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Managing Water in the West

Technical Report No. SRH-2014-14

Two-Dimensional Modeling of Reach 1A of the San Joaquin River between Friant Dam and Highway 99

San Joaquin River Restoration Project
Mid-Pacific Region

U.S. Department of the Interior
Bureau of Reclamation

May 2014

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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San Joaquin River Restoration Project
Mid-Pacific Region

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1 Introduction

The San Joaquin River Restoration Program (SJRRP) aims to “restore and maintain fish populations in good condition in the main stem of the San Joaquin River below Friant Dam to the confluence of the Merced River, including naturally-reproducing and self-sustaining populations of salmon and other fish.” The SJRRP Fisheries Management Plan identifies spawning and incubation as a life stage to be supported for successful completion of the salmon life cycle.

SJRRP’s current understanding of the system is that sufficient availability and quality of spawning habitat within Reach 1A of the San Joaquin River is imperative to sustaining a population of Chinook salmon. Uncertainties include the suitability of existing spawning gravels within Reach 1A and the effect of sediment transport on spawning and incubation habitat.

Multiple studies are currently underway or have been completed to help identify the quality of the hyporheic environment as it relates to successful spawning and fry emergence (current efforts summarized in Section 3.2 of 2014 MAP; SJRRP, 2013a). These include efforts to evaluate water quality within the hyporheic zone (DO [USBR, 2012], water temperature effects [USBR, 2012a], fine sediment accumulation [SJRRP, 2010; SJRRP, 2013b]), egg survival (SJRRP, 2012), mesohabitat characterization (SJRRP, 2010), spawning habitat use by transported fall-run Chinook (SJRRP, 2011; SJRRP, 2013c), bed material size and mobility (Tetra Tech, 2012a,b; SJRRP, 2012; SJRRP, 2013d), scour and deposition (SJRRP, 2011), and channel morphology changes associated with alteration to the flow regime (SJRRP, 2011; SJRRP, 2012; SJRRP, 2013e). In addition, bedload and suspended load monitoring have been conducted within the reach since 2010 (Graham, Mathews & Associates, 2012; USBR, 2013).

SJRRP has requested spatial characterization of hydraulic conditions for predicting spawning activities in Reach 1A. This report documents the development, calibration and preliminary results of two-dimensional (2D) hydraulic modeling of Reach 1A. For computational efficiency, the reach has been modeled in two sections: the first is from Friant Dam (Mile Post (MP) 267) downstream to Highway 41 (HW41) Bridge (MP 255), and the second extends from HW41 downstream to Highway 99 (HW99) Bridge (MP 243; Figure 1). Results from the model simulations will be processed using habitat suitability criteria representative of the San Joaquin River. This effort is part of a larger study to characterize suitability of spawning habitat based on physical, biological, and chemical criteria. The results of the evaluation will ultimately be integrated into a GIS database.

