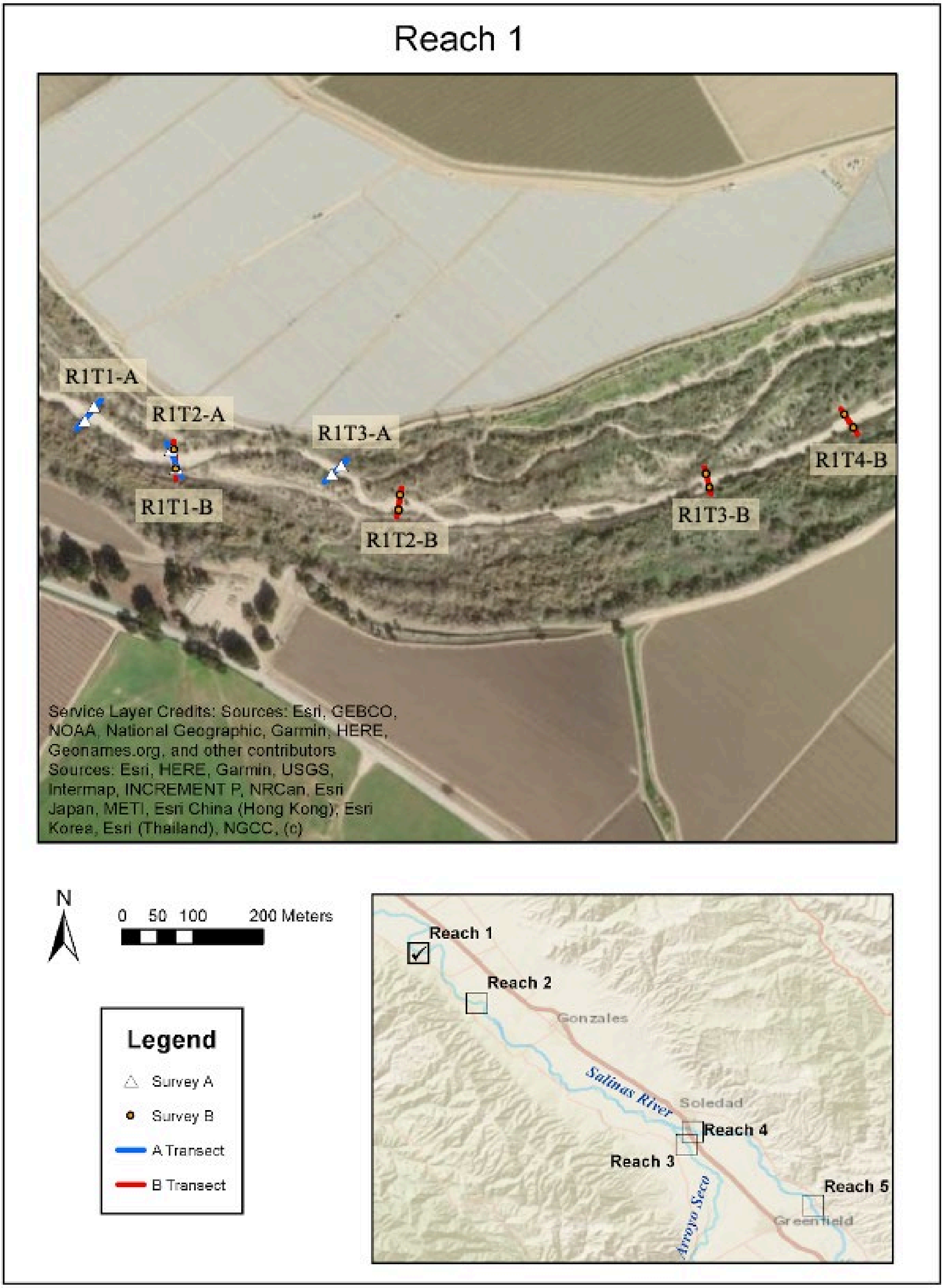
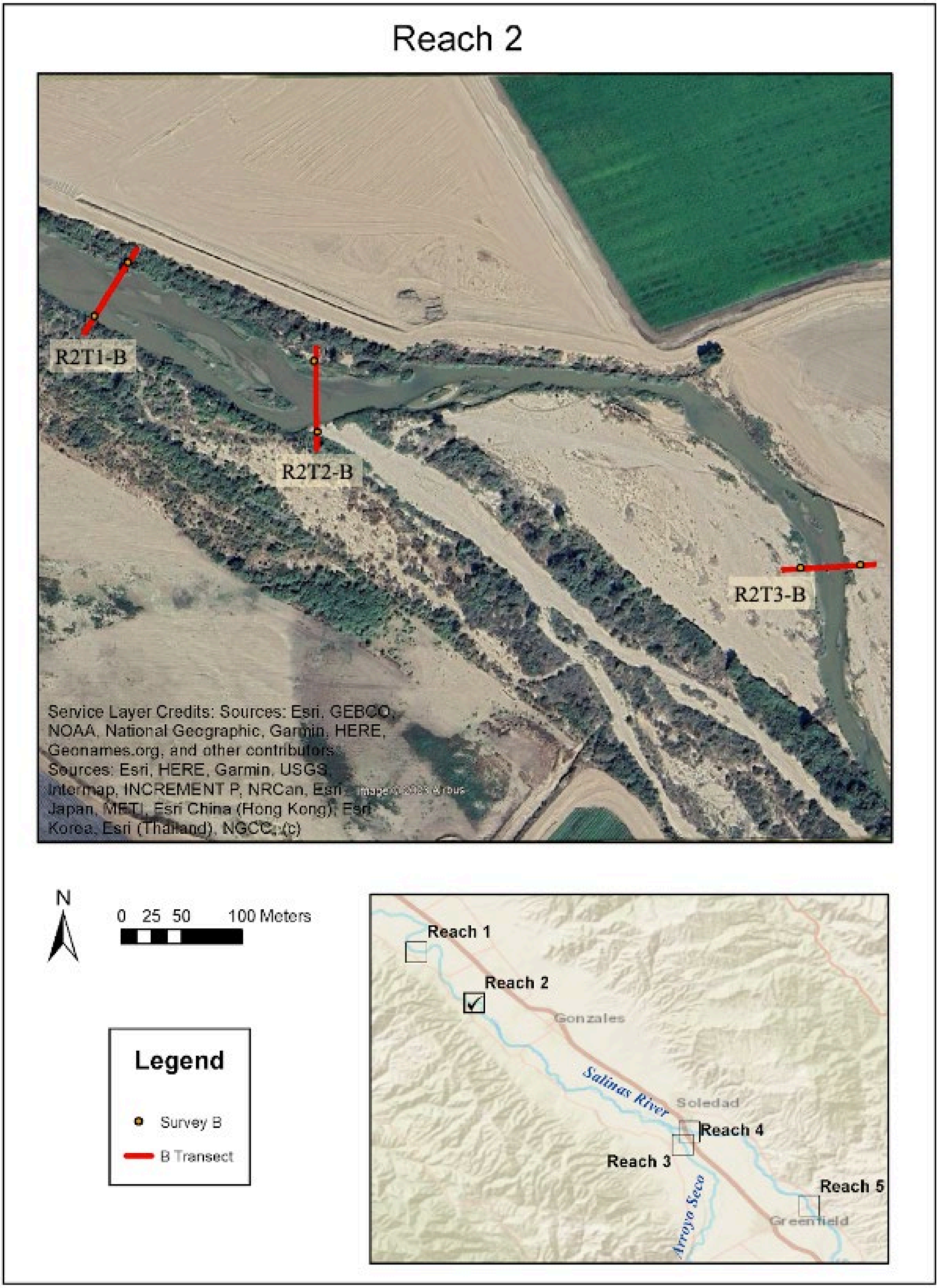
