# Lower Owens River Project Hydraulic Model

## Los Angeles Department of Water and Power

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# DRAFT

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# 1. BACKGROUND AND PURPOSE

## 1.1 Lower Owens River Project

The Lower Owens River Project (LORP) has restored flows to approximately 60 miles of the river and adjacent floodplain between Aberdeen and Owens Lake in Inyo County. The project purpose and general operational criteria are described in a Memorandum of Understanding (MOU) agreed to by the Los Angeles Department of Water and Power (LADWP) and Inyo County (1997), as well as other amici parties. According to the MOU, the goal of the LORP is "the establishment of a healthy, functioning Lower Owens River Riverine-Riparian ecosystem, and the establishment of healthy, functioning ecosystems in the other physical features of the LORP, for the benefit of biodiversity and Threatened and Endangered Species, while providing for the continuation of sustainable uses including recreation, livestock grazing, agriculture and other activities."

The project currently provides a minimum of 40 cfs base flow to the river channel downstream of the Los Angeles Aqueduct Intake. In addition to the base flows, seasonal habitat flows are provided each year, with magnitudes up to 200 cfs in general proportion to snowmelt runoff conditions. For average and above average years, the MOU provides for a seasonal habitat flow release of up to 200 cfs into the river at the Intake release structure.

Within a few years of implementation, the project began meeting its environmental goal for enhancement of the riverine-riparian ecosystem. With the sustained base flow and seasonal high flows, vegetation along and in the river channel has increased significantly. Vegetative growth includes abundant and dense bulrush and cattail stands (tules) in the river channel. Current conditions are considerably different than when the project was initiated and the flow management criteria were established in 2006.

## 1.2 Study Objectives

LADWP and Inyo County are interested in developing a hydraulic model to support management activities, including consideration of potential flow management options to discourage encroachment by emergent aquatic vegetation. The purpose of this study is to develop a hydraulic model of five representative areas within the LORP area that can be used to simulate hydraulic conditions in the main channel over a range of flows, with emphasis on determination of depths of flow in the main river channel relevant to encroachment by tules. The model results may also provide information on flow characteristics relevant to water quality and fish habitat for use in the evaluations outside the scope of this study.

## 1.3 Approach

The model selected for use in the study is HEC-RAS. HEC-RAS is a one-dimensional hydraulic model developed and supported by the US Army Corp of Engineers Hydrologic Engineering Center (HEC, 2010). The model is capable of simulating steady and unsteady flows and has routines for sediment transport analysis, water temperature modeling, and hydraulic design of stable channels. This one-dimensional model is limited in its ability to simulate complex channel-floodplain interactions, but was selected for this study based on available data for model geometry and the focus on main channel hydraulic conditions.

The representative areas for which topographic information is available are monitoring plots in the LORP area, designated as Plots 1 through 5. Each plot is approximately 2 miles in length, and approximately 60 to 80 cross sections are available in each area from recent LADWP topographic surveys. The plots are not contiguous, and models were developed for each area independently (i.e., the models do not link the five representative areas).

The basic modeling approach involves development of model geometry from the survey data, calibration of the model to the extent feasible using observed water surface measurements, and use of the model to simulate a range of flows in each representative area. Flows between 20 cfs and 200 cfs were simulated.

### 1.4 Limitations

The Lower Owens River is a sinuous low gradient stream with a bed slope of approximately 0.001. There are numerous complex remnant channel segments on the floodplain that are inundated by higher flows and groundwater movement. Because HEC-RAS is a one-dimensional model, its capabilities for simulating complex multi-directional flows on the floodplain and the interaction between the sinuous channel and the floodplain are limited. Therefore, the model developed for this study is primarily limited to main channel hydraulic conditions.

An initial review of model results with a range of flows indicated that flows leave the main channel at various locations at flows less than the maximum simulated flow of 200 cfs. Many of these locations are secondary channels formed by remnant channels on the floodplain. LADWP conducts inundation mapping at base and seasonal habitat flows, and these secondary flow paths are evident in the mapping. Some of these channels are discontinuous, and the flows at which overflow begins and the capacities of the secondary channels are variable. Loss of flow to these secondary channels results in a corresponding loss of flow in the main channel, and the split flow affects the relationship between total flow and stage in the main channel.

To improve the model’s ability to represent main channel hydraulic conditions over a range of flows, additional survey data on the secondary channels was obtained by LADWP during the course of the study and split flows were calculated. This allows the model simulations to be used with reasonable confidence up to flow rates that produce some overflow into the secondary channels. Because the floodplain has very complex topography and dense vegetation, the additional survey data is limited to the most significant channels and locations that were feasible to survey during this study.

As flows increase, the number of locations at which flow leaves the main channel increases, involving more secondary flow paths and eventually overtopping longer sections of channel banks into the floodplain. The flow rate at which this occurs varies substantially between plots, but is typically less than the 200 cfs maximum for the study. Under these conditions shallow flow occurs in multiple sinuous paths on the floodplain, and flow patterns become too complex to represent accurately in the one dimensional HEC-RAS model. Therefore, in each of the plots this study identifies a maximum flow at which the model can be used with confidence.

The assignment of roughness coefficients to represent vegetative friction losses is a commonly applied but somewhat subjective technique in hydraulic modeling. The vegetative roughness in portions of LORP is extremely high, and includes not just channel boundary roughness but the effects of blockage of a portion of the flow area by tule stems and the hydraulic drag around the stems.  Numerous beaver dams also play a significant role affecting the hydraulics of the system. The applicability of typical roughness coefficients and hydraulic friction loss computations in this situation is not strictly physically based and may be theoretically questionable.  The accuracy of water surfaces profiles therefore depends on the ability to make reasonable adjustments in model parameters that represent observed channel behavior over a range of flows.  Limited water surface measurements for calibration affect the ability to predict water surface profiles under different flow conditions.

# 2. MODEL DEVELOPMENT

This section describes the methods used to develop steady state HEC-RAS models of the representative areas (Plots 1 through 5) and to calibrate the model, to the extent feasible, to observed water surface elevations.

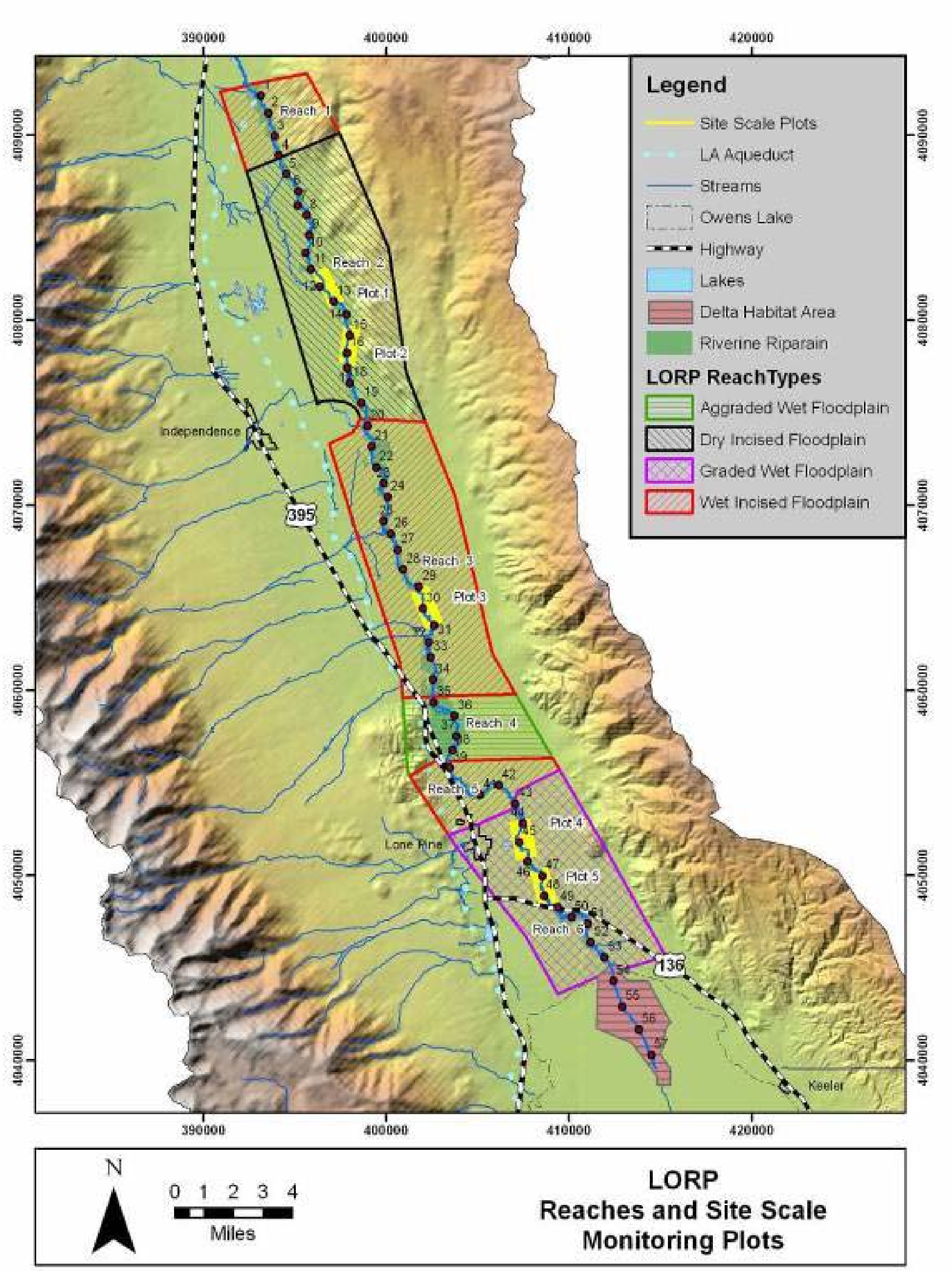



**Figure 2.1 - LORP Monitoring Plots (Representative Areas for Models)**
*Source: LORP 2011 Annual Report*

## 2.1 MODEL REQUIREMENTS

The basic data needed to perform steady state hydraulic computations in HEC-RAS are flow boundary conditions and geometry data for cross sections. Flow boundary conditions for subcritical flow are an upstream flow rate and a downstream water surface elevation. The downstream water surface elevation may be an observed value, rating curve (flow vs. elevation relationship), or depth computation at the most downstream cross section using a specified energy slope (normal depth computation). The initial model set-up was made with a series of steady state flows between 20 cfs and 200 cfs, and with normal depth computations for an energy slope equal to the channel approximate bed slope (0.001) at the downstream end of each plot.

The basic geometric data required for the model consists of cross sections defined by horizontal station and elevation pairs, left and right bank stations, hydraulic roughness coefficients, distance to the next section downstream, and contraction and expansion energy loss coefficients. The first step in assembling a geometry file for the model is to define a channel centerline alignment, so that the cross sections can be designated in terms of river station (distance along the centerline). Numerous options are available in HEC-RAS to vary roughness coefficients with horizontal or vertical distance in a cross section, and to represent ineffective areas and flow obstructions.

## 2.2 TOPOGRAPHIC DATA

High resolution aerial photographs (LADWP, 2009) were used to delineate an alignment along the apparent main channel in each of the areas to be modeled (Plots 1 through 5). The alignment was estimated in some regions where dense tule growth causes the main channel to not be clearly defined in the aerial photography. Cross sections surveyed by LADWP in 2009 and 2010 were also located on the aerial photograph, and each cross section was assigned a river station that defines its location along the alignment measured in feet from the downstream end of the plot. River alignments and stations are assigned for each plot and are not continuous through the five modeled areas. Channel alignments and cross section locations for each plot are included in Appendix C.

### Cross Sections

Cross section surveys were conducted by the LADWP for Plots 1 through 5 from October 2009 to January 2010. Table 2.1 summarizes the survey dates by plot.

**Table 2.1 Survey dates by Plot**

| Plot Number | Survey Dates |
|---|---|
| 1 | January 26, 2010 – January 28, 2010 |
| 2 | December 16, 2009 – January 14, 2010 |
| 3 | November 30, 2009 – December 9, 2009 |
| 4 | November 10, 2009 – November 23, 2009 |
| 5 | October 19, 2009 – November 4, 2009 |

Survey points (California State Plane Coordinate System Zone 4, NAD 83 datum, NAVD 88) were imported into AutoCAD, and station and elevation information was extracted for cross sections. A plot contained approximately 60 to 80 surveyed cross sections, and the spacing between cross sections is generally about 150 to 200 feet. In addition to x-y coordinates and elevation information, each survey point contained a code describing the physical feature (i.e., channel invert, tules, top, channel end or beginning, water's edge, etc) of the point. These descriptors were used to estimate the locations of tules, main (open) channel, vegetated floodplain, and other features for designating channel roughness values in the model cross sections.

Additional surveys (completed in January 2012) of selected secondary channels were conducted in order to improve the model results. The representation of secondary channels in the model is discussed in Section 2.5.

### Corrections for Alignment and Skew

Dense tule stands made the surveys difficult, and often prevented the cross sections from being completed in a straight line perpendicular to the main channel. Therefore, some adjustments were necessary to correct for zig-zag and skew in the cross section survey data.

HEC-RAS represents the flow area at each cross section according to the distance and ground elevation along the cross section. Therefore it is important that cross sections be nearly perpendicular to the flow direction and that distances be measured along a straight line in order to avoid over-representation of cross sectional area. Because most of the available cross sections included some zig-zag in direction and skew to the channel, a Station-Offset routine was used in AutoCAD to generate perpendicular distance from the centerline alignment to each survey point. Offset distances were then converted into horizontal stations, starting from the left bank looking downstream. In some cases, where the cross section was located on a curved segment of the alignment, the Station-Offset routine did not provide correct results, and manual adjustment was needed using the aerial photography and cross section points in AutoCAD.