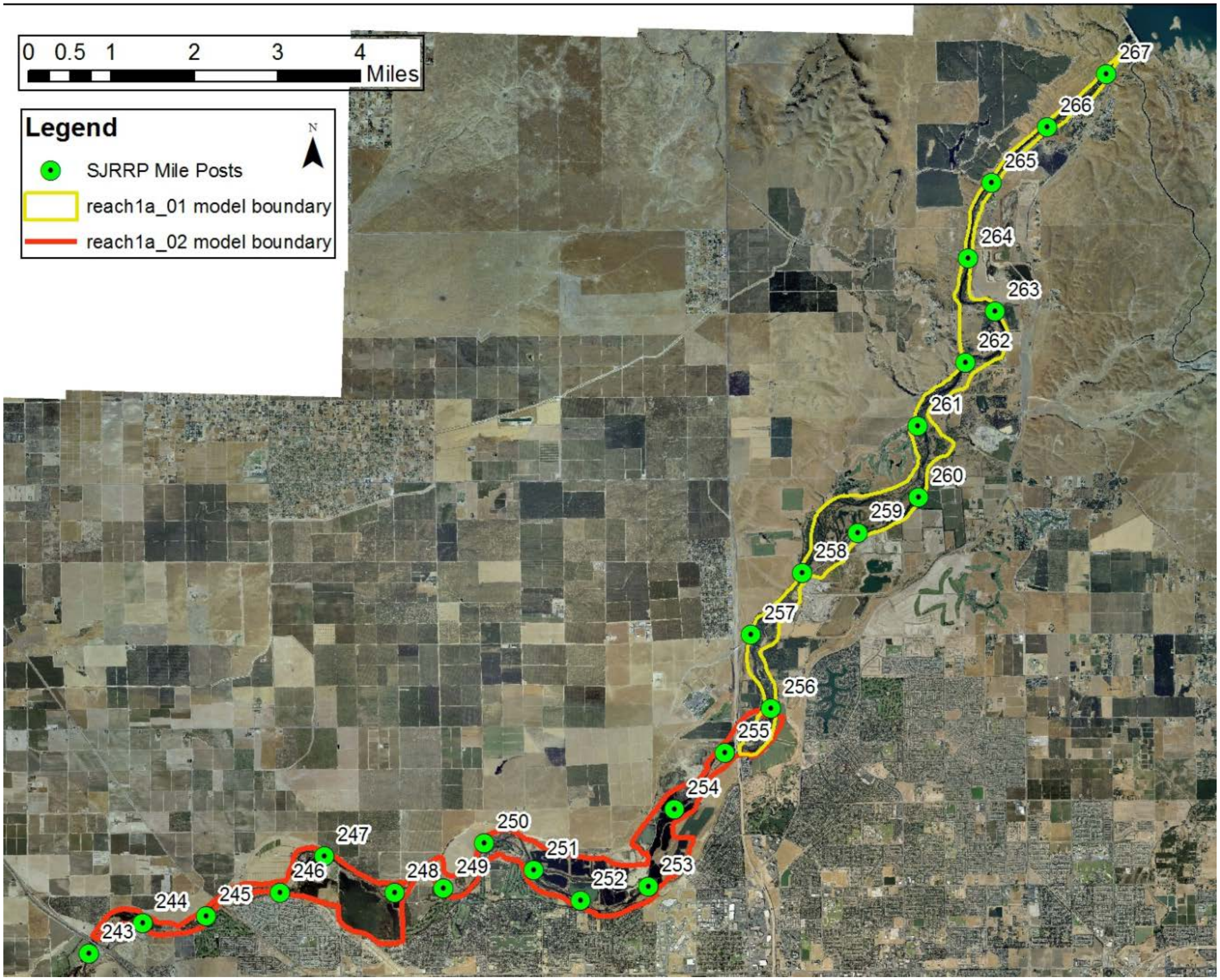

Figure 1. Map of Reach 1 of the San Joaquin River showing the two model boundaries used in this effort. Reach 1A_01 extends from Friant Dam to HW 41, and Reach 1A_02 extends from HW41 to HW99.

2 Mesh Development

Preliminary 2D hydraulic modeling was conducted within Reach 1A by California Department of Water Resources (DWR) in 2010 using the SRH-2D computational package (USBR, 2008). The reach was divided into two subreaches for computational efficiency. The first subreach (Reach 1A_01) extends from Friant Dam to HW41, and the second subreach (Reach 1A_02) extends from HW41 to HW99. Calibration of the preliminary models was not completed due to the unavailability of measured water surface elevation and topographic data, information that has since been acquired.   The computational grids developed by DWR were reused to the extent possible. Within Reach 1A_01, the topography was updated to reflect the most current elevations and project datum, and the material zones were adjusted during model calibration. No adjustments to the grid configuration were necessary for the Reach 1A_01 model.

The preliminary computational mesh for the Reach 1A_02 model did not define the gravel pits, side channels and levee breach locations (gravel pit entrances) in detail. To improve understanding of the flow and temperature interactions between the gravel pits and the river, a refined Reach 1A_02 model mesh was developed from approximately 1 mi upstream of HW41 downstream to MP 250. The new mesh was merged with the existing DWR mesh from MP 250 to HW99. In addition, a new mesh was developed within the vicinity of Milburn Pond, the large gravel pit located on the left side of the river at MP 248, to better represent a nearby side channel and the entrance conditions to the gravel pit. Within the existing DWR mesh, the topography was updated to reflect the most current elevations and project datum. The material zones were changed throughout to refine large areas mapped as a single material zone, to add consistency with the upstream portion of the mesh, and to calibrate channel and floodplain areas having poor comparisons with water surface elevations.

In general, rectangular cells were used to represent the main channel and most side channels, while triangular cells were used to represent the floodplain. Within the channel, rectangular cell sizes ranged between 5-10 ft laterally and 20-30 ft longitudinally. Smaller lateral cell extents are consistent with a general expectation of greater spatial gradients across the channel than along the channel. However, longitudinal spacing may not capture the peak elevations of the riffle crests and deepest pools due to spatial averaging. The final grids were comprised of approximately 117,000 cells within the Reach 1A_01 model and 138,000 cells within the Reach 1A_02 model. A representative portion of the mesh is illustrated in Figure 2.