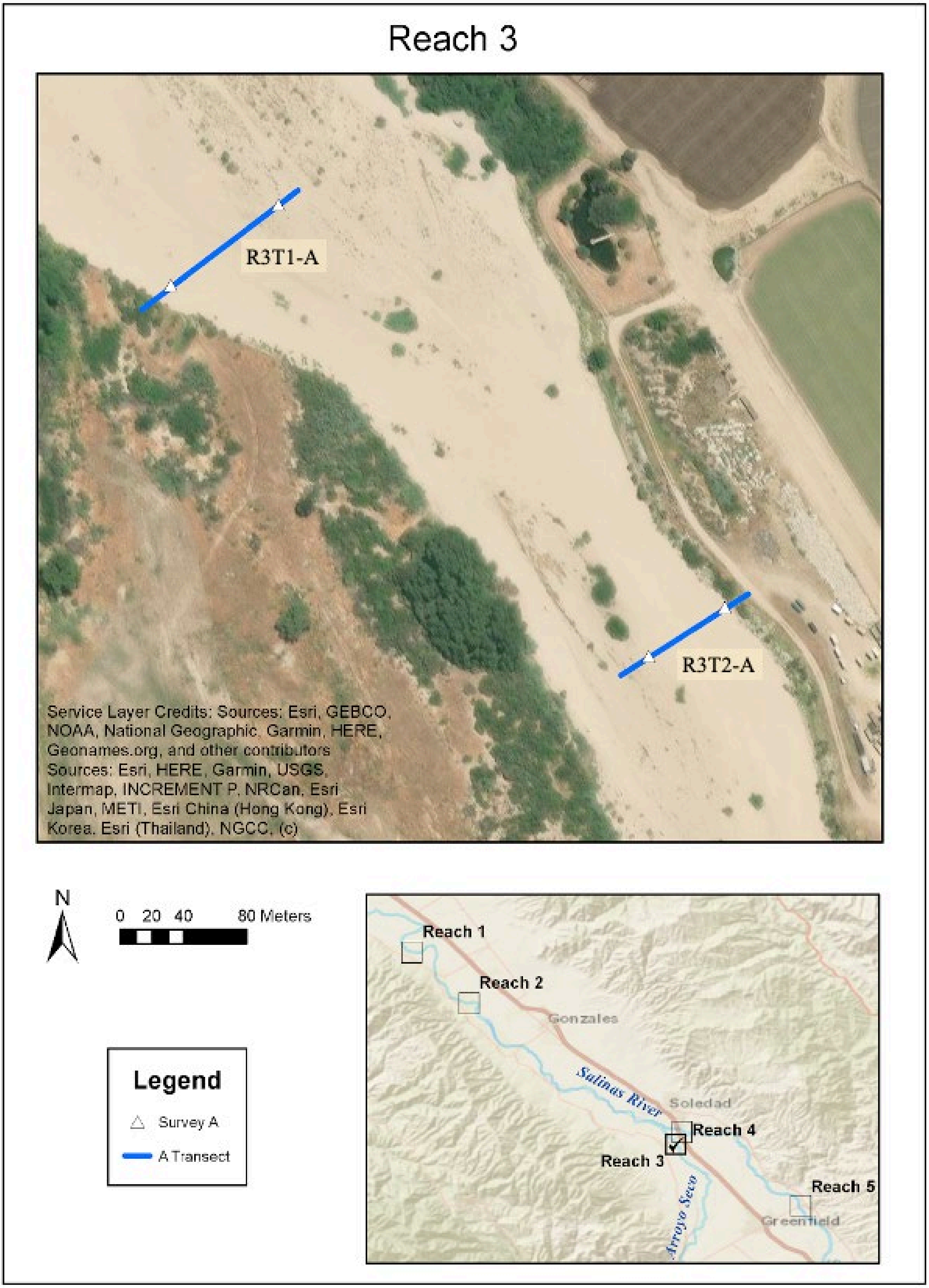