### Ineffective Flow Areas

HEC-RAS allows the user to specify areas in a cross section that contain water but are not actively conveying flow (ineffective flow areas). Situations that required the use of the ineffective flow area option were:1) cross sections that included a side channel or adjacent wetland created by backwater or ground water that are not hydraulically connected to the main channel; 2)portions of cross sections within the hydraulic shadow or influence of a downstream or upstream roadway embankment (condition present in Plot 3);and 3) portions of cross sections formed by topographic irregularities that are unlikely to convey significant flow. During the model calibration process, ineffective areas were also used to represent the impact of the densest portion of the tules on the channel conveyance. This application of ineffective area is discussed in Section 2.6.

## 2.3 Channel Roughness Parameters

HEC-RAS applies user defined channel roughness parameters to calculate friction loss between two cross sections. The most commonly applied roughness coefficients are Manning's "n" values, empirical coefficients that are used in solving Manning's equation. HEC-RAS uses Manning's equation to compute friction energy slopes at each cross section. For subcritical flow (applicable to the Lower Owens River), water surface profiles are calculated in an iterative procedure that adds estimated energy losses between an upstream and downstream cross section to the energy grade line (water surface elevation and velocity component of energy) at a downstream cross section to obtain an energy grade line and water surface elevation at the upstream cross section. The profile computation progresses one cross section at a time in an upstream direction. Manning's n values are a primary factor in estimating energy loss between cross sections and are therefore important to model calibration.

### Channel Subdivision

HEC-RAS allows the cross section to be subdivided into a main channel and left and right (looking downstream) overbanks. Bank stations are used to define the breaks between the main channel and overbanks. Conveyance is normally computed separately for the main channel and each overbank. This subdivision allows segmentation of the channel into areas of more uniform hydraulic characteristics.

In river models, bank stations are frequently defined at the topographic break between the main channel and floodplain. However, because the focus of this study is on the main channel and because significant differences in flow capacity occur between open water areas and areas with tules, the bank stations in the models were generally defined as the edge of open water in the main channel. This also facilitates output that separately describes velocity and depth in the open water vs. tule areas. Thus, the "overbanks" for the purposes of this study include heavily vegetated areas within the main channel that are inundated even at base flow. The overbanks were further subdivided according to vegetation types, with tules assigned higher n values than other riparian vegetation.

The subdivision of each cross section was achieved by manually providing Manning's n value break points for each cross section. The break points were initially determined from the descriptors for the survey points. Although the descriptors at some cross sections include some ambiguity, the survey data generally indicate the edges of open water or open channel and the limits of tules in the cross section.

### Manning's n Values

Initial Manning's n values for the main channel, overbank with tules, and overbank with other vegetation were estimated from field visit observations, literature sources (e.g., Chow, 1959), and experience with other river models. The initial estimates were:

n=0.05 for open water/channel between tule stands
n=0.20 for tules
n=0.10 for other vegetated overbanks

## 2.4 Calibration Data

HEC-RAS model results in Plots 1 through 5 were calibrated, to the extent feasible, to measured water surfaces. The primary calibration data are measured water surface elevations taken as edge of water shots during the cross section surveys. Measured water surfaces during habitat flows are not available for calibration, but LADWP inundation mapping for habitat flows in 2011 was used as an indirect check on model results. Where topographic data on secondary channels were available, the model was checked and adjusted to predict overflow into the secondary channels consistent with the inundation mapping for base and seasonal habitat flows. This is a qualitative check only because it is limited to comparing whether the model predicts that a secondary channel is connected or not at the base or seasonal habitat flow rate. Water surface elevations during seasonal habitat flows were also inferred from the ground elevations at the margin of the habitat flow inundation mapping, but this method was found to be subject to significant errors due to the accuracy of topographic information and large differences in ground elevation associated with minor changes in inundation limits in some areas. These elevations were therefore not used directly for calibration, but were considered qualitatively along with the inundation mapping limits.

### Surveyed Water Surface Elevations

Water surface elevations were extracted from cross sectional survey data conducted by the LADWP between October 2009 and January 2010. Edge of water shots were generally taken at both right and left banks, but some cross section data are missing edge of water shots at one or both banks. Surveyed edge of water shots vary from one bank to another in a cross section, sometimes by more than one foot. These variations may be due to skew in the cross sections or, more probably, the survey rod sinking below the water surface on the soft channel bottom. Because the edge of water is near the edge of tules in many areas, distinguishing the water surface may have been difficult during the surveys. In general, calibration of the model aimed towards the higher of the two water surface elevation readings.

### Corresponding Flows for Survey Periods

Flows corresponding to the measured water surface elevations are needed for input to the model for calibration to the water surface elevations. Flow records during the period of cross section surveys were provided by LADWP and are summarized in Table 2.2. The Plot 1 calibration flow was estimated using the average daily flows measured at the Intake measuring station. The calibration flow at Plot 2 was estimated by summing the flows recorded at Mazourka East and Mazourka West stations and subtracting the flow from the Billy Lake Return. The Plot 3 calibration flow was estimated using average daily flows at the Reinhackle measuring station, and calibration flows in Plots 4 and 5 are based on the average daily flow measured at the Keeler Bridge station. Inspection of the daily average flow rates indicates that they vary less than 4 cfs through the survey periods.

**Table 2.2 Calibration flows by Plot**

| Plot Number | Measuring Station | Daily Average Flow Rate (cfs) |
|---|---|---|
| 1 | Intake | 43 |
| 2 | Mazourka minus Billy Lake Return | 49 |
| 3 | Reinhackle | 59 |
| 4 | Keeler Bridge | 49 |
| 5 | Keeler Bridge | 48 |

### Seasonal Habitat Flow Study

A seasonal habitat flow study was conducted by LADWP in June 2011. A maximum flow of 205 cfs was released at the Intake and the daily average flows were recorded at measuring stations downstream between June 15, 2011 and July 19, 2011. These data indicate a significant attenuation of the peak flow wave going downstream, as would be expected from the channel and floodplain characteristics. Flow measurements during the 2011 seasonal habitat flow period were provided by the LADWP and were used to establish the seasonal habitat flows for modeling, as shown in Table 2.3. Flows at the measuring stations listed in Table 2.3 were used for Plots 2 to 5. Due to its distance from the Intake and the attenuation of peak flows as they travel downstream, the seasonal habitat flow for Plot 1 was interpolated between the flow measurements for the Intake and Mazourka stations. The table also summarizes the flow measurements taken at base flow prior to initiation of the seasonal habitat flow. The base flow measurements are similar to those recorded during the 2009 through 2010 cross section survey (Table 2.2), and it was assumed that inundation would be similar at the calibration flows.

**Table 2.3 Seasonal Habitat flows by Plot**

| Plot Number | Measuring Station | Habitat Flow Rate (cfs) | Daily Average Base Flow Rate (cfs) |
|---|---|---|---|
| 1 | Intake | 160 (interpolated) | 45 |
| 2 | Mazourka | 120 | 51 |
| 3 | Reinhackle | 116 | 55 |
| 4 | Keeler Bridge | 75 | 46 |
| 5 | Keeler Bridge | 75 | 46 |

Aerial digital imagery was taken from helicopter flights over Plots 1 through 5 prior to the habitat release (base flow condition) and when the peak flow occurred in various reaches. The digital imagery data were used to generate the flood delineation maps showing flooded extent at base and seasonal habitat flow conditions.

Additional inundation mapping was provided by LADWP for the seasonal habitat flow study conducted in 2008. The comparison of 2008 and 2011 inundation mapping for the base flow condition were significantly different for similar flows, and thus the 2008 inundation mapping was not used. The difference in inundation area is probably a result of alteration in flow paths due to tule growth and beaver activities.

### 2.5 Secondary Channels

An active secondary channel will convey a portion of the main channel flow whenever flow leaves the main channel and occupies the secondary channel. If a considerable portion of the total flow occurs in the secondary channel, the flow and hydraulic conditions in the main channel are affected. In the base flow condition inundated floodplain channel segments in most plots appear to be backwatered from their downstream end at the main channel, and in this case the effect of the secondary channel on main channel hydraulics is insignificant. However, some secondary channels are connected as flow paths at base flow, and more are active at the seasonal habitat flow. In order to better represent flow distribution between the main channel and secondary channels, some of these secondary flow paths were modeled.

## Additional Survey

Inundation maps (Appendix C) were inspected to select and prioritize areas for collection of additional topographic information. Prominent secondary channels were identified, and cross sections of upstream and downstream ends of the channels were requested from LADWP. Cross sections along the secondary channels were also requested for long channel lengths and if obvious hydraulic controls (topographic constrictions or high points) were present.

Because there are numerous secondary channels and limited resources to the conduct surveying, it was focused primarily on secondary channels that appear to be connected on the base flow inundation maps and on relatively long secondary channels. Where secondary channels connect back to the main channel within a couple of cross sections, (several hundred feet), their influence on channel hydraulic conditions upstream is presumed to be relatively small. Secondary channels that are connected at base flow may carry a considerable portion of the main channel flow at higher flows and were therefore believed to have the most significant potential effects on main channel hydraulics.

## Representation of Secondary Channels in HEC-RAS

With selected secondary channels included in the model, the HEC-RAS optimization feature was used to iteratively solve for a flow split between the main channel and the secondary channels. Depending on available information, the secondary channels were represented in the model as a lateral weir or split reach.

The lateral weir option in HEC-RAS was used when survey information was not adequate to characterize the entire geometry of a secondary channel. In this methodology, the model computes flow into the secondary channel over a lateral weir, and the flow in the main channel is reduced by computed weir discharge. The overtopped flow in the secondary channel is reintroduced to the main channel at the confluence of the downstream end of the secondary channel and the main channel. The weir geometry was generally taken from survey information but was estimated in some locations from inundation mapping where data was unavailable. If a topographic constriction was evident from survey ground shots or inundation maps, the weir geometry was adjusted to reflect the hydraulic control imposed by the topography.

In HEC-RAS weir discharge is calculated by integrating the general weir equation (1) over the weir length and does not consider potential submergence effects due to downstream tailwater. During a submerged condition discharge becomes a function of downstream water surface elevation. For this reason, modeling the overtopped flow as a weir flow, especially at high flow simulations, could lead to overestimation of secondary channel flows.

Weir coefficients typically range from 2.6 to 4.0 depending on the shape of the weir crest. For the purposes of this study, a value of 2.0 was used to account for the weir inefficiency associated with potential weir submergence, vegetation, and irregular weir shape.

$$Q=CLH^{1.5} \qquad (1)$$

Where:

Q= discharge
C=weir coefficient
L= length of weir
H = head above weir

**Split Reach**

Secondary channels were modeled as a split reach if enough cross sections were available to characterize the channel geometry. In a split reach, the upstream and downstream connections to the main channel are represented by junctions. HEC-RAS solves for water surface across the junction between the main channel and a secondary channel by balancing the energy equation (2) with an initial flow split specified by a user.

$$Z_2+Y_2+V_2^2/2g = Z_1+Y_1+V_1^2/2g + h_e \qquad (2)$$

Where:

$Z_1$, $Z_2$ = elevation of the bottom of the main channel at the two adjacent cross sections
$Y_1$, $Y_2$ = depths of flow
$V_1$, $V_2$ = average velocities of flow (total flow/total flow area)
g = gravitational acceleration constant, and
$h_e$ = energy loss between the cross sections, expressed as head loss

The optimization feature sometimes failed to converge when multiple split reaches were represented in a single plot or when flow in the secondary channel was very shallow. In these cases, the split reaches were modeled individually.

### 2.6 Model Calibration by Plot

Each of the modeled plots has different channel characteristics, and calibration to measured water surfaces required slightly different approaches in each. To the extent feasible, calibration was done systematically, such that assumptions in each plot are consistent with others. In some cases, initial calibrations in one plot were revised after adjustments in approach were determined necessary in another. The resulting calibration models for all plots are based on a relatively consistent set of n value and ineffective area assumptions.

**Plot 1**

The Plot 1 channel is the most regular and narrowest of the five modeled areas. The channel is generally trapezoidal in shape with a central open water channel and tules along both margins (Figure 2.2). Model runs with the initial n values described in Section 2.3 showed that the computed water surfaces were about 0.5 feet low compared to a profile formed by the higher of the water edge shots at the cross sections. Based in part on calibration tests in other plots, the n values were increased to:

n=0.065 for open water/channel between tule stands
n=0.70 for tules
n=0.15 for other vegetated overbanks

The tule n value is consistent with the high end of the range reported in the literature (Hall and Freeman, 1994). Because it was determined necessary to use ineffective areas in Plot 2 (see discussion below), they were added using the same criteria in Plot 1. In Plot 1 the ineffective areas have little effect on the computed profile, but their use maintains consistency between Plots 1 and 2.

**Figure 2.2 – Plot 1 channel**

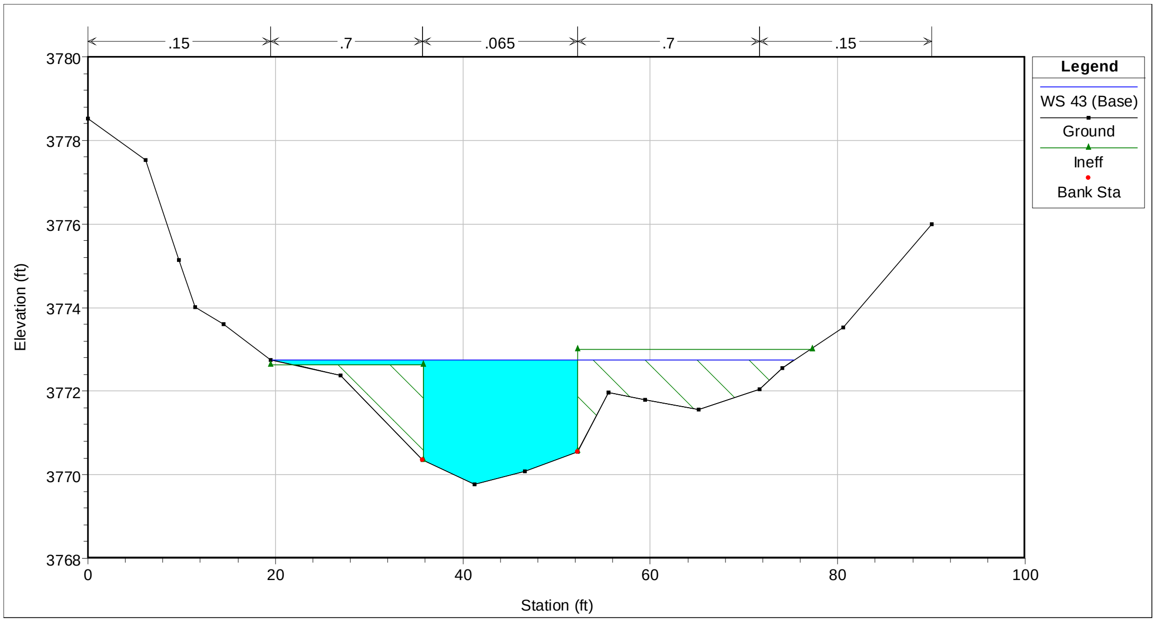
Table 2.4 summarizes split and return stations of the secondary channels that were included in the model for Plot 1. Secondary channel 1-S1 was added as a split reach because survey data was adequate to characterize the reach geometry. Secondary channel 1-W1 was added as a lateral weir because limited survey data was available. The elevation of the weir crest was chosen to be approximately 0.2 ft below the habitat flow water surface elevation to be consistent with inundation mapped at the habitat flow, but not at base flow. The weir length approximately matches the narrowest flow width (constriction) on the inundation map.