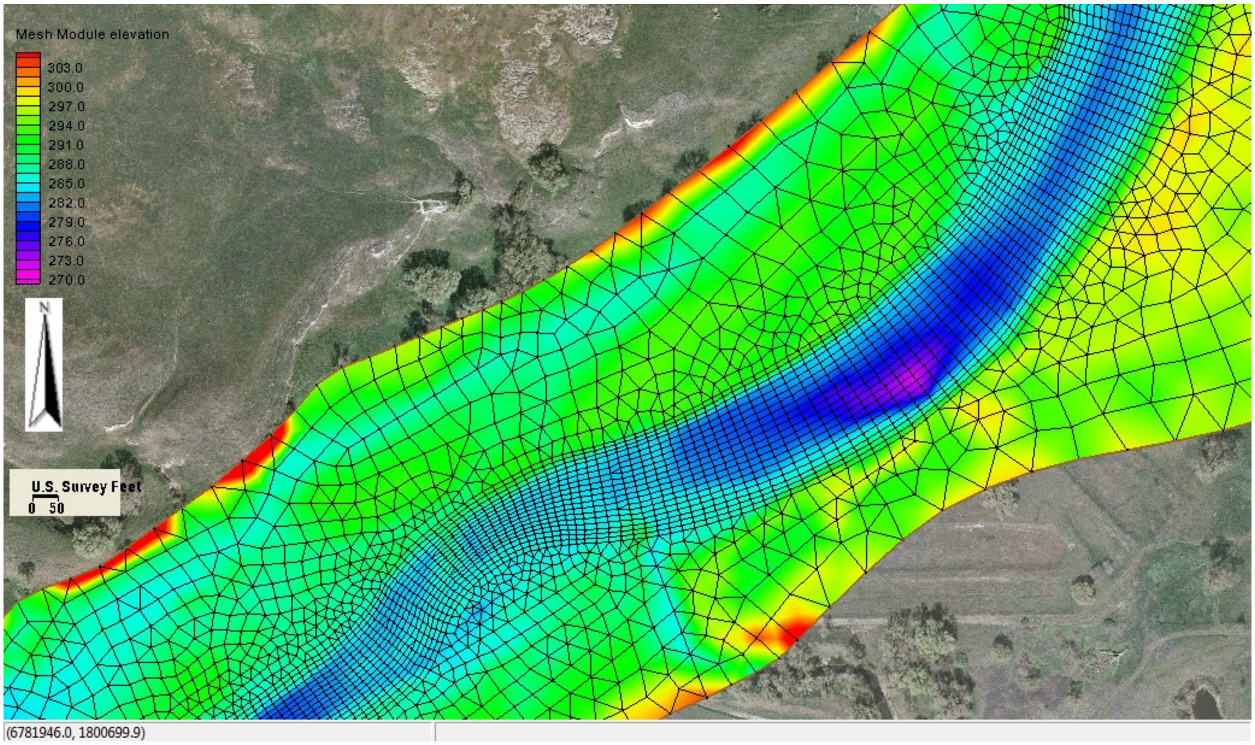

Figure 2. Representative portion (near MP 261.5) of Reach 1A computational mesh developed for SRH-2D hydraulic solver. Bottom elevation (ft, NAVD 88) is mapped to color scale.

3 Topography

The terrain data for Reach 1A are a compilation of ground-based survey points and photogrammetry collected in 1998, combined with in-channel bathymetry collected by boat in 2009. TetraTech determined that portions of the 2009 survey data were inaccurate and replaced the elevations with 1998 elevations (Ayers Data). The locations where the 2009 in-channel survey points were replaced with 1998 data are delineated with polygons and can be identified within the terrain. An example of the terrain used to populate the mesh cells with elevations (State Plane CA III, NAVD88 ft) is illustrated in Figure 3.