Figure A1. Map of assessed transects in Reach 1 on the Salinas River near Chualar.



Service Layer Credits: Sources: Esri, GEBCO, NOAA, National Geographic, Garmin, HERE, Geonames.org, and other contributors
Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri (Thailand), NGCC, (c)

Figure A2. Map of assessed transects in Reach 2 on the Salinas River near Chualar.



Service Layer Credits: Sources: Esri, GEBCO, NOAA, National Geographic, Garmin, HERE, Geonames.org, and other contributors Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri (Thailand), NGCC, (c)

Figure A3. Map of assessed transects in Reach 3 on the lower Arroyo Seco.

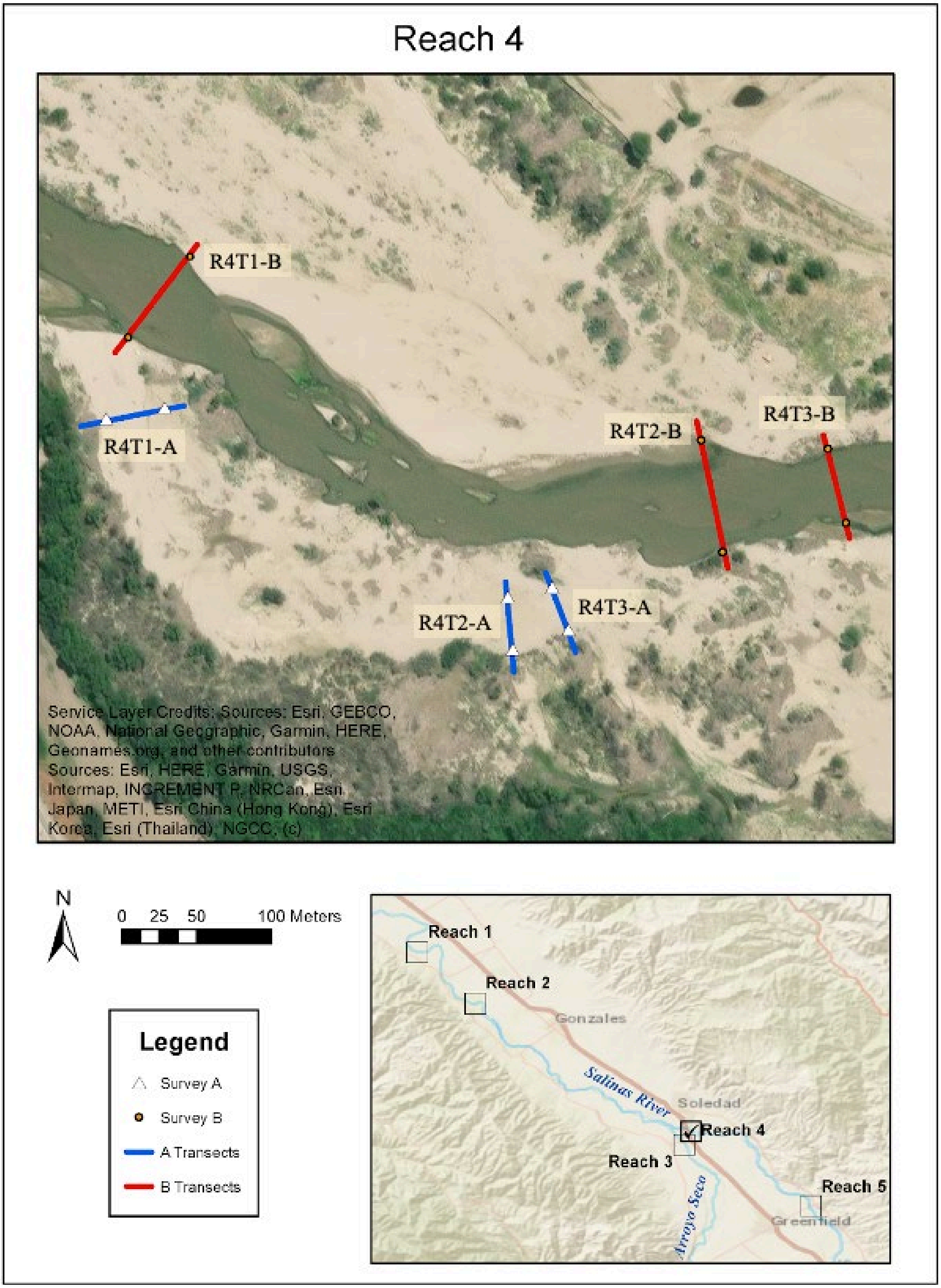
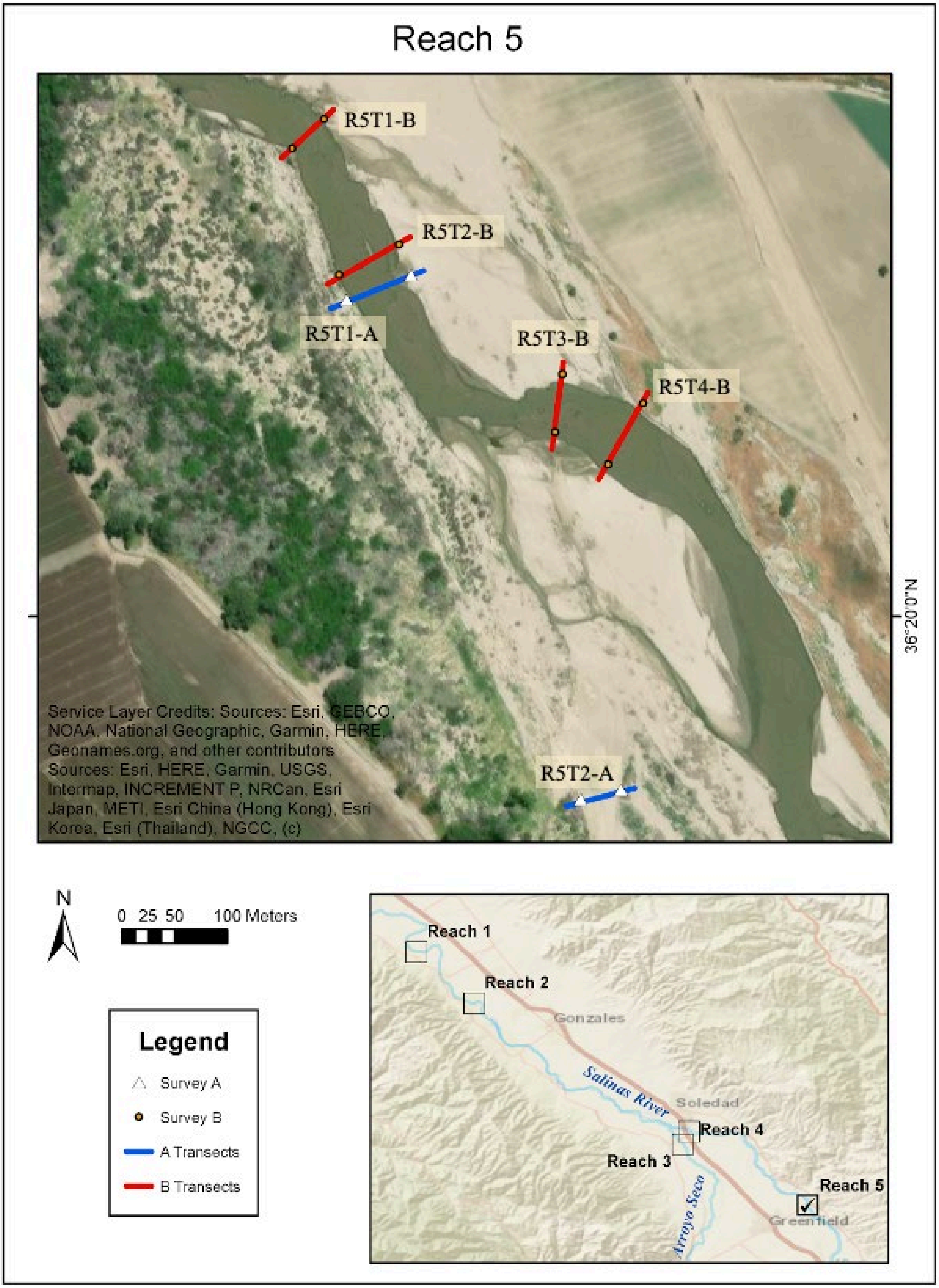