**Table 2.4 Secondary channels in Plot 1**

| Secondary Channel ID | Split d/s of: | Return d/s of: |
|---|---|---|
| 1-S1 | STA 82+35 | STA 51+65 |
| 1-W1 | STA 53+88 | STA 43+20 |

Figure 2.3 shows a typical cross section in Plot 1, and Figure 2.12(page 24) shows the computed water surface profiles for three of the calibration tests. The surveyed water surface elevations are shown as dashed lines, the initial n value run is shown as Profile 1a, the run with increased n values is represented by Profile 1b-ii, and the run with increased n values and ineffective areas is shown as Profile a1-p1. Profile a1-p1 also includes split reaches.

**Figure 2.3 – Plot 1 Typical cross section**




The results of the best model (Profile a1-p1) were checked against the inundation mapping for 2011, so that the model predicts overflow into the split reaches for flow conditions in which the inundation maps indicate that the secondary channels were occupied. Table 2.5 summarizes the potential impact of the secondary channels on the flow in the main channel as a percent difference for base flow and habitat flow. As indicated in Table 2.5, HEC-RAS predicts that both 1-S1 and 1-W1 are empty at base flow (i.e., no flow change in the main channel) but some flow is conveyed at the seasonal habitat flow. These general characteristics match the Plot 1 inundation map, with the secondary channels disconnected at base flow but connected at habitat flow. The model's sensitivity to the assumed weir crest elevation was tested by lowering the crest elevation. The weir crest was set to be approximately 0.2 feet below the 60 cfs water surface elevation, or 2.4 feet below the originally assumed crest elevation. The analysis showed that the water surface elevations near the weir varied by no more than 0.2 feet, and are thus not particularly sensitive to the weir elevation.

**Table 2.5 Impact of the secondary channels on the main channel flow**

| Secondary Channel ID | Calibration (Base) Flow | | | Habitat Flow | | |
|---|---|---|---|---|---|---|
| | Q (cfs) u/s of Split | Q (cfs) d/s of Split | % change | Q (cfs) u/s of Split | Q (cfs) d/s of Split | % change |
| 1-S1 | 43.0 | 43.0 | 0.0 | 160.0 | 154.8 | 3.2 |
| 1-W1 | 43.0 | 43.0 | 0.0 | 154.8 | 153.8 | 0.6 |

## Plot 2

Plot 2 is similar to Plot 1 but the main channel is less uniform and the top width is wider, with larger stands of tules on the margin of the open water channel. The Plot 2 bed profile is non-uniform – a lowered section is apparently present upstream of the 2 Culverts (formerly 5 Culverts) road crossing and extending to the junction of a side channel about 5,000 feet upstream. Figure 2.4 shows a typical portion of channel in Plot 2.

**Figure 2.4 – Plot 2 channel**

Plot 2 calibration runs tested the effects of higher n values in the main channel (0.085) than were used for Plot 1. Although this n value reproduced the observed water surface more closely, its use in other plots pushed the computed water surfaces above observed values. In addition, this value is higher reported in the literature or expected from previous modeling experience. In Plot 2, the effects of an increased roughness coefficient (0.15) for vegetated (non-tule) overbank areas was tested and adopted. This value is consistent with the literature for areas with dense riparian growth (Barnes, 1967; Chow, 1959) and is considered appropriate to represent irregularity in the channel banks and generally shallow flow depths over the areas outside of the tule areas.

Because the computed water surface profile was below observed values after the overbank n values were increased, an alternative approach was taken that employs ineffective areas in HEC-RAS. In HEC-RAS, ineffective areas are formed by a left and/or right station and an elevation; this essentially blocks out the flow area between the channel bed and the specified elevation to the left and/or right of the selected stations. When flows overtop the ineffective elevation (for ineffective areas designated as permanent), the flow area above the ineffective area is included in the computations.

The ineffective areas were established for each cross section that had stands of tules (overbanks) adjacent to the open water channel. The depth of ineffective areas was limited to approximately one foot. Some adjustments were made to these criteria to locate ineffective areas at depressions in the cross section and to avoid blocking too much of the vegetated floodplain outside the tule areas. This approach assumes that the dense and rigid bases of tule stems inhibit flow conveyance in the channel, and that water near the base of tule stems is essentially still. This representation of the tule areas is supported by field observations and velocity measurements conducted in several cross sections in Plots 1 and 2 that indicated:1) velocities at the boundary of the open water channel dropped rapidly at the margin of the tules; 2) velocities in the upper part of the water column in the tule areas were much slower than the open water channel but relatively constant with distance from the open water channel; and 3) the bed of the channel in the tule areas is indistinct with very high stem density and little open flow area. In collecting survey data, it is likely that the rod penetrates the area of very dense stems and likely over-represents the flow area available.

Table 2.6 summarizes split and return stations of the secondary channel that was included in the model for Plot 2. Although the inundation map shows multiple secondary channels that appear to be connected; only one was included in the model, because the majority of them are small loops. The secondary channel was added as a split reach because survey data was adequate to characterize the reach geometry.

**Table 2.6 Secondary channel in Plot 2**

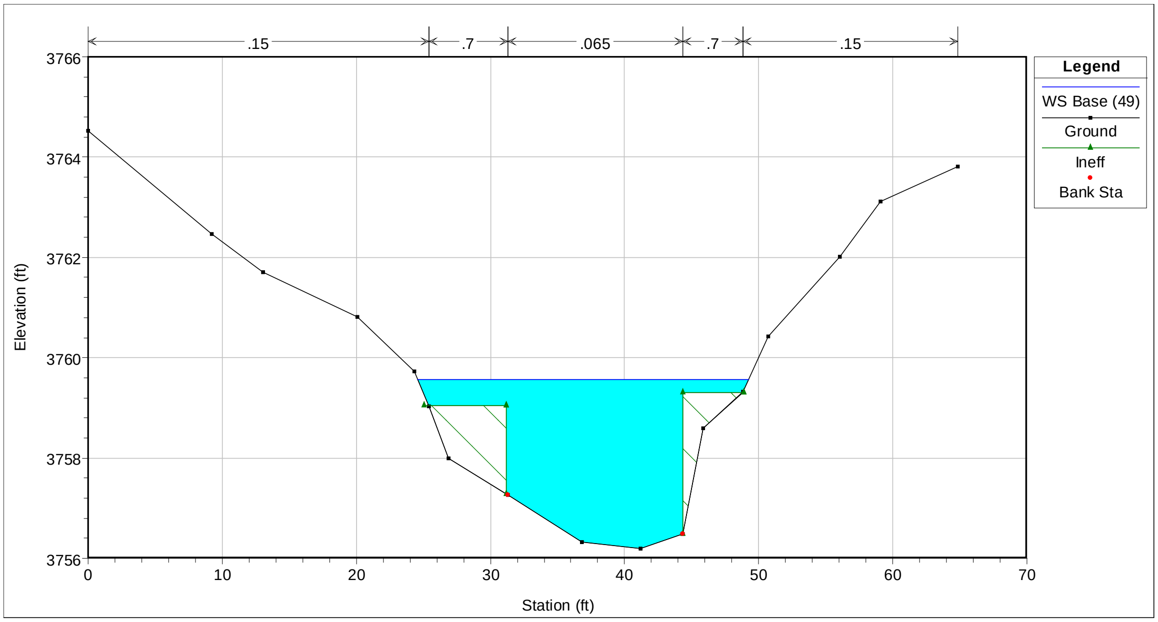
| Secondary Channel ID | Split d/s of: | Return d/s of: |
|---|---|---|
| 2-S1 | STA 96+80 | STA 93+66 |

Figure 2.5 shows a typical cross section in Plot 2, and Figure 2.13 (page 25) shows the computed water surface profiles for three of the calibration tests performed. Profile 2b has n values of:

n=0.065 for open water/channel between tule stands
n=0.70 for tules
n=0.10 for other vegetated overbanks

Profile 2b-ii adopted an n value of 0.15 in the non-tule vegetated overbanks. Profile a2-p1 uses ineffective areas and other adjustments to open channel widths based on the aerial photos. Two cross sections were also added (by duplication of surveyed sections) near the 2 Culvert crossing to better represent limited flow capacity upstream and downstream of the crossing. Profile a2-p1 also includes the split reach.

**Figure 2.5 – Plot 2 typical cross section**




The results of the best model (Profile a2-p1) were checked against the inundation mapping for 2011, so that the model predicts overflow into the split reach for flow conditions in which the inundation maps indicate that the secondary channel was occupied. Table 2.7 summarizes the potential impact of the secondary channel on the flow in the main channel as a percent difference for base flow and habitat flow. The HEC-RAS model predicts that the split reach is not connected at base flow but is at the habitat flow, which generally matches the inundation mapping.

**Table 2.7 Impact of the secondary channel on the main channel flow**

| Secondary Channel ID | Calibration (Base) Flow | | | Habitat Flow | | |
|---|---|---|---|---|---|---|
| | Q (cfs) u/s of Split | Q (cfs) d/s of Split | % change | Q (cfs) u/s of Split | Q (cfs) d/s of Split | % change |
| 2-S1 | 49.0 | 49.0 | 0.0 | 120.0 | 118.1 | 1.6 |

## Plot 3

Plot 3 generally has the widest channel of the five modeled areas and has numerous areas of channel that are completely occupied by tule stands (no open water). Figure 2.6 shows a typical portion of channel in Plot 3. In the absence of an open water channel, the distribution of flows between the open water channel and tule areas was less significant to model calibration than for Plots 1 and 2 and the ineffective fow area approach was not used. In Plot 3, initial runs with the n values for Plots 1 and 2 produced water surface profiles below the observed profiles. In this area, higher n values (1.0) were tested for the tule areas. Although this produced water surface profiles that more closely matched the observed elevations , this value is outside the range reported in the literature and its use in other areas produced water surfaces that were too high.

**Figure 2.6 – Plot 3 channel**

Calibration in Plot 3 therefore used the aerial photos to adjust n values for cross sections with substantial channel blockage by tules downstream. Because the surveyed sections tend to be located in areas without tules, direct use of the survey point descriptors underestimates the channel friction losses. The open water widths and n values were therefore adjusted at many sections in Plot 3 to better represent roughness conditions immediately downstream. While this method unfortunately combines geometry from one location with roughness from an area immediately downstream, it is considered a better overall representation of the channel. The channel blockages by tules appear to be the hydraulic controls on water surface profiles and are not represented by the cross section descriptors. Figure 2.7 shows a typical cross section from HEC-RAS in Plot 3.

**Figure 2.7 – Plot 3 typical cross section**

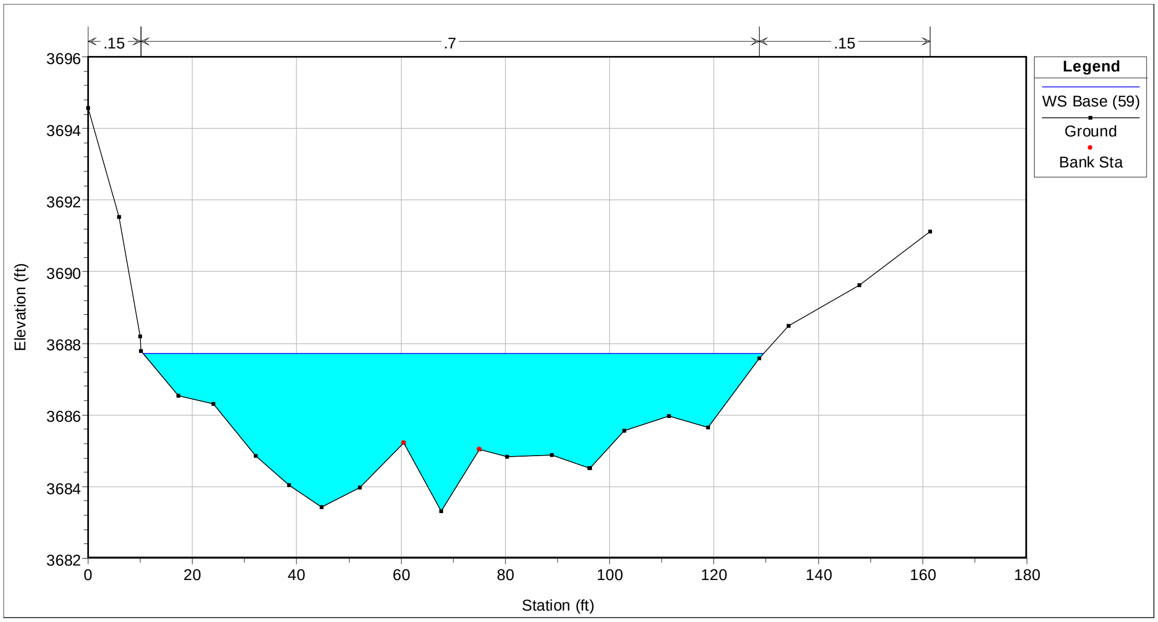



Table 2.8 summarizes split and return stations of secondary channels that were included in the model for Plot 3. Both 3-S1 and 3-S2 were added as split reaches because cross sectional survey was adequate to characterize the reach geometry.