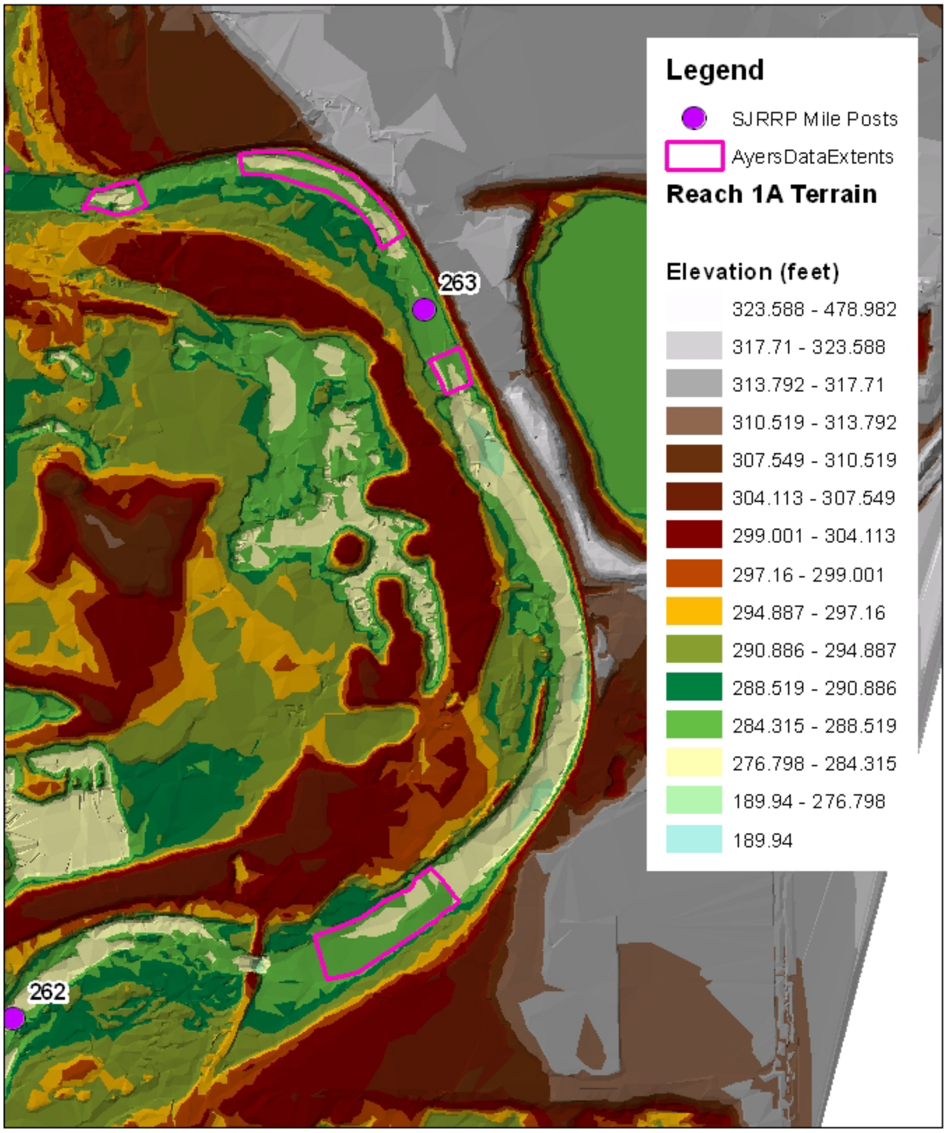

Figure 3. Representative portion of Reach 1A terrain used to populate computational mesh cells. Also shown (purple polygons) are locations where Ayers 1998 data were used in place of 2009 bathymetric data.

4 Boundary Conditions

4.1 Reach 1A_01

Calibration flows ranged from 350 cfs to 7,650 cfs, and were based upon measured water surface elevations within the reach. The downstream boundary condition is based upon measured data at Highway 41 (HW41). The rating curve developed from the measured flows is illustrated in Figure 4. Compiled in Table 1 are measured flow and water surface elevation data organized by date and location within Reach 1A. Dates and locations of measured water surface elevations do not have exact correspondence with dates and locations of measured flows. Therefore, the modeled flows represent estimated discharges at the time water surface elevations were measured. For the Reach 1A_01 model, the simulated discharge typically matched the flow measured at the San Joaquin River Below Friant Dam gage (SJF). The actual flows in the channel downstream from SJF may vary due to inflows from Little Dry Creek. During the dates water surface elevations were measured, tributary flows were typically minimal. An exception was March 2011, when the high flow in Little Dry Creek was near 320 cfs and flow at the SJF gage was 7,650 cfs. At these discharges, Little Dry Creek is theoretically contributing approximately 4% of the total flow. However, the degree to which Little Dry Creek is connected to San Joaquin River at this discharge is unknown, and therefore the actual contribution of flow to the main channel versus to gravel pits adjacent to the tributary is uncertain.