Figure A4. Map of assessed transects in Reach 4 on the Salinas River near Soledad. The period A transects appear to be out of the river due to movement of the channel that occurred in March of 2023.



Service Layer Credits: Sources: Esri, GEBCO, NOAA, National Geographic, Garmin, HERE, Geonames.org, and other contributors Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri (Thailand), NGCC, (c)

Figure A5. Map of assessed transects in Reach 5 on the Salinas River near Soledad. The period A transects appear to be out of the river due to movement of the channel that occurred in March of 2023.

Appendix B - Model Passage Threshold Predictions

Site	Model A [0.7 ft x 25%] Predicted Threshold (cfs)	Model B [0.6 ft by 25%] Predicted Threshold (cfs)	Model C [1 ft by 10 ft] Predicted Threshold (cfs)	Model D [0.7 ft by 2 ft] Predicted Threshold (cfs)	Profile Data Source	Slope Data Source	Date of Profile Survey	Date of Slope Survey
R1T1-A	60	50	130	40	Drone	Drone	12/19/22	12/19/22
R1T2-A	40	30	90	40	Drone	Drone	12/19/22	12/19/22
R1T3-A	40	30	200	40	Drone	Drone	12/19/22	12/19/22
R4T1-A	30	20	70	20	Drone	Drone	12/20/22	12/20/22
R4T2-A	30	20	140	30	Drone	Drone	12/20/22	12/20/22
R4T3-A	50	40	160	40	Drone	Drone	12/20/22	12/20/22
R4T4-A	80	50	150	40	Drone	Drone	12/20/22	12/20/22
R5T1-A	40	30	70	30	Drone	Drone	12/20/22	12/20/22
R5T2-A	110	70	160	50	Drone	Drone	12/20/22	12/20/22
R1T1-B	30	30	90	30	Drone	Drone	11/07/23	11/07/23
R1T2-B	20	20	140	20	Drone	Drone	11/07/23	11/07/23
R1T3-B	40	30	110	30	Drone	Drone	11/07/23	11/07/23
R1T4-B	60	40	150	20	Drone	Drone	11/07/23	11/07/23
R2T1-B	60	40	150	20	Drone	Drone	11/07/23	11/07/23
R2T2-B	40	30	110	30	Drone	Drone	11/07/23	11/07/23
R2T3-B	40	30	70	30	Drone	Drone	11/07/23	11/07/23
R4T1-B	90	70	120	40	Laser Level	Laser Level	12/19/23	12/19/23
R4T2-B	180	140	190	40	Laser Level	Laser Level	12/19/23	12/19/23
R4T3-B	80	50	140	40	Laser Level	Laser Level	12/19/23	12/19/23
R5T1-B	80	60	100	10	Laser Level	Laser Level	12/18/23	12/18/23
R5T2-B	190	140	300	110	Laser Level	Laser Level	12/18/23	12/18/23
R5T3-B	20	20	150	20	Laser Level	Laser Level	12/18/23	12/18/23
R5T4-B	220	170	180	40	Laser Level	Laser Level	12/18/23	12/18/23
Model	**A**	**B**	**C**	**D**				
Average CFS at Chualar	43.00	33.00	124.00	30.00				
Average CFS at Soledad	92.31	67.69	148.46	39.23				
Max CFS at Chualar	60	50	200	40				
Max CFS at Soledad	220	170	300	110				

Appendix C – Field Validation of Model Outputs

Site	Date	Time	Model Mean Depth (ft)	Field Mean Depth (ft)	Model Mean minus Field Mean (in)	Flow at Chualar (cfs)	Flow at Soledad (cfs)	Slope Measurement	Profile Measurement	Field Method
R1T1-A	12/13/22	13:47	0.7	0.68	0.24	120	10	Drone	Drone	Stadia
R1T2-A	12/13/22	13:35	0.81	0.76	0.6	120	10	Drone	Drone	ADCP
R1T3-A	12/13/22	14:27	0.68	1.13	-5.4	120	10	Drone	Drone	Stadia
R4T1-A	01/03/23	14:59	0.67	0.81	-1.68	100	90	Drone	Drone	ADCP
R4T2-A	01/03/23	16:01	0.99	0.89	1.2	100	80	Drone	Drone	ADCP
R4T3-A	01/03/23	15:49	0.79	0.99	-2.4	100	90	Drone	Drone	ADCP
R4T4-A	01/03/23	16:59	0.8	0.85	-0.6	100	90	Drone	Drone	ADCP
R5T1-A	01/03/23	12:07	0.87	0.86	0.12	100	80	Drone	Drone	ADCP
R5T2-A	01/03/23	10:18	0.69	0.88	-2.28	100	90	Drone	Drone	ADCP
R2T1-B	06/15/23	10:50	0.4	0.66	-3.12	110	210	Drone	Drone	Stadia
R2T2-B	06/15/23	10:15	0.36	0.66	-3.6	110	210	Drone	Drone	Stadia
R2T3-B	06/15/23	9:30	0.62	0.96	-4.08	110	210	Drone	Drone	Stadia
R1T1-B	09/13/23	17:10	0.56	0.8	-2.88	100	230	Drone	Drone	Stadia
R1T2-B	09/13/23	17:25	0.85	0.98	-1.56	100	230	Drone	Drone	Stadia
R1T3-B	09/13/23	17:45	0.83	0.82	0.12	100	230	Drone	Drone	Stadia
R1T4-B	09/13/23	18:05	0.72	0.75	-0.36	100	230	Drone	Drone	Stadia
R2T1-B	09/13/23	16:00	0.39	0.72	-3.96	100	230	Drone	Drone	Stadia
R2T2-B	09/13/23	15:50	0.36	0.57	-2.52	100	230	Drone	Drone	Stadia
R2T3-B	09/13/23	15:30	0.61	0.84	-2.76	100	230	Drone	Drone	Stadia
R1T1-B	09/25/23	5:15 PM	0.52	0.67	-1.8	80	210	Drone	Drone	Stadia
R1T2-B	09/25/23	5:30 PM	0.78	0.71	0.84	80	210	Drone	Drone	Stadia
R1T3-B	09/25/23	5:45 PM	0.77	0.78	-0.12	80	210	Drone	Drone	Stadia
R1T4-B	09/25/23	5:50 PM	0.65	0.71	-0.72	80	210	Drone	Drone	Stadia
R4T1-B	09/25/23	11:20 AM	0.81	0.87	-0.72	80	210	Drone	Drone	Stadia
R4T2-B	09/25/23	11:35 AM	0.54	0.83	-3.48	80	210	Drone	Drone	Stadia
R4T3-B	09/25/23	12:05 PM	0.44	1.02	-6.96	80	210	Drone	Drone	Stadia
R4T1-B	12/19/23	9:15 AM	0.33	0.26	0.84	0	30	Laser Level	Laser Level	Stadia
R4T2-B	12/19/23	10:10 AM	0.29	0.25	0.48	0	30	Laser Level	Laser Level	Stadia
R4T3-B	12/19/23	10:55 AM	0.26	0.44	-2.16	0	30	Laser Level	Laser Level	Stadia
R5T1-B	12/18/23	2:00 PM	0.34	0.5	-1.92	0	30	Laser Level	Laser Level	Stadia
R5T2-B	12/18/23	2:45 PM	0.22	0.32	-1.2	0	30	Laser Level	Laser Level	Stadia
R5T3-B	12/18/23	3:40 PM	0.47	0.29	2.16	0	30	Laser Level	Laser Level	Stadia
R5T4-B	12/18/23	4:45 PM	0.24	0.42	-2.16	0	30	Laser Level	Laser Level	Stadia
				Mean Difference	**-1.57 inches**					
				Std. Dev. of Difference	**2.01 inches**					