**Table 2.8 Secondary channel in Plot 3**

| Secondary Channel ID | Split d/s of: | Return d/s of: |
|---|---|---|
| 3-S1 | STA 73+98 | STA 69+07 |
| 3-S2 | STA 51+48 | STA 41+79 |

Figure 2.14 (page 26) shows the computed water surface profiles for three of the calibration tests performed. Profile 3b has n values of:

n=0.065 for open water/channel between tule stands
n=0.70 for tules
n=0.15 for other vegetated overbanks

Profile 3b-i tested an n value of 1.0 for tules. Profile a3-p1 uses the n values listed above, but adjusts the n values at some sections using the aerial photos to represent areas where the channel is nearly completely blocked by tules. Profile a3-p1 uses the observed water surface at the downstream end of the plot as the starting water surface elevation. Because there are no observed water surface elevations for higher flows, the downstream water surface elevations were estimated by assuming that downstream end acts as a weir. The aerial photograph shows the blockage of the channel by tules and field observations (See Section 2.7) identified a large beaver dam downstream of Plot 3, indicating a condition that is best simulated as a weir. Additionally, Profile a3-p1 includes split reaches.

The results of the best model (Profile a3-p1) were checked against the inundation mapping for 2011, so that the model predicts overflow into the split reaches for flow conditions in which the inundation maps indicate that the secondary channels were occupied. Table 2.9 summarizes the potential impact of the secondary channel on the flow in the main channel as a percent difference for base flow and habitat flow.

**Table 2.9 Impact of the secondary channel on the main channel flow**

| Secondary Channel ID | Calibration (Base) Flow | | | Habitat Flow | | |
|---|---|---|---|---|---|---|
| | Q (cfs) u/s of Split | Q (cfs) d/s of Split | % change | Q (cfs) u/s of Split | Q (cfs) d/s of Split | % change |
| 3-S1 | 59.0 | 59.0 | 0.0 | 116.0 | 112.2 | 3.2 |
| 3-S2 | 59.0 | 59.0 | 0.0 | 116.0 | 103.9 | 10.4 |

The HEC-RAS model predicted that 3-S1 would not be flowing at base flow while the inundation map indicated 3-S1 to be connected. The predicted water surface elevation is not sufficiently high (although very close) to overtop a high point located approximately 50 feet downstream of the bank. The model was not altered to match this condition because the predicted water surface elevation was observed to be very close to that of measured data in the calibration model of Plot 3. It is likely that a very small amount of flow enters this secondary channel at base flow conditions, and the model is considered reasonably accurate to model higher flows.

### Plot 4

Plot 4 has a moderately wide channel characterized in part by large areas of open water separated by relatively short lengths of channel that are completed blocked or bridged by tules and sometimes reinforced with large woody material. Water depth between these bridged areas is sometimes more than 8 feet in base flow conditions. The origin of the bridged sections is unknown, but may be partly the result of beaver activity. Plot 4 also includes some sections similar to Plot 2 with broad areas of tules along the margins of the open water channel. Figure 2.8 shows a typical portion of channel in the upstream portion of Plot 4. Plot 4 also has a large drop in observed water surface profiles about 4000 feet upstream of the downstream end in an area where the channel becomes indistinct. The drop is associated with a high section in the bed profile that is about 600 feet long. This area was reviewed in the field and found to contain multiple flow paths with indistinct and discontinuous channels and a few areas with debris jams or beaver dams in the remaining open channels. The area appears to function as a very densely vegetated floodplain with no continuous open channel.

**Figure 2.8 – Plot 4 channel**

Calibration runs in Plot 4 were similar to Plot 3. However, in the upper portion of Plot 4 there are numerous areas of wide open water that are represented in the cross sections and produce almost no energy losses because of their large conveyance capacities. In Plot 4, assigning n values to represent downstream roughness was found to provide insufficient increase in water surface elevations to match the observed water surface elevations. Therefore, in areas where tule “bridges” crossed the channel it was assumed that the bed elevations were higher than in the surveyed cross sections located upstream of the tule bridges. This assumption appears to be justified by the open water depths observed in the profile. It is unlikely that tules would grow in water in excess of 6 feet of depth and reach sufficient height to extend out of the water several feet.

In areas identified as tule bridges in the aerial photos, the obstruction option in HEC-RAS was used to raise the bed elevations to be 2 to 3 feet below the observed water surface elevations. The length of the obstructions was estimated by the length of blocked tule area along the channel, and cross sections were added by duplication of upstream or downstream sections to represent the upstream and downstream limits of the blocked (bridge) areas. The combination of the obstructions and n values as used in Plot 3 produced a reasonable calibration to observed water surface elevations. Figure 2.9 shows a typical section from HEC-RAS in Plot 4 using an obstructed area.

**Figure 2.9 – Plot 4 typical section with obstruction**

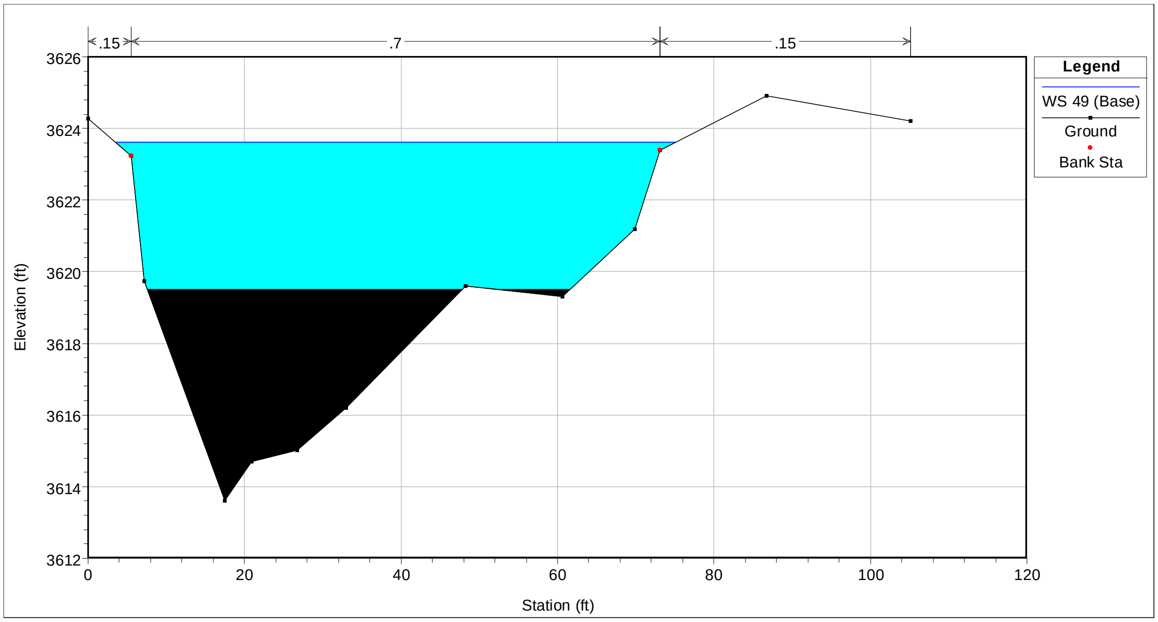



Table 2.10 summarizes split and return stations of secondary channels that were included in the model for Plot 4. Secondary channel 4-W1 was added as a lateral weir because limited survey data was available. The weir geometry was adopted from the cross sectional survey information located approximately 110 feet downstream of the channel bank because a high point in the channel at this location appears to be the hydraulic control. Secondary channels 4-S1, 4-S2, 4-S3, and 4S-4 were added as split reaches because survey data was adequate to characterize the reach geometry.

**Table 2.10 Secondary channels for Plot 4**

| Secondary Channel ID | Split d/s of: | Return d/s of: |
|---|---|---|
| 4-W1 | STA 107+60 | STA 104+15 |
| 4-S1 | STA 97+22 | STA 89+76 |
| 4-S2 | STA 84+15 | STA 80+39 |
| 4-S3 | STA 85+93 | STA 73+39 |
| 4-S4 | STA 42+08 | STA 22+38 |

Figure 2.15 (page 27) shows the computed water surface profiles for three of the calibration tests performed. Profile 4b has n values of:

n=0.065 for open water/channel between tule stands
n=0.70 for tules
n=0.15 for other vegetated overbanks

Profile 4c uses the n values listed above, and adds ineffective areas in cross sections with stands of tules as for Plot 2. Profile a4-p1 adds obstructions to represent tule bridges between large open water areas in the upstream portion of Plot 4 and makes other minor adjustments to cross sections to better represent open water widths. Profile a4-p1 uses the observed water surface at the downstream end of the plot as the starting water surface elevation. Because there are no observed water surface elevations for higher flows, the downstream water surface elevations were approximated by assuming that the downstream end acts as a weir. The aerial photograph shows the blockage of the channel by tules downstream of Plot 4, indicating a condition best simulated as a weir. Profile a4-p1 also includes secondary channels.

The results of the best model (Profile a4-p1) were checked against the inundation mapping for 2011, so that the model predicts overflow into the split reaches for flow conditions in which the inundation maps indicate that the secondary channels were occupied. Table 2.11 summarizes the potential impact of the secondary channel on the flow in the main channel as a percent difference for base flow and habitat flow.

**Table 2.11 Impact of the secondary channel on the main channel flow**

| Secondary Channel ID | Calibration (Base) Flow | | | Habitat Flow | | |
|---|---|---|---|---|---|---|
| | Q (cfs) u/s of Split | Q (cfs) d/s of Split | % change | Q (cfs) u/s of Split | Q (cfs) d/s of Split | % change |
| 4-W1 | 49.0 | 49.0 | 0.0 | 75.0 | 69.4 | 7.4 |
| 4-S1 | 49.0 | 49.0 | 0.0 | 75.0 | 69.2 | 7.7 |
| 4-S2 | 49.0 | 47.8 | 2.1 | 68.9 | 62.1 | 9.9 |
| 4-S3 | 49.0 | 49.0 | 0.0 | 75.0 | 68.9 | 8.1 |
| 4-S4 | 49.0 | 48.3 | 1.5 | 75.0 | 72.4 | 3.5 |

The HEC-RAS model predicted that 4W-1 would not be flowing at base flow while the inundation map indicated it to be connected. The simulation result shows that the water surface elevation modeled for the base flow at STA 107+60 is approximately 0.2 feet below the assumed weir crest elevation. The model was not altered to match this condition because the weir crest is based on survey data and the predicted water surface elevation was observed to be very close to that of measured data in the calibration model of Plot 4. It is likely that a very small amount of flow enters this secondary channel at base flow conditions, and the model is considered reasonably accurate to model higher flows.

### Plot 5

Plot 5 has a slightly narrower channel than Plot 4, but has similar morphology. Plot 5 also includes some areas of channel bridging by tules and large woody material, but the open water areas are much less pronounced and depths are lower. Figure 2.10 shows a typical portion of channel in Plot 5.

**Figure 2.10 – Plot 5 channel**

Plot 5 calibration runs were similar to Plot 4, except that obstructions were not required to obtain a reasonable match to observed water surface elevations. Figure 2.11 shows a typical section from HEC-RAS in Plot 5.

**Figure 2.11 – Plot 5 typical section**

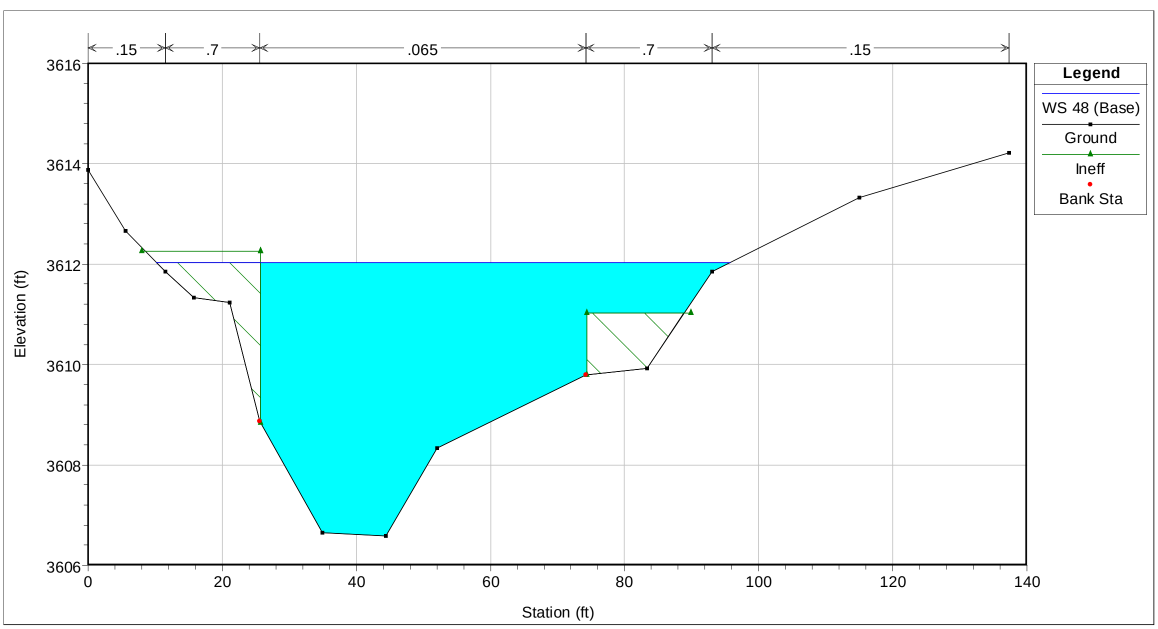


Table 2.12 summarizes split and return stations of secondary channels that were included in the model for Plot 5. Both 5-S1 and 5-S2 were added as split reaches because survey data was adequate to characterize the reach geometry. 5-W1 was added as lateral weir because limited survey data was available. The elevation of the weir crest was chosen to be approximately 0.2 feet below the base flow water surface elevation. The weir length was defined so that the top width would approximately match that of the apparent channel constriction on the inundation map. Secondary channel 5-S3 was modeled separately, because its downstream connection with the main channel was unidentified in inundation mapping. The reach geometry was based on the survey data and normal depth was specified as a downstream boundary condition. To determine the flow split between 5-S3 and the main channel, a manual iterative approach was implemented that approximately matched the water surface elevation at the upstream end of 5-S3 with that of STA 24+22 in the main channel.