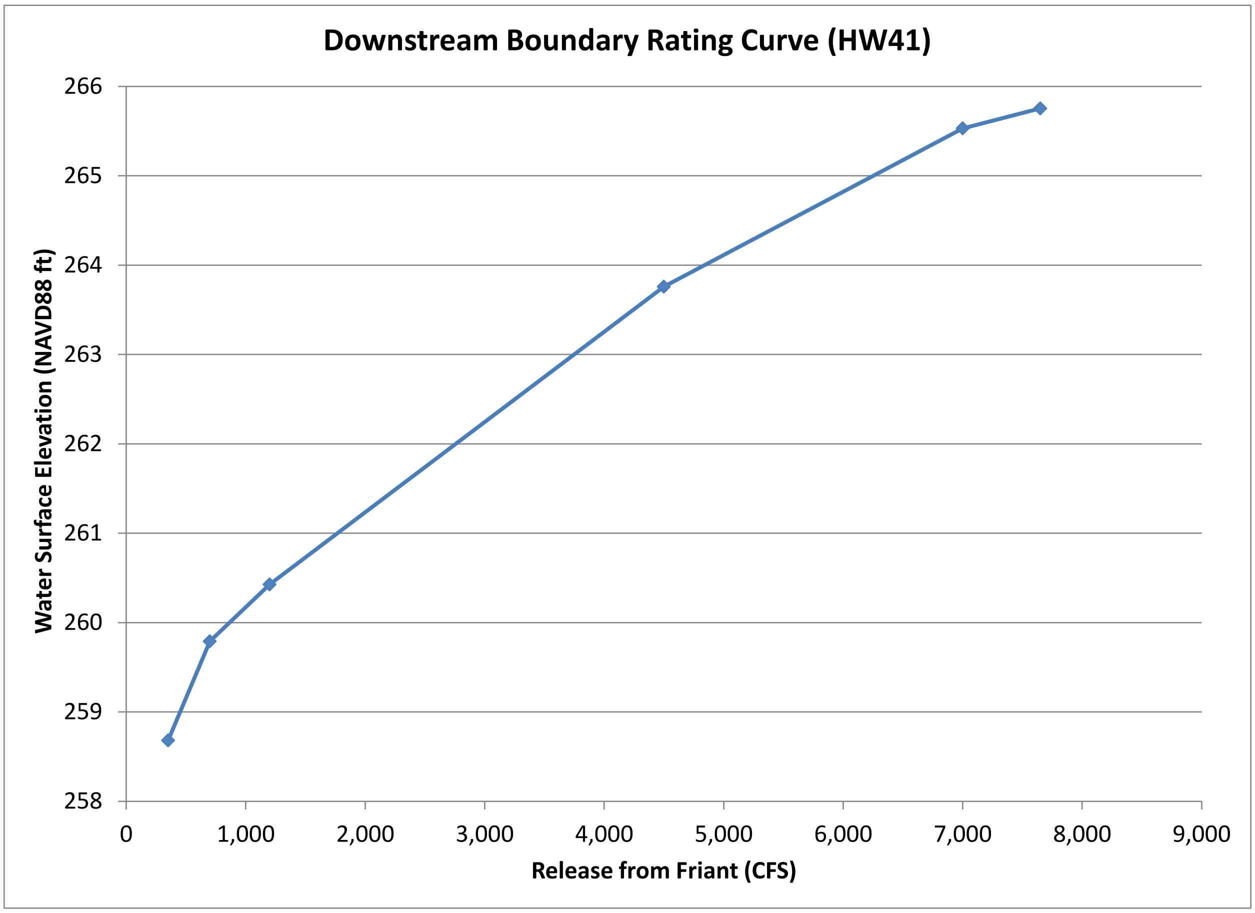

Figure 4. Rating curve used to define downstream boundary condition for Reach 1A_01 model. Rating data is based on measured water surface elevations at Highway 41 (HW41).

Table 1. Measured flow and water surface elevation data organized by date and location within Reach 1A.

				DWR Measured Flows (cfs)				DWR Measured WSE (NAVD88 ft)		
Date	**Calibration Flow (cfs)**	**Modeled Reach**	**Below Friant Dam (SJF gage)**	**MP 255.1 (HW41)**	**MP 251.2 (Sycamore Island)**	**MP 248.3 (upstream of Millburn Pond)**	**MP 245.2 (HW99)**	**Average Measured WSE at HW41**	**Average Measured WSE at HW99**	**WSE Measurement Extent**
10/19/2009	350	Reach1A_01	360	NA	NA	NA	NA	NA	NA	MP 267 to 260.5
10/20/09	350	Reach1A_01	350	337	NA	NA	NA	258.85	NA	MP 260.5 to 252.7
10/21/09	270	Reach1A_02	450	NA	289, 312	295	269	NA	223.8	MP 252.7 to 243
11/9/09	700	Reach1A_01	700	729	NA	NA	NA	259.79	NA	MP 267 to 255.1
11/10/09	700	Reach1A_02	700	NA	686	682	608	NA	225.445	MP 255.1 to 243
4/19/10	1200	Reach1A_01	1200	1377	NA	NA	NA	260.4267	NA	MP 267 to 255.1
4/20/10	1150	Reach1A_02	1240	1146	1300	NA	NA	NA	NA	MP 255.1 to 250
4/21/10	1150	Reach1A_02	1260	NA	NA	1140	1100	NA	227.0511	MP 250 to 243
5/3/11	4500	Reach1A_01	4500	4470	4460	NA	NA	263.7586	NA	MP261 to 255
5/4/11	4500	Reach1A_02	4500	NA	4470	4080	4690	NA	231.249	MP255 to 243
1/5/11	NA	Reach1A_01	7000	NA	NA	NA	NA	265.531	NA	MP267 to 255
1/6/11	7000	Reach1A_02	6950	6290	6350	6380	6430	NA	233.8245	MP 255 to 243.3
3/29/11	7650	Reach1A_01	7650	6849	6575	NA	NA	265.755	NA	MP 267 to 255.1
3/30/11	7650	Reach1A_02	7600	NA	6580	6770	6950	NA	233.9754	MP 255.1 to 243.1