Appendix D - Literature Review of Steelhead Passage Criteria

A substantial amount of literature has been published on steelhead passage criteria and critical riffle analysis methods, although much of the underlying methodology and critical riffle criteria (water depths and widths) are based on a recommended methodology developed in Oregon (Thompson 1972). Although these passage criteria have been relied on for years and are a useful guideline for understanding passage ability, they have not been validated with empirical data on fish passage, and it remains unclear whether fish passage may be possible at lower thresholds. Thompson (1972) even warned that the methods had never been biologically validated, stating "*I might caution that the relationship between flow conditions on the transect and the relative ability of fish to pass has not been evaluated.*" As part of this modeling effort, a literature review was conducted to determine whether updated criteria are warranted for the Salinas Basin. For example, the current criteria (depths of 0.7 feet or greater contiguously for at least 10% of the total wetted width *and* 0.7 feet or greater for at least 25% of the total wetted width for adult steelhead; Model A) may be excessive for wide rivers such as the Salinas, where a passage corridor that is only a few feet wide (and greater than 0.7 feet in depth) may provide sufficient passage.

Available literature on steelhead passage was reviewed and summarized for the purposes of testing several variations with the newly developed model (Table D1). Thompson's (1972) minimum of 0.7 feet was found to be the most commonly cited threshold related to steelhead passage criteria, but minimum depth ranges across all reviewed publications and reports varied from 0.6 feet to 1 foot for adult steelhead, with minima for non-anadromous *O. mykiss* being as low as 0.35 feet (Table D1).

In general, there seems to be a lack of empirical data related to steelhead passage capabilities, and management plans and studies have relied on the theoretical thresholds established in documents such as Thompson (1972). Because of the lack of physical evidence, selecting a threshold value that falls towards the upper end of estimated depth minima seems the prudent choice, and the standard CDFW criteria of 0.7 feet across 25% of the wetted width appears to achieve this approach. Future monitoring of steelhead movement in the Salinas River through the use of PIT tag systems or similar technology may help provide data that could be used to inform the development of passage criteria that are more relevant to the specific characteristics of the basin and of SCCC steelhead.

Table D1. Summary of available peer-reviewed and gray literature related to establishing depth thresholds for adult steelhead passage and conducting associated critical riffle assessments.

Publication	Years of Study	Study Systems	Riffle Substrates	Passage Thresholds Used	Model(s) Used	Notes
Allen, M. A. (2015). Steelhead population and habitat assessment in the Ventura River/Matilija Creek Basin 2006-2012.	2006-2012	Ventura River Matilija Creek	Gravel, cobble, boulder, bedrock	**Primary HSI Model Thresholds:** Mean critical riffle thalweg depth of **0.6 feet set as maximum suitability**, and mean thalweg depth of **0.4 feet set as 0 suitability** (values derived from Thompson 1972) **Alternative HSI Model Thresholds:** Mean critical riffle thalweg depth of **1 foot set as maximum suitability** and mean thalweg depth of **0.5 feet set as zero suitability** (values derived from measured riffle depths in 95 locations across 13 reaches of the Ventura River and associated subjective assessment)	Two different riffle depth Habitat Suitability Index (HSI) curves	The authors note that this approach of basing passage criteria on summer measurements is speculative, and that the appropriateness of its use should be carefully evaluated
Booth, D. B., Cui, Y., Diggory, Z., Pedersen, D., Kear, J., and Bowen, M. (2014). Determining appropriate instream flows for anadromous fish passage on an intermittent mainstem river, coastal southern California, USA. *Ecohydrology*. 7: 745-759.	2010-2011	Santa Maria River	Sand	A minimum depth of **0.7 feet** was selected for upstream passage of adult steelhead based on the largest size of steelhead expected to pass (value based on Thompson 1972; Webb 1975; Dryden and Stein 1975 as cited in Powers and Orsborn 1985; Bell 1986)	Manning's equation used in conjunction with LiDAR data to estimate flows at 26 transects Field measurements at cross-sections during low to medium flow events	Manning's equation was assumed to result in overestimates of minimum flows to meet passage criteria Conventional approaches to setting instream flows are not appropriate for intermittent streams Surpassing flow thresholds is not enough, flow duration is also critically important

Publication	Years of Study	Study Systems	Riffle Substrates	Passage Thresholds Used	Model(s) Used	Notes
DeVries, P., Reiser, D., Huang, C., Beck, S., Ramey, M., Olson, A., Hendrix, N., Oliver, K., and Nightengale, T. (2007). North Coast Instream Flow Policy: Scientific basis and development of alternatives protecting anadromous salmonids. R2 Resource Consultants.	2007	North Coast California Streams	Variable	Passage was considered feasible when **a minimum 2-foot-wide contiguous portion of the cross-section** profile had a **depth equaling or exceeding 0.7 feet** (values based on references in Appendix G of report)	Habitat-flow curves generated for multiple sites (habitat in this context refers to suitable width for passage)	A consistent, quantitative, biologically meaningful basis could not be identified to select a specific threshold in terms of passage days that distinguished between protective and non-protective flow conditions Provision of spawning habitat appears to require more flow than passage on a regional basis, and therefore protection of the former should also protect the latter
Grantham, T. E. (2013). Use of hydraulic modeling to assess passage flow connectivity for salmon in streams. *River Research and Applications*, *29*(2), 250-267.	2008-2009	Russian River Basin	Cobble	A minimum depth threshold of **0.25 meters (~0.82 feet)** was selected for upstream passage of salmonids (value based on Thompson 1970; Evans and Johnston 1980; Powers and Orsborn 1985; Bjornn and Resier 1991).	2D hydraulic modeling calibrated with field measurements across 3-4 discharges	Predictions from the calibrated models accurately reproduced patterns in observed data, but the strength of the relationship between flow and water surface elevation varied by site The State's regionally-derived formula for setting minimum passage flows led to requirements higher than those estimated by the models in many sites