**Table 2.12 Secondary channels for Plot 5**

| Secondary Channel ID | Split d/s of: | Return d/s of: |
|---|---|---|
| 5-W1 | STA 108+59 | STA 94+83 |
| 5-S1 | STA 76+23 | STA 68+05 |
| 5-S2 | STA 66+41 | STA 45+73 |
| 5-S3 | STA 24+22 | N/A |

Figure 2.16 (page 28) shows the computed water surface profiles for three of the calibration tests performed. Profile 5b has n values of:

n=0.065 for open water/channel between tule stands
n=0.70 for tules
n=0.15 for other vegetated overbanks

Profile 5c uses the n values listed above, and adds ineffective areas in cross sections with stands of tules as for Plot 2. Profile a5-p1 increases n values in some sections to represent roughness immediately downstream and makes other minor adjustments to cross sections to better represent open water widths. Profile a5-p1 uses the observed water surface at the Keeler measuring station as the starting water surface elevation for the calibration (base flow) and habitat flow runs. Water surfaces at the measuring station were found to be very similar to the water surfaces measured during the cross section surveys. The starting water surface for higher flows was extrapolated using a stage-discharge relationship for the Keeler measuring station. Profile a5-p1 also includes split reaches.

The HEC-RAS model predicts that all the Plot 5 secondary channels are connected at the habitat flow and that 5W-1 and 5S-1 are connected at base flow, which matches the inundation mapping.

**Table 2.13 Summary of secondary channels for Plot 5**

| Secondary Channel ID | Calibration (Base) Flow | | | Habitat Flow | | |
|---|---|---|---|---|---|---|
| | Q (cfs) u/s of Split | Q (cfs) d/s of Split | % change | Q (cfs) u/s of Split | Q (cfs) d/s of Split | % change |
| 5-W1 | 48.0 | 46.3 | 3.5 | 75.0 | 56.8 | 24.3 |
| 5-S1 | 48.0 | 47.5 | 0.8 | 75.0 | 68.8 | 8.3 |
| 5-S2 | 48.0 | 48.0 | 0.0 | 75.0 | 74.9 | 0.1 |
| 5-S3 | 48.0 | 48.0 | 0.0 | 75.0 | 73.2 | 2.4 |

Because the model predicted high weir discharge at 5-W1 for the habitat flow simulation, the model's sensitivity to the flow split between 5-W1 and the main channel was tested. The model was run assuming that the weir would discharge fifty percent less flow than what was predicted initially. The analysis showed that, when the weir discharged fifty percent less flow, the water surface elevation in the main channel near the weir was approximately 0.2 feet higher for the habitat flow simulation. The analysis also showed that this difference in water surface elevations doubled for the 120 cfs simulation. Because the water surface elevations are somewhat sensitive to the weir discharge, the model can be used to at flows up to 100 cfs. The water surface elevations are also generally predicted to be contained within the main channel for flows up to this magnitude. At higher flows, the banks are overtopped at multiple locations.

## 2.6 Comparison of Channel Characteristics

Calibration adjustments are generally consistent for all plots, but calibration methods were different in each modeled area.  These differences generally reflect differences in channel characteristics, which are relevant to flow and aquatic vegetation management.  Table 2.14 and Table 2.15 compare basic hydraulic characteristics modeled at base flow and habitat flow conditions, respectively.  Flow, depth, and velocity values are shown separately for main channel and overbank areas in Plots 1 and 2, where there is a consistent open water channel. In other reaches, values are shown for averages in the entire cross section. As mentioned in Section 2.3, the term "overbank" is not necessarily the topographic break between the main channel and floodplain. Instead, it denotes the area outside of an open water channel that is heavily vegetated  by tules and other riparian vegetation.  In Plots 1 and 2, roughness values assumed for the overbank areas and open channel are significantly different, and hydraulic characteristics are reported in Table 2.14 for both areas.  In the other plots, the open water areas are not as uniform and higher roughness is needed to represent the main channel – therefore, hydraulic characteristics are reported as average values for the entire cross section in Table 2.14.

**Table 2.14 – Average channel characteristics modeled at base flow**

| Characteristics | Plot 1 | Plot 2 | Plot 3 | Plot 4 | Plot 5 |
|---|---|---|---|---|---|
| Total flow area (sq. ft) | 46.6 | 92.6 | 407.6 | 253.3 | 141.1 |
| Main channel flow (cfs) | 42.4 | 49.0 | N/A | N/A | N/A |
| Overbank flow (cfs) | 0.6 | 5.1 | N/A | N/A | N/A |
| Cross section average depth (ft) | 1.8 | 1.9 | 3.4 | 3.1 | 2.6 |
| Main channel depth (ft) | 2.9 | 3.6 | N/A | N/A | N/A |
| Overbank depth (ft) | 0.6 | 1.2 | N/A | N/A | N/A |
| Cross section average velocity (fps) | 1.0 | 0.7 | 0.2 | 0.2 | 0.4 |
| Main channel velocity (fps) | 1.2 | 1.2 | N/A | N/A | N/A |
| Overbank velocity (fps) | 0.1 | 0.1 | N/A | N/A | N/A |

**Table 2.15 – Average channel characteristics modeled at habitat flow**

| Characteristics | Plot 1 | Plot 2 | Plot 3 | Plot 4 | Plot 5 |
|---|---|---|---|---|---|
| Total flow area (sq. ft) | 169.3 | 225.0 | 594.3 | 358.1 | 193.9 |
| Main channel flow (cfs) | 131.1 | 116.0 | N/A | N/A | N/A |
| Overbank flow (cfs) | 18.8 | 25.5 | N/A | N/A | N/A |
| Cross section average depth (ft) | 3.3 | 2.8 | 4.1 | 2.8 | 3.0 |
| Main channel depth (ft) | 5.8 | 5.4 | N/A | N/A | N/A |
| Overbank depth (ft) | 2.3 | 2.2 | N/A | N/A | N/A |
| Cross section average velocity (fps) | 1.0 | 0.6 | 0.2 | 0.2 | 0.4 |
| Main channel velocity (fps) | 1.9 | 1.7 | N/A | N/A | N/A |
| Overbank velocity (fps) | 0.2 | 0.2 | N/A | N/A | N/A |

## 2.7 Channel Anomalies

Unusual water surface or channel bed profiles from the survey data were noted in several locations, and field checks were completed to improve the understanding of these areas and their representation in the model. In Plot 2, a lowered section of channel bed between station 40+00 and 90+00 is evident in the profile. Field observations didn't identify reasons for this lowered section, but also didn't identify any problems with survey information or computed water surface profiles. In Plot 3, a complex of beaver dams was observed approximately 500 feet downstream of the study area, causing the downstream water surface elevation to rise about 2 feet. In Plot 4, a drop in water surface profile and raised bed elevation in the middle of the plot (stations 39+00 to 46+00) were confirmed to exist as a result of beaver activities and blockage of the channel created by tules and debris. In Plot 5, multiple blocked sections associated with large woody material and tules were observed.