4.2 Reach 1A_02

Calibration flows for the Reach 1A_02 model varied slightly from the Reach 1A_01 model due to variations in the water surface elevation measurements. Water surface elevations between HW41 and HW99 were typically measured at least one day following the measurements between Friant Dam and HW41. The downstream boundary condition for the Reach 1A_02 model is approximately 400 feet upstream from the HW99 Bridge. The rating curve developed from the measured flows is illustrated in Figure 5. Measured flow and water surface elevation data organized by date and location are shown in Table 1. Because the inlet boundary condition for the Reach 1A_02 model is located approximately 12 miles downstream from Friant Dam, the flow reported at the stream gage located just downstream from the dam (SJF) was not always representative of the flow between HW41 and HW 99, particularly under low flow conditions. Therefore, DWR discharge measurements were used to estimate discharge at lower flows. At high flows (above 4,500 cfs), measured discharges were consistently lower than gaged data at several locations throughout the river, which may be related to substantial floodplain connectivity at discharge cross sections. Therefore, for calibration purposes, high flows were estimated from the SJF gage.

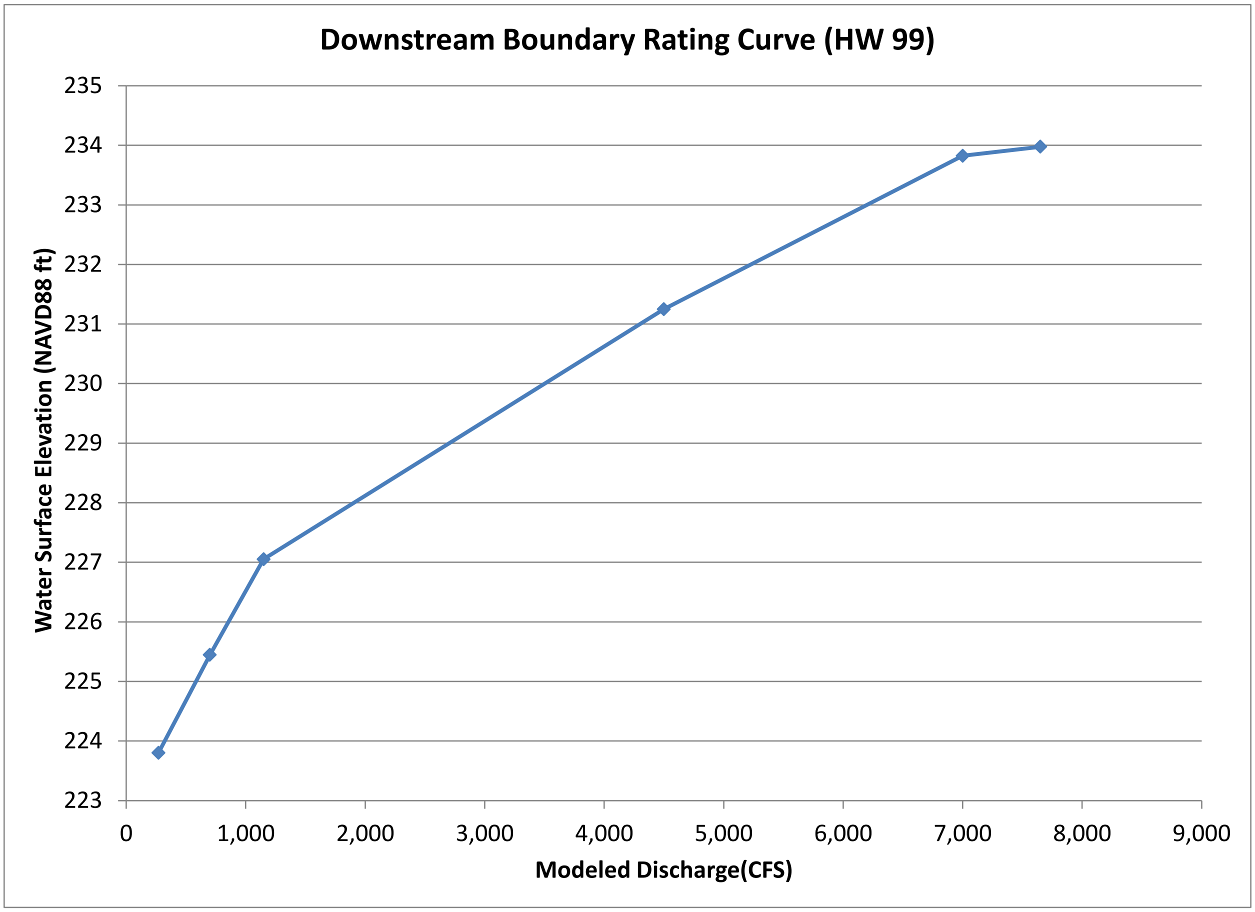

Figure 5. Rating curve used to define downstream boundary condition for Reach 1A_02 model. Rating data based on measured water surface elevation near Highway 99 (HW99).