Publication	Years of Study	Study Systems	Riffle Substrates	Passage Thresholds Used	Model(s) Used	Notes
Harrison, L. R., Keller, E. A., & Mertes, L. A. K. (2006). Minimum Flow Requirements for Southern Steelhead Passage on the Lower Santa Clara River.	Analysis of data from 1955-2004	Santa Clara River	Sand, gravel, coarse-grained sandstone particles	A **depth of 0.6 feet** was selected as the minimum depth required for adult steelhead passage (value based on Thompson 1972)	HEC-RAS hydraulic model (one-dimensional fixed-bed model) combined with a hydrologic model to estimate changes in discharge between reaches; calibrated with USGS gauge data Watershed Analysis Risk Management Framework (WARMF) to assess rainfall-runoff relationship	Number of passage opportunities per year was highly correlated with total annual runoff Once natural flows were achieved in the upper mainstem, lower reaches always exceeded minimum flows Passage flows were found to occur in all assessed reaches of the mainstem at the same time
Holmes, R. W., Rankin, D. E., Ballard, E., & Gard, M. (2015). Evaluation of Steelhead passage flows using hydraulic modeling on an unregulated coastal California River. *River Research and Applications*, *32*(4), 697-710.	2009-2011	Big Sur River	Cobble	A minimum of **21 centimeters (~0.69 feet) for adult passage, 12 centimeters (~0.39 feet) for 1–2-year-old juveniles, and 9 centimeters (~0.3 feet) for young of year (YOY) juvenile steelhead** (values based on Thompson 1972; CDFW 2012; SWRCB 2014) For each transect, the flow was selected that meets the criterion on **at least 25% of the total transect width and a continuous portion equaling at least 10% of the total width**	River2D two-dimensional hydraulic habitat model Critical riffle field measurements over a range of discharges Regional regression formula (SWRCB 20114) Riffle crest thalweg procedure (SWRCB 2014)	Flows predicted by the hydraulic models and flows predicted by the empirical field measurement method were found to be strongly correlated Values generated by the regional formula were surprisingly comparable to the values generated by the critical riffle analysis The riffle crest thalweg approach consistently failed to provide for passage through the natural riffle site for any steelhead life stage (likely because this approach does not consider the proportion of width across which depth criteria are met)

Publication	Years of Study	Study Systems	Riffle Substrates	Passage Thresholds Used	Model(s) Used	Notes
Hwan, J. L., & Holmes, R. W. (2020). Flow regimes in coastal California steelhead trout streams: Spatiotemporal patterns in magnitude, duration and timing. *River Research and Applications*, *36*(2), 247-258.	Analysis of data from 2019 back 11 to 115 years ago (mean = 44 years)	37 different California Coastal streams	Variable	A mean **depth of 0.4 feet was selected as the minimum** (based on Thompson 1972), and at least one of the other two modeled hydraulic parameters had to be met: (a) **mean velocity equaled or exceeded 0.3 m/s**, and/or (b) **50% of the bankfull channel perimeter was wetted** Note: this study focused on downstream passage of age-1+ juveniles, not upstream passage of adults	Hydraulic modeling using Manning's equation, calibrated with field measurements using a stadia rod and auto-level	Onset of meeting flow thresholds was found to be dependent on stream size, with wider streams achieving flow thresholds earlier than narrower streams on the rising limb of the hydrograph Threshold duration was largely driven by precipitation, with streams in wetter regions maintaining thresholds longer The hydraulic modeling approach used is not well suited for complex channels, because hydraulic parameters are difficult to accurately estimate using single-transect methods

Publication	Years of Study	Study Systems	Riffle Substrates	Passage Thresholds Used	Model(s) Used	Notes
Mosley, M. P. (1982). Critical depths for passage in braided rivers, Canterbury, New Zealand. *New Zealand Journal of Marine and Freshwater Research*, *16*(3-4), 351-357.	1979-1982	Ashley, Hurunui, and Rakaia rivers (New Zealand)	Gravel and cobble	Minimum depths of **0.25 meters (0.82 feet), 0.18 meters (0.59 feet), and 0.12 meters (0.39 feet) were selected for Chinook, large trout, and small trout, respectively** (based on values from Thompson 1972) **Velocity requirements of 2.4, 2.4, and 1.2 meters/second** for Chinook, large trout, and small trout, respectively (based on values from Thompson 1972)	Flow-depth equations for whole rivers as well as extended reaches derived from field measurement across multiple discharges	The author cautions that before these equations can be used for selecting minimum discharges, more work is needed to establish defensible minimum depth requirements To highlight this need, the author describes personal observation of 40cm long trout passing up riffles only 0.1 meters deep with discharges of less than 1 m^3/s, with many cobbles exposed to the air
NMFS (National Marine Fisheries Service). (2001). Guidelines for salmonid passage at stream crossings.	N/A	NMFS Southwest Region	N/A	This guiding document establishes criteria for development of salmonid passageways at stream crossings. Among the thresholds set in this document are **12-inch minimum depths to facilitate adult salmon passage and six-inch minimum depths for juvenile salmon passage** at non-embedded culverts	Stream crossing design specifications are based on the previous works of other resource agencies along the U.S. West Coast	Note that these guidelines were developed for salmonids in general, and are not specific to steelhead
NMFS (National Marine Fisheries Service). 2011. Anadromous Salmonid Passage Facility Design. NMFS, Northwest Region, Portland, Oregon.	N/A	NMFS Northwest Region	N/A	This document contains criteria, rationale, and guidelines for design of effective fish passage facilities, as well as NMFS fishway design standards. **The minimum passage depths presented in these guidelines were 1 foot for adult steelhead**, Chinook, Coho, and sockeye salmon, 0.75 feet for pink and chum salmon, and **0.5 feet for juveniles of all species**	Recommendations were developed based on consultation with NWR fish passage engineers and further refined through a collaborative process with regional fishway design experts	This is considered to be a working document and was designed with the intention of periodically updating it given new research or information