**Figure 2.12 – Selected calibration runs (43 cfs) for Plot 1**

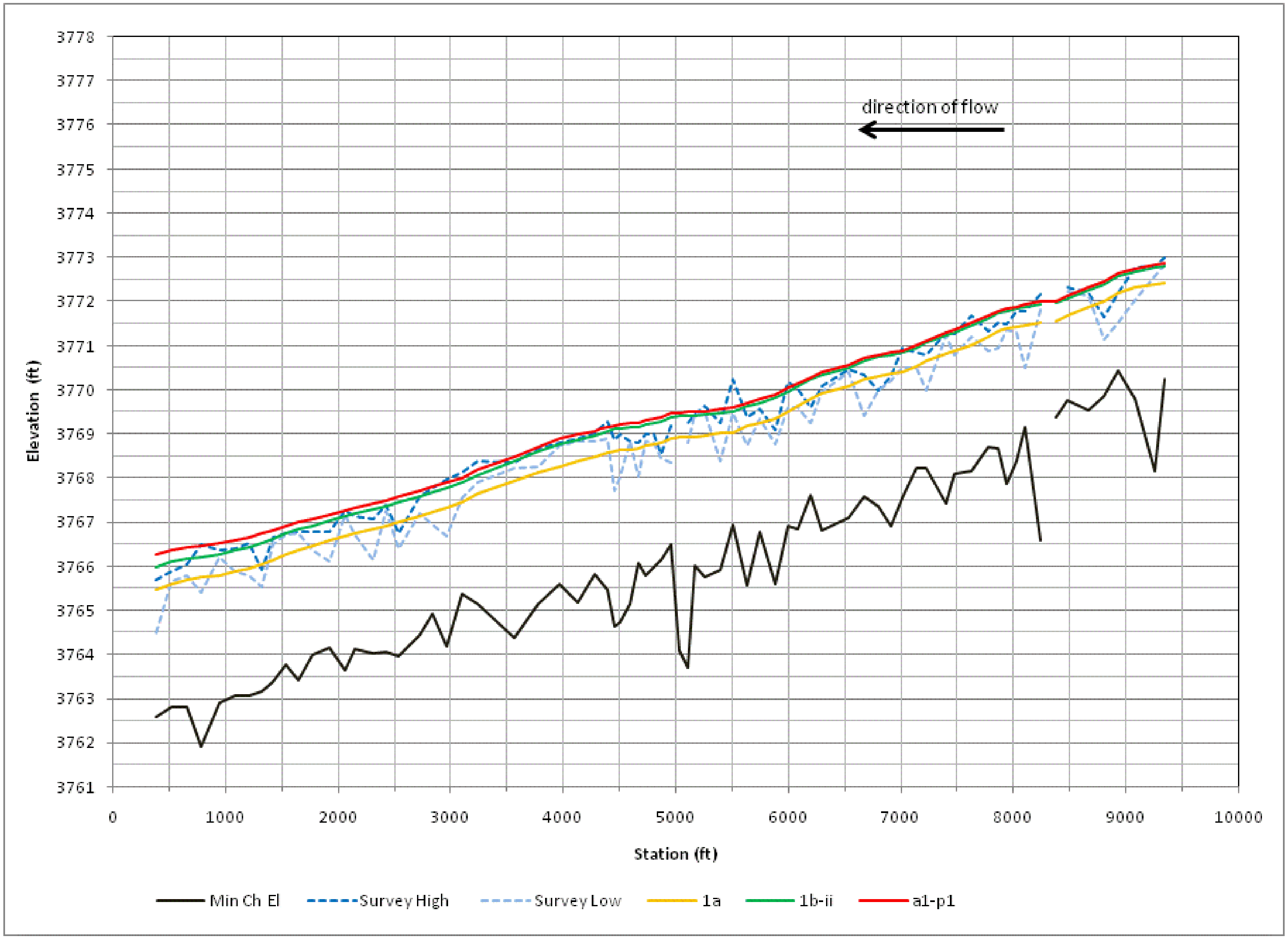


**Figure 2.13 – Selected calibration runs (49 cfs) for Plot 2**

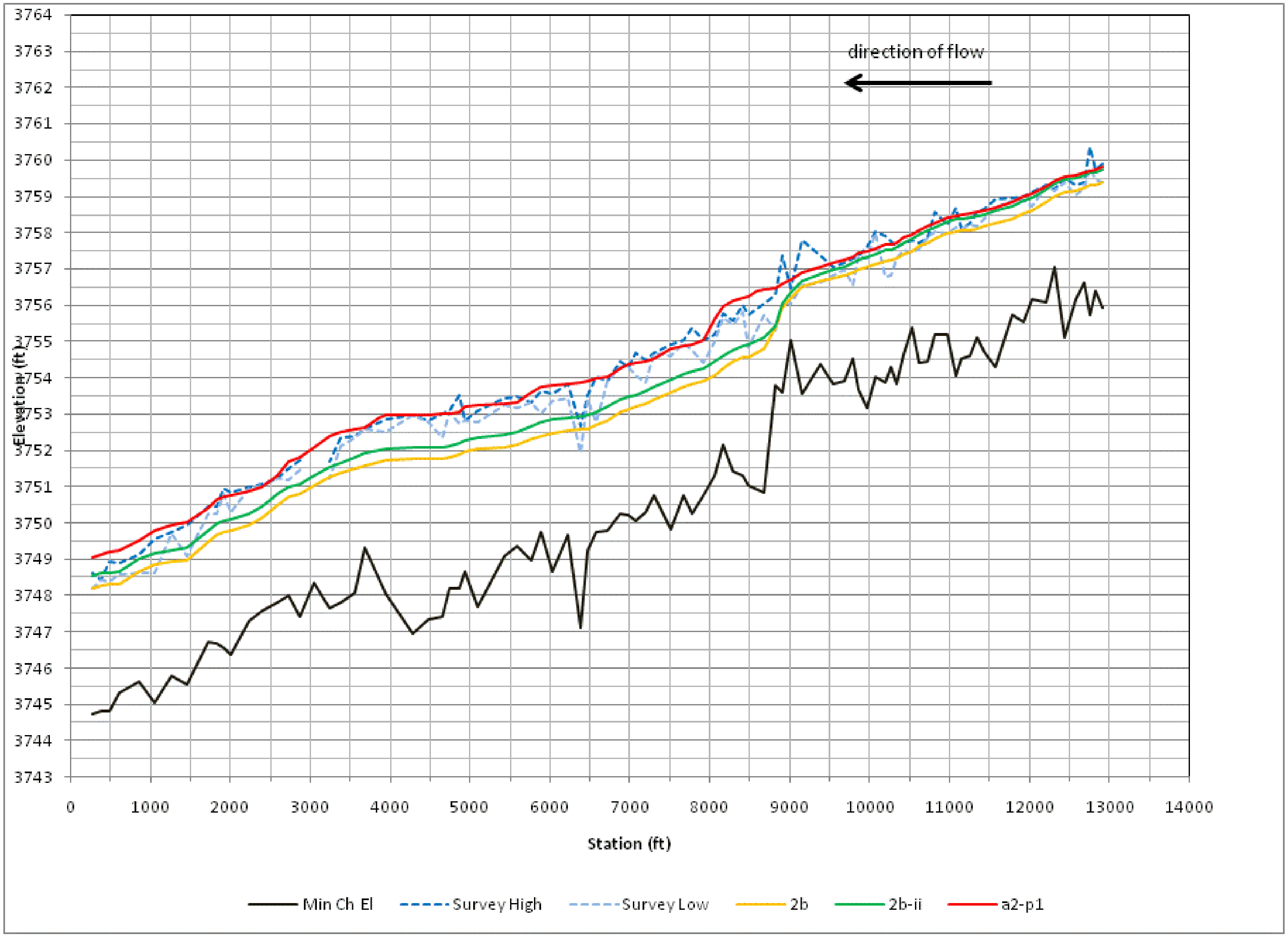


**Figure 2.14 – Selected calibration runs (59 cfs) for Plot 3**

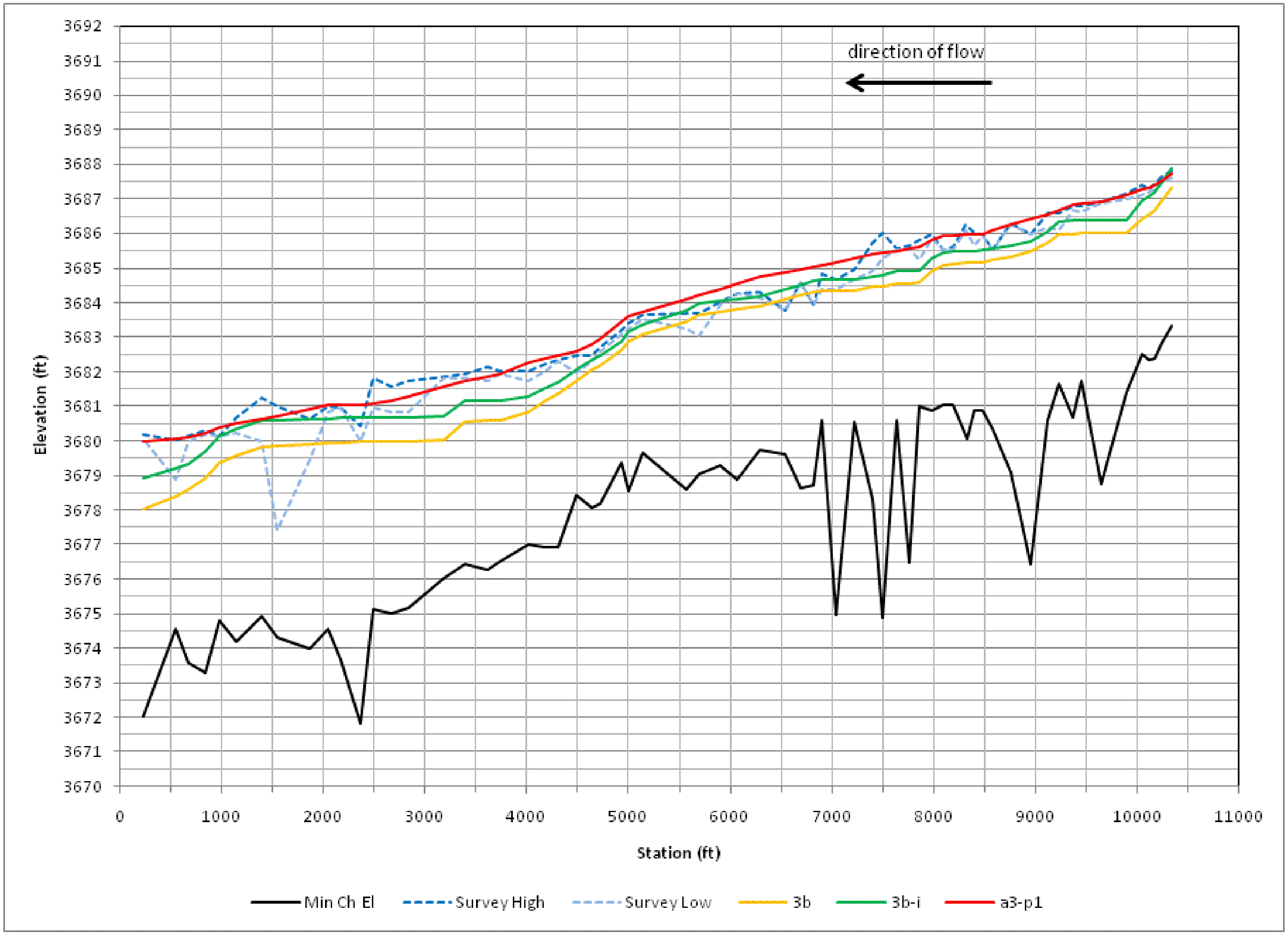


**Figure 2.15 – Selected calibration runs (49 cfs) for Plot4**

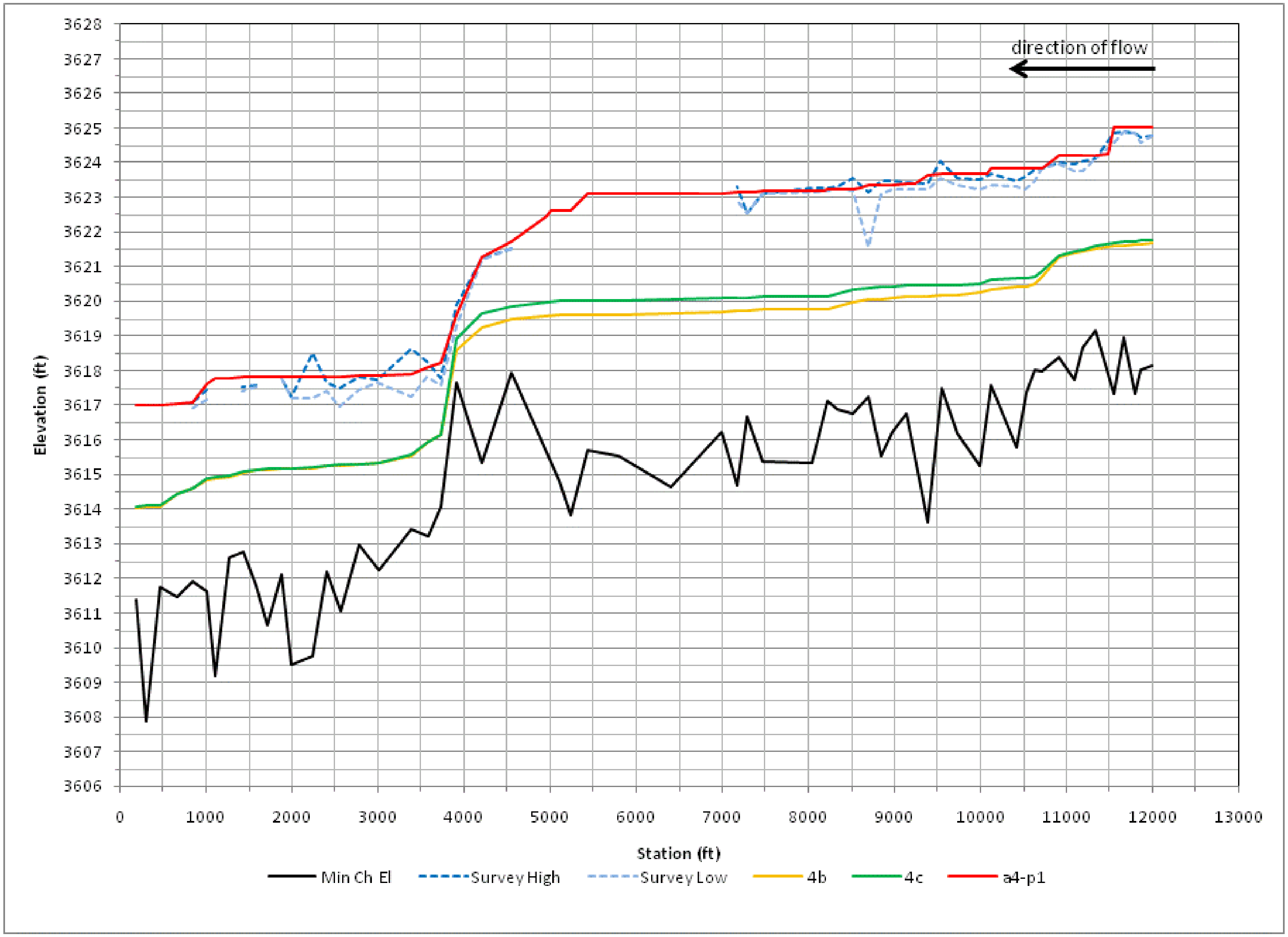
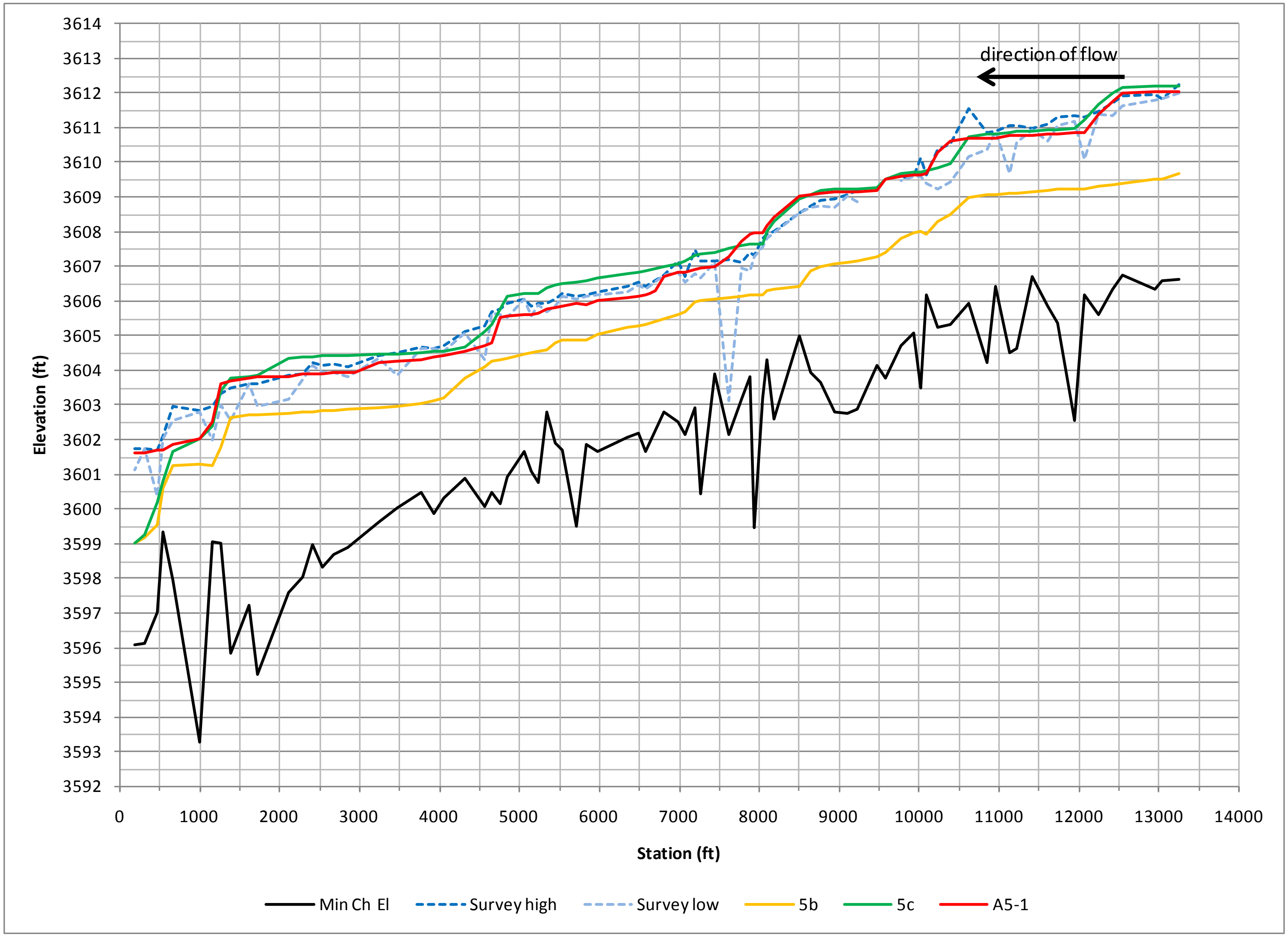


**Figure 2.16 – Selected calibration runs (48 cfs) for Plot 5**



# 3. MULTIPLE FLOW SIMULATIONS

Calibrated models were used develop to water surface profiles and channel characteristics for a range of flows. The objective of the higher flow simulations is to investigate the relationship between changes in flow and hydraulic characteristics relevant to aquatic vegetation and habitat management.

The model accounts for flow in the most prominent secondary channels, but does include all secondary flow paths. As flows increase, the number of active secondary channels increases and eventually flow overtops long sections of bank not associated with specific secondary channels. At these flow rates, the actual water surface would extend well beyond the limits of the channel and secondary channel cross section data. HEC-RAS vertically extends the ends of the cross sections to contain the flow, and therefore would overestimate the water surface elevations in the channel for these conditions. For this reason, the models for each plot have limits on the maximum flow that can be modeled with confidence. These limits vary between plots because of differences in channel and secondary channel morphology, and are described below. In general, for flows in the river above the suggested model limits, relatively small increases in stage would occur with increases in flow due to widespread overtopping of the banks. This section presents the water surface elevations computed for various flow conditions. The cross sections with multiple water surface elevations are presented in Appendix A, followed by tabulated HEC-RAS results in Appendix B.