5 Channel and Floodplain Roughness

Hydraulic roughness (Manning's *n*) is defined at each cell in a computational mesh and is the primary tuning parameter used in calibrating the models. Initial roughness values were delineated based on zones of vegetation density and land use (Figure 6) from 2007 aerial photographs (MEI, 2000; DWR, 2010). Roughness zones were modified in some areas to better reflect current conditions and to improve calibration with initial model results. The initial Reach 1A_02 model mesh lacked sufficient resolution of roughness features, particularly on the floodplain and channel margins. The roughness mapping was refined based upon 2007 and 2011 aerial photos; the updated computational meshes for model Reach 1A_01 and Reach 1A_02 consist of 8 roughness categories (Table 2).

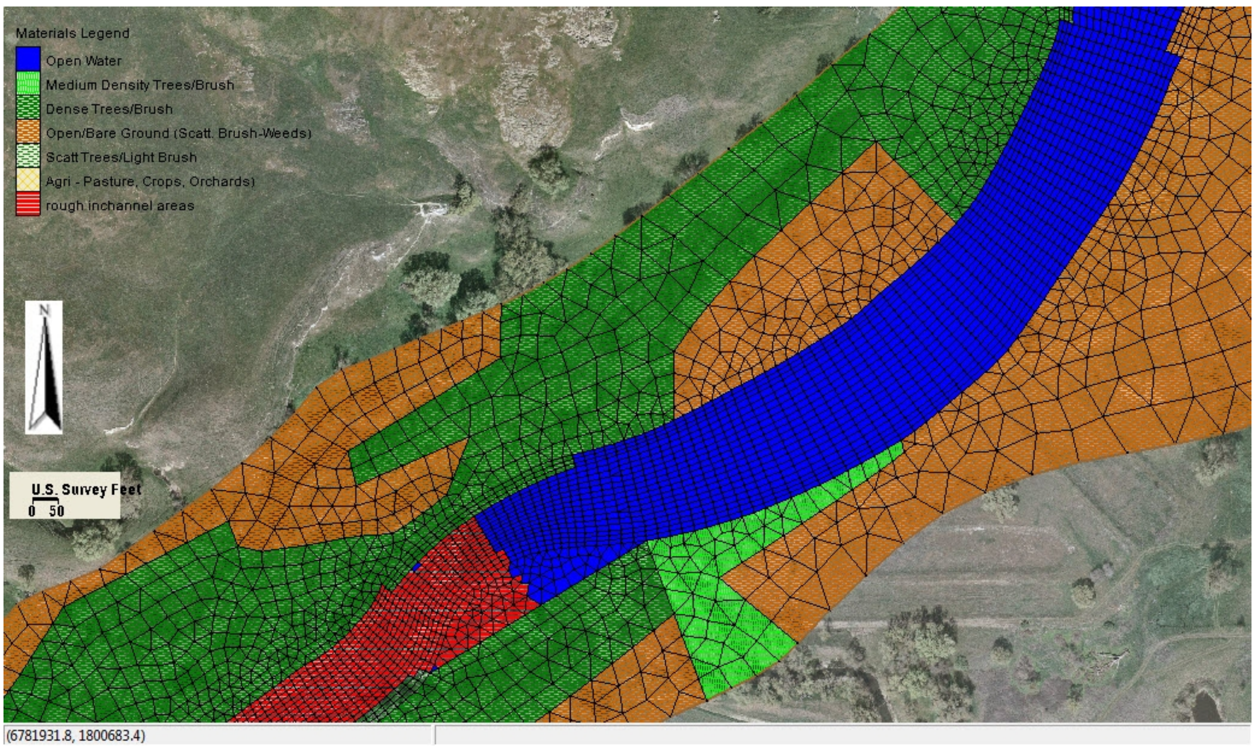

Figure 6. Representative portion of Reach 1A computational mesh near MP 261.5 with land use zones mapped to color scale.

Table 2. Roughness categories used in computational meshes.