Publication	Years of Study	Study Systems	Riffle Substrates	Passage Thresholds Used	Model(s) Used	Notes
Powers, P.D., and Orsborn, J.F. (1985). *New Concepts in Fish Ladder Design: Analysis of Barriers to Upstream Fish Migration, Volume IV of IV, Investigation of the Physical and Biological Conditions Affecting Fish Passage Success at Culverts and Waterfalls, 1982-1984 Final Report.*. United States: N. p., 1985. Web. doi:10.2172/917018.	1982-1984	Columbia River Basin	Variable	This paper provides a detailed analysis of waterfalls and culverts as physical barriers to upstream migration by salmon and trout, using analysis techniques based on combining barrier geometry and stream hydrology to define existing hydraulic conditions within the barrier A number of parameters related to the swimming ability of various salmonid species were summarized in this paper, including the **sustained, prolonged, and burst swim speeds of steelhead (0-4.6; 4.6-13.7; and 13.7-26.5 feet per second;** see Bell 1973) and minimum passage depths were regarded as those sufficient to submerge the largest fish attempting to pass (see Dryden and Stein 1975), which they set as **1 foot of depth** (see Evans and Johnston 1972)	Manning's equation was used to evaluate hydraulic parameters of multiple passage chutes, and field passage experiments were conducted using Coho salmon	This document provides recommendations for assisting in the enhancement of fish passageways at barriers like falls, culverts, and dams, and does not include assessments of riffles
Ryan, E. R., Bledsoe, B., & Stephens, T. (2016). Modeling: Effects of Hydraulic Structures on Fish Passage: An Evaluation of 2D vs 3D Hydraulic Analysis Methods.	2013-2016	Saint Vrain River, Colorado	Boulder, bedrock, cobble	This study compared results of 2D and 3D computational fluid dynamics models to evaluate passage of rainbow trout and brown trout at a site in a whitewater park The key hydraulic variables identified by their models included **a minimum passage depth of 0.11 meters (0.36 feet) and flow velocity of less than 25 body lengths per second**	2D and 3D CFD models used; evaluated potential swim paths, described hydraulics, applied physical criteria, and performed a statistical analysis	This study focused on resident *Oncorhynchus mykiss* and *Salmo trutta* in a non-anadromous stream, and did not assess passage capabilities of steelhead
State Water Resources Control Board. (2010). Policy for maintaining instream flows in Northern California coastal streams.	2010	North Coast California Rivers	N/A	This document describes the criteria established in the North Coast Instream Flow Policy **The minimum depth threshold for passage of adult steelhead set forth in this policy is 0.7 feet** (value taken from DeVries et al. 2007)	This policy document does not include any modeling	The document notes that if values lower than the minimum threshold of 0.7 feet are to be used, scientifically defensible justification must be provided in the study plan for SWRCB review and approval

Publication	Years of Study	Study Systems	Riffle Substrates	Passage Thresholds Used	Model(s) Used	Notes
Thompson, K. (1972). *Determining stream flows for fish life*. Pacific Northwest River Basins Commissions.	1961-1972	18 different basins in Oregon	Gravel	**A minimum depth of 0.6 feet and a maximum flow of 8.0 feet/second** selected as the criteria for adult steelhead passage Depth criteria must be met across **at least 25% of the total transect and a continuous portion equaling at least 10% of the total width**	Field measurement of depth and velocity at multiple transects across multiple flows to establish passage-discharge relationships	It is emphasized that the relationship between flow conditions on the transect and the relative ability of fish to pass has not been evaluated
Summary of findings			**Most commonly used depth threshold**	**0.7 feet**	**Total range of adult depth thresholds used across all studies**	**0.6 feet – 1 foot** *(Values as low as 0.35 feet used for non-anadromous trout)*
			Literature referenced in setting thresholds		Bell 1986 Bjornn and Resier 1991 CDFW 2012 Dane 1978 Dryden and Stein 1975 Evans and Johnston 1980 Powers and Orsborn 1985 SWRCB 2014 Thompson 1970 **Thompson 1972 – most commonly cited** Webb 1975	

Appendix E - Field Collected Depth Data

Field depth measurement data available at:
https://docs.google.com/spreadsheets/d/1Q0cNZw0m6Wk2FpBMfuxr3jB7yM8_oVJD/edit?usp=drive_link&ouid=112105464581370982890&rtpof=true&sd=true