Figure 3.1 (Page 31) shows the computed water surface profiles for 20, 43 (base flow), 60, 80, 100, 120, 140, 160 (habitat flow), 180, and 200 cfs in Plot 1. The model predicts that flows up to 200 cfs are generally contained within the channel or conveyed through the secondary channels, and the model can be used up to this flow.

Figure 3.2 (Page 32) shows the computed water surface profiles for 20, 49 (base flow), 60, 80, 100, 120 (habitat flow), 140, 160, 180 cfs in Plot 2. Apart from the downstream portion in this plot, the model predicts that flows up to 180 cfs are generally contained within the main channel and the secondary channel. The banks in the downstream portion appear to overtop around 80 cfs, but the cross section data may not represent the actual top of banks. Because the cross sections are extended vertically in the area where the banks are overtopped, the model may overestimate water surfaces at the downstream end of the reach. However, a slight error introduced in the water surface elevation computation at the downstream section would propagate only ten or fifteen cross sections upstream. Therefore, the model can be used to simulate flows up to 180 cfs with the caveat that the downstream 1000 feet of Plot 2 may have slightly lower actual water surfaces than modeled for flows exceeding 100 cfs. Above 180 cfs, banks in most cross sections are overtopped.

Figure 3.3 (Page 33) shows the computed water surface profiles for 59 (base flow), 80, 100, 116 (habitat flow), 140, and 160 cfs in Plot 3. The model predicts that the most flows up to 160 cfs are contained within the main channel and the secondary channel. The model can be used up to flow of this magnitude. Above this flow, the banks in most cross section are overtopped.

Because of the need to simulate the downstream end of this Plot as a weir, water surfaces in the downstream portion of the plot (800 feet) are subject to some uncertainty.

Figure 3.4 (Page 34) shows the computed water surface profiles modeled for 49 (base), 60, and 75 (habitat flow) in Plot 4. The computed water surface elevations are predicted to overtop the banks at multiple locations in Plot 4 at relatively low flows, and the model can be used at flows up to about 75 cfs. At higher flows, the change in water surface with increased flow will be small because of extensive bank overtopping. Because of the need to simulate the downstream end of Plot 4 as a weir, water surfaces in the downstream portion of the plot (800 feet) of the are subject to some uncertainty.

Figure 3.5 (Page 35) shows the computed water surface profiles modeled for 48(base), 60, 75 (habitat flow) and 100 cfs in Plot 5. Because the water surface elevations are somewhat sensitive to the weir discharge used to simulate one of the secondary channels, the model can be used to at flows up to 100 cfs. The water surface elevations are also generally predicted to be contained within the main channel for flows up to this magnitude. At about 120 cfs, the banks are overtopped at multiple locations.

**Figure 3.1 – 20, 43 (base flow), 60, 80, 100, 120, 140, 160 (habitat flow), 180, and 200 cfs runs for Plot 1**

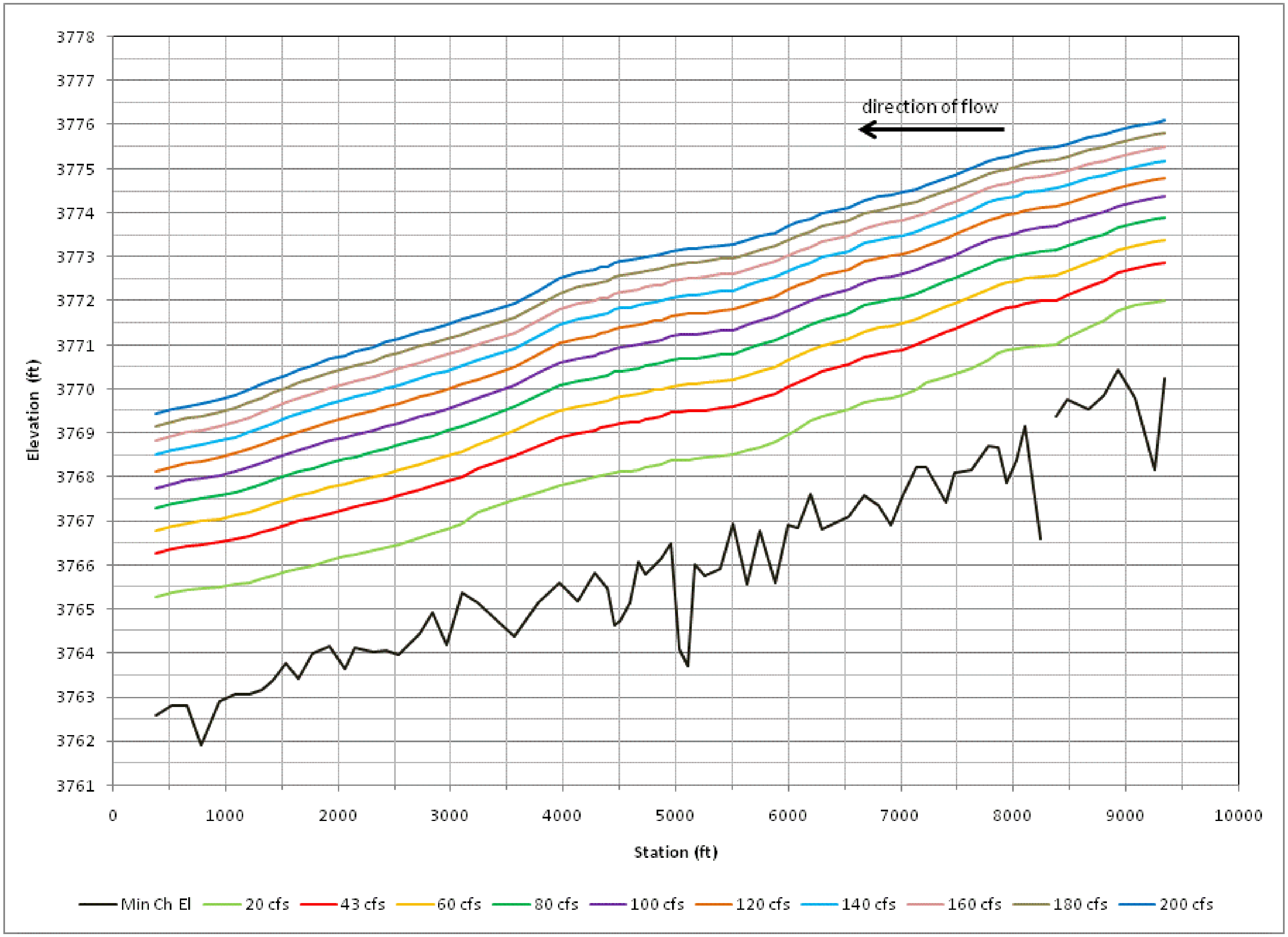


**Figure 3.2 – 20, 49 (base flow), 60, 80, 100, 120 (habitat flow), 140, 160, 180 cfs runs for Plot 2**

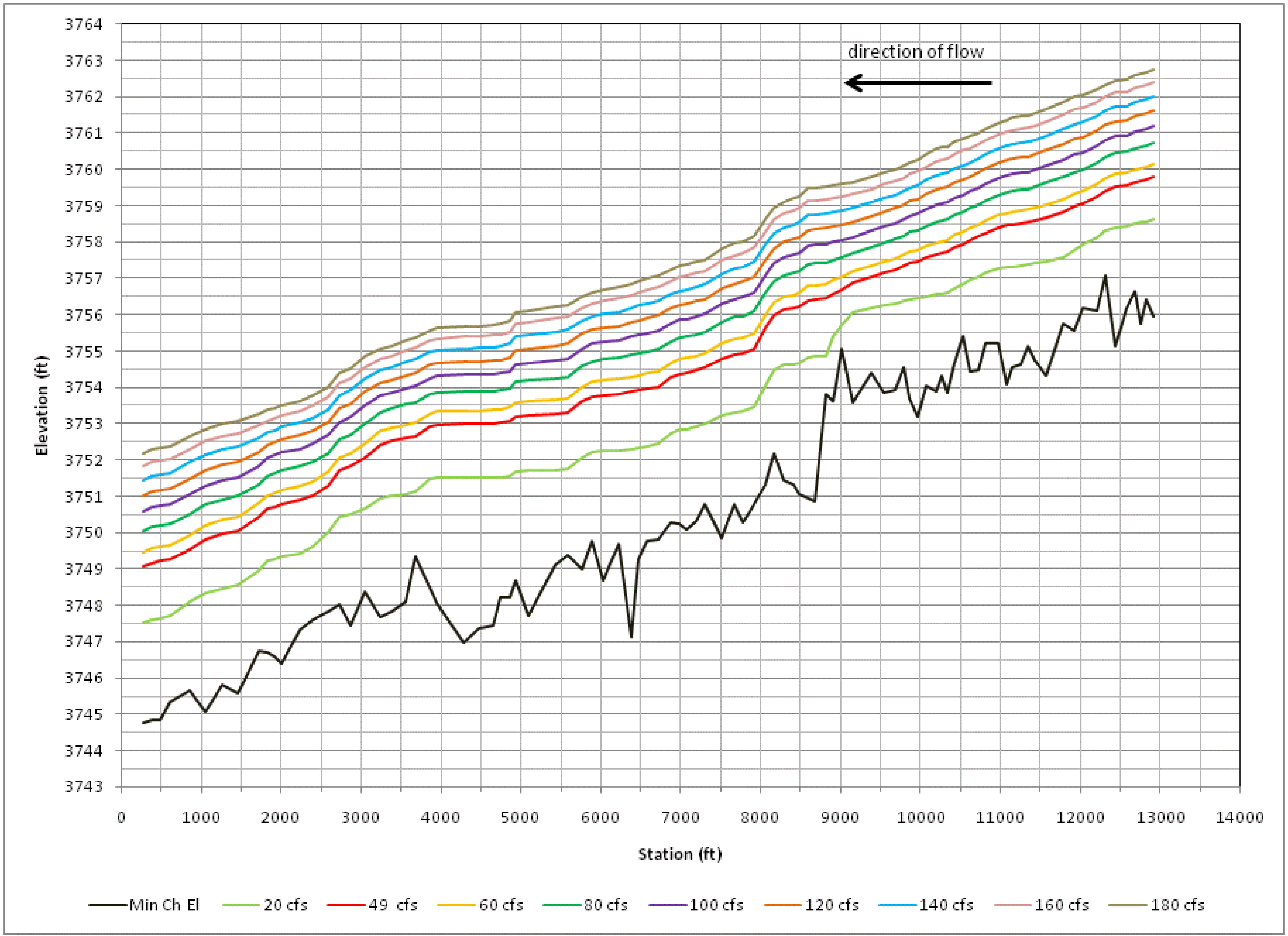


**Figure 3.3 – 59 (base flow), 80, 100, 116 (habitat flow), 140, and 160 cfs runs for Plot 3**

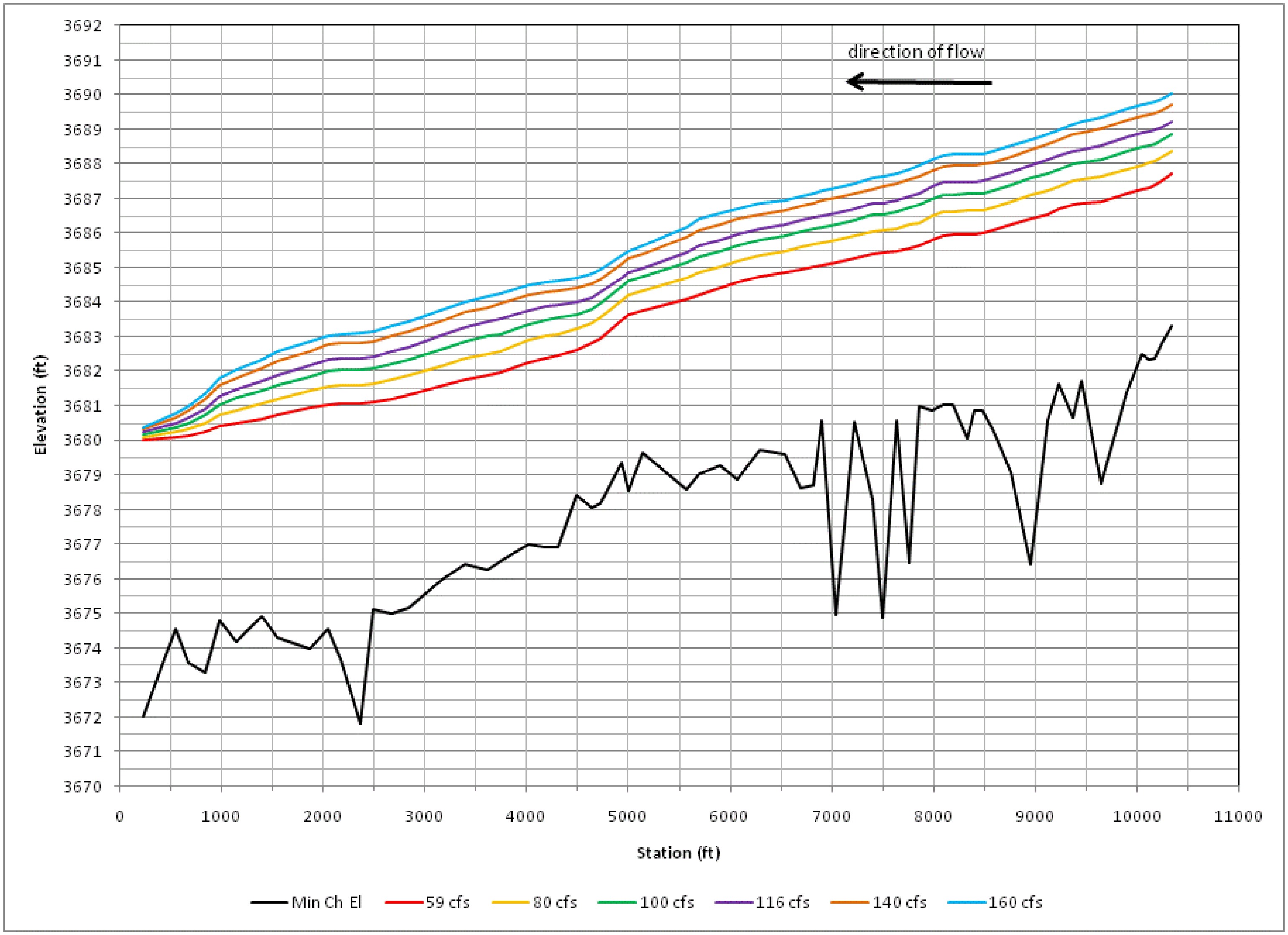


**Figure 3.4 – 49 (base flow), 60, and 75 (habitat flow) runs for Plot 4**

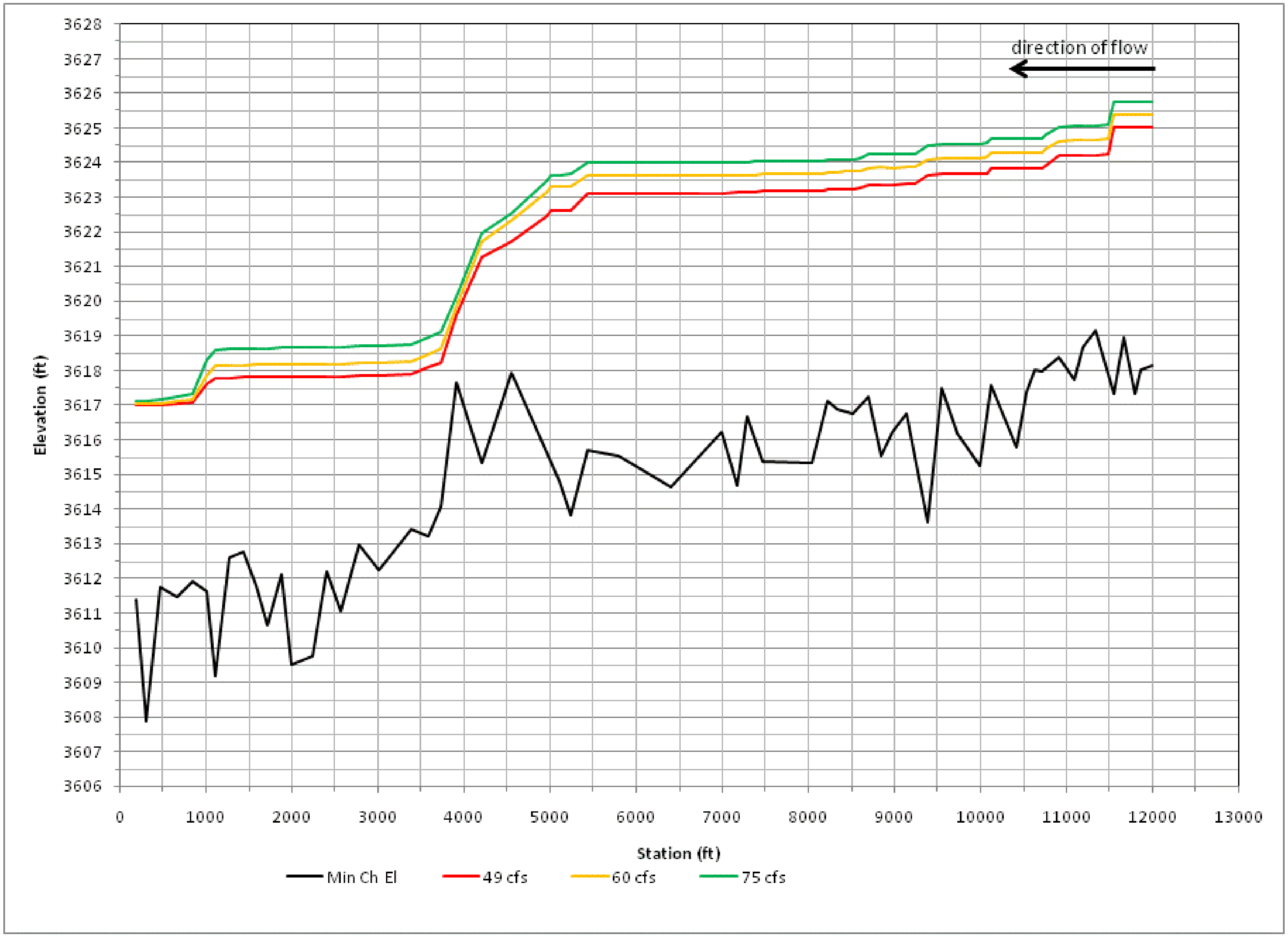
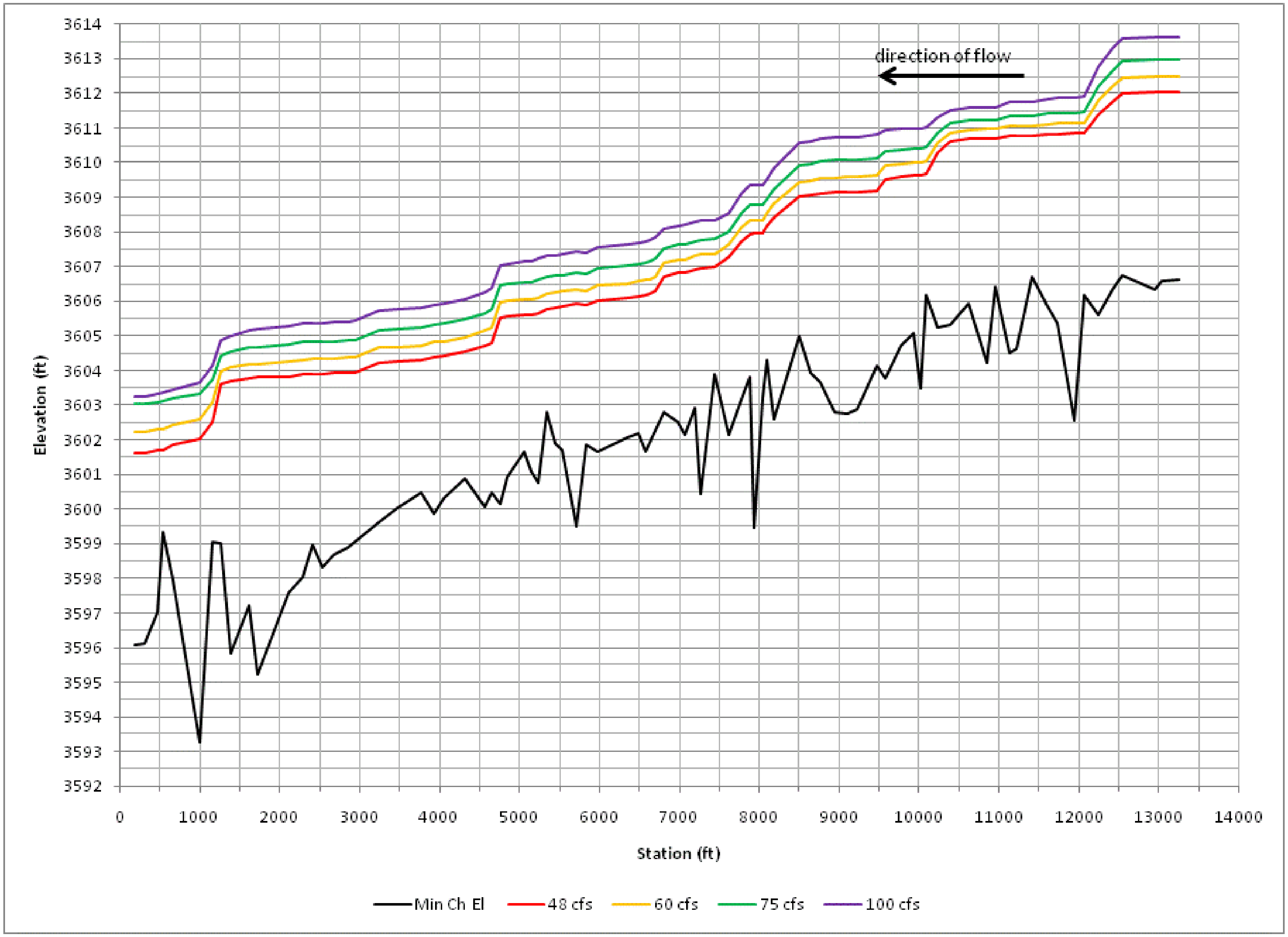


**Figure 3.5 – 48 (base flow), 60, 75 (habitat flow), and 100 cfs runs for Plot 5**



# 4. Summary and Conclusions

HEC-RAS models were developed for 5 study reaches (Plots 1 through 5) in the Lower Owens River Project (LORP). The models were developed from survey information provided by LADWP, comprising about 100 cross sections of the main river channel per plot. The models were developed for the flow range most relevant to management of the LORP – from base flows near 40 cfs up to approximately 200 cfs, the current target for seasonal habitat flows. The objective of the study was to develop stage-discharge relationships and hydraulic characteristics for the study reaches that can be used in ecological management of the project. The results of the modeling may be used to consider alternative flow management schemes and their effectiveness at minimizing further encroachment by tules or achieving other ecological benefits.

The hydraulic modeling focused on main channel characteristics due to limited information on floodplain topography, use of a one-dimensional hydraulic model, and the emphasis on potential use of study results for management of tules in the main river channel.
During the course of the study it became clear that flow in secondary channels may affect flow characteristics in the main channel when river flow is less than 200 cfs. LADWP conducted additional surveying to obtain limited data on the secondary channels and NHC included the most active channels in the modeling. Due to limited study time and resources, only the most significant secondary flow paths were considered and limited topographic information was available for most of these. Nevertheless, the addition of the secondary channel data widens the flow range over which the models can be applied with confidence.

The models were calibrated primarily to water surface elevations surveyed at the time of the cross section surveys. The calibrations to observed water surfaces show that the models can generally be expected to reproduce actual water surfaces to within about 0.5 feet. In addition, the inundation mapping completed by LADWP in 2011 for the base and seasonal habitat flows were used as a check on the model performance. The maps were used primarily to adjust the model so that the secondary flow paths in the model were either connected or disconnected from the main channel at the base and seasonal habitat flow rates as indicated in the inundation mapping.

Channel morphology and capacity vary considerably between the 5 plots. In general, main channel capacity is highest at the upstream end of the LORP (Plots 1, 2, and 3) and lowest at the downstream end (Plots 4 and 5). In Plots 1, 2, and 3 the main channel and the most significant secondary channels contain flows near the seasonal habitat flow release target (160-200 cfs). In Plots 4 and 5, the channel capacities are much lower (75 to 100 cfs), but the 2011 flow data indicate that the seasonal habitat flow was also near this magnitude in Plots 4 and 5. This is due to attenuation of the peak (205 cfs at Intake) in the seasonal habitat flow as it moves downstream.

Key observations for the modeling conducted for this study include:

1) Topographic data collection on the LORP is difficult due to the scale of the project, variability in channel characteristics, and dense vegetation. Because of the low river gradient and relatively low flows, controls such as beaver dams and channel constrictions or obstructions cause a significant fraction of the total energy loss. These locations are also typically the most difficult to survey, and the data set used to develop the models did not include many obstructions that were evident in aerial photos or field observations.

2) Model parameters for channel roughness were developed using values reported in the literature and adjusted by calibrating to surveyed water surface elevations. Because the channel typically has areas of both open water and dense tule growth, the hydraulic computations were made using cross sections partitioned into different roughness values. Assumptions were made when calibration runs indicated that channel constrictions, as noted above, were causing energy losses higher than would be expected from channel geometry and roughness alone. These assumptions were based on aerial photography and assumed physical conditions (but not survey data) and were adjusted to produce water surface profiles that matched the surveyed elevations reasonably well. The distribution of roughness values in the cross section and the distribution of flows in the model between open water and tule areas were checked against several field observations and velocity measurements. The boundary between the tules and open water was observed to produce a sharp boundary with an order of magnitude velocity change (e.g., 1 to 2 fps in the open water to 0.1 to 0.2 fps in the tules). The channel bottom in the tule areas is indistinct due to the number of stems and accumulated organic material, and the portion of the channel near the bed is believed to be ineffective at conveying flow due to the density and stiffness of stems. These observations were used to make adjustments in the HEC-RAS models for some plots.

3) Secondary channels play a role in the stage-discharge relationship in the main channel and the effects of the most significant channels are included to the extent feasible in the models. At the higher end of the range, model results may be sensitive to the assumptions made for the overflow points or secondary channels. Sensitivity tests using the model indicated relatively small effects on water surface elevation within the flow ranges recommended for use in the model. With the secondary channels added, model accuracy is expected to be about the same as the variations seen in calibration runs (generally about 0.5 feet) – larger differences may occur at cross sections near an obstruction or channel anomaly. As flows increase above the limits described above, general overtopping of the banks occurs and multiple secondary flow paths become active in some plots. As flows increase under these conditions, the corresponding change in stage will be relatively small due to the increased flow area available.

The model results are presented as profiles for multiple flows in each of the five plots and as a series of water surface elevations in the model cross sections corresponding to different flows. These may be used in channel management to consider changes that alternative flow release schemes or other actions would produce in depth. Model output tables are also included that provide velocity and other hydraulic parameters (flow area, top width, etc.) at each cross section.

Future use of the results should consider the sensitivity of model results to changes in vegetative roughness (e.g., encroachment by tules), and perhaps more significantly, to changes in obstructions such as those formed by beaver dams, tule “bridges”, and large woody material. The model could be improved with collection of additional topographic data, and floodplain interactions could be better modeled with detailed floodplain topography and a 2-dimensional model. It should be noted, however, that field data collection is extremely time consuming due to vegetative and channel conditions, and aerial data (e.g., LiDAR) is not useful for subaqueous topography and may be unreliable in heavily vegetated areas. For these reasons, improvements or updates of the model in the future might best be made using focused topographic surveys and accurate measurements of water surface elevations and flows at known river discharges. These measurements would provide information to verify or re-calibrate the models and would be useful for properly distributing flows in the models between the main channel and major secondary channels.

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