Land Use Types
Main Channel Bed
In-channel Riffles/Rough areas
Off-Channel Open Water
Open /Bare Ground/ Scattered Brush
Scattered Trees
Medium Density Trees/Brush
Dense Trees/ Brush
Agriculture

6 In-Channel Calibration

Model calibration was conducted for the Reach 1A_01 and Reach 1A_02 models using available water surface elevation and flow measurements. First in-channel calibration was performed to define roughness within the channel, and then a subsequent calibration was conducted to define roughness within the floodplain. Calibration was performed by varying roughness in model simulations to determine the best match to measured water surface elevations. The goal of the model calibration was to predict water surface elevations with a root mean squared error (RMSE) of less than 0.5 ft.

6.1 Reach 1A_01 Model

Roughness values in the channel can be most directly calibrated at low-to-moderate flows since the majority of the discharge is conveyed within the channel. Flows used to calibrate the in-channel portion of Reach 1A from Friant Dam to HW41 include 350 cfs, 700 cfs, and 1200 cfs. Combinations of roughness values used for in-channel calibration are given in Table 3. The riffles controlling water surface elevations are not adequately represented with a single in-channel roughness value. Therefore, an additional channel roughness zone was introduced to represent riffles and other features (e.g., the Lost Lake weirs) upstream of MP 257.6. Riffles downstream of this section appear to be adequately represented with a single channel roughness and may not be as influential in raising water surface as upstream riffles.

Three large drops in the water surface elevation caused by the two Lost Lake weirs and the concrete rubble adjacent to the Friant Rd Bridge (Road 206) were not resolved in the terrain. To better simulate measured water surface elevation upstream of the Lost Lake weirs, mesh cell elevations in the vicinity of the weirs and concrete rubble were increased based on the difference between simulated and measured water surface elevation at 350 cfs.

Water surface profiles from calibration simulations of 350 cfs, 700 cfs, and 1200 cfs for various combinations of roughness values (Table 3) are illustrated in Figure 7 to Figure 9. The roughness value combinations were based upon professional judgment and varied through the calibration process. Variation in roughness values resulted in differences in simulated water surface elevation of less than 0.5 ft (Figure 12) between the lowest roughness values (0.035 channel bed and 0.065 riffles and rough areas) and the highest roughness values (0.045 channel and 0.080 riffles and rough areas). Simulated water surface was typically within 1 ft of measured water surface for all in-channel discharges. Based upon all the simulations between 350 cfs and 1200 cfs, roughness values of 0.040 for the channel bed and 0.065 for the riffles and rough in-channel areas produced the best overall water surface elevation agreement (RMSE < 0.5 ft). Figure 7 through Figure 9 show the computed differences between measured and simulated water surface elevations with the roughness combination of 0.04 for the channel bed and 0.065 for the riffles and rough in-channel areas.

During the 1200 cfs data collection effort, water surface elevations were collected such that they had the greatest spatial frequency across riffles. Two examples illustrating localized differences in measured and simulated water surfaces along riffles are shown in Figure 10 and Figure 11. At MP 260.7 (Figure 10), the model simulation underpredicts measured water surface elevation across the crest of the riffle, while at MP 263.3 (Figure 11), the model simulation slightly overpredicts water surface elevation at the riffle crest.

Table 3. Roughness combinations used for in-channel model calibration.

Land Use	DWR (2010)	In-Channel Calibration Combinations					
Channel Bed/Open Water	0.035	0.035	0.035	0.04	0.04	0.045	0.045
In-channel Riffles/Rough areas	NA	0.065	0.08	0.065	0.08	0.065	0.08

Two locations where the model prediction is poor are at approximately 13,500 feet and 17,500 feet upstream from HW 41 (MP 257.7 and MP 258.5, respectively). At MP 257.7, a gravel mining operation appears to use artificial blocks to create a backwater condition (Figure 13). At this location, the current terrain model does not incorporate the artificial elements and does a poor job in defining the mid-channel bar that is also located here, resulting in under prediction of water surface. At MP 258.5, there was a low water crossing in 1998 (when ground surveys were conducted) that is no longer present. Remnants of the presence of this feature in the terrain model are likely responsible for model over predicting water surface elevation at this location. Other locations where simulated and measured values are different are typically due to poor representation of a channel feature in the mesh or surface, such as a side channel.

For in-channel flows, the model results and sensitivity plots illustrate that the greatest differences in simulated and measured water surface elevations tend to occur at the riffle crests, which are also the locations of the least sensitivity to roughness changes. The mesh does not capture the elevations of the tops of the riffles due to the cell length of 20-30 feet, resulting in a lower elevation than truly exists. For most riffles, roughness was increased in part to account for this topographic difference. However, because flow is supercritical through most of the riffles, the sensitivity to variation in roughness at these locations is minimal. The greatest sensitivities to roughness tend to occur at the riffle tails and within pools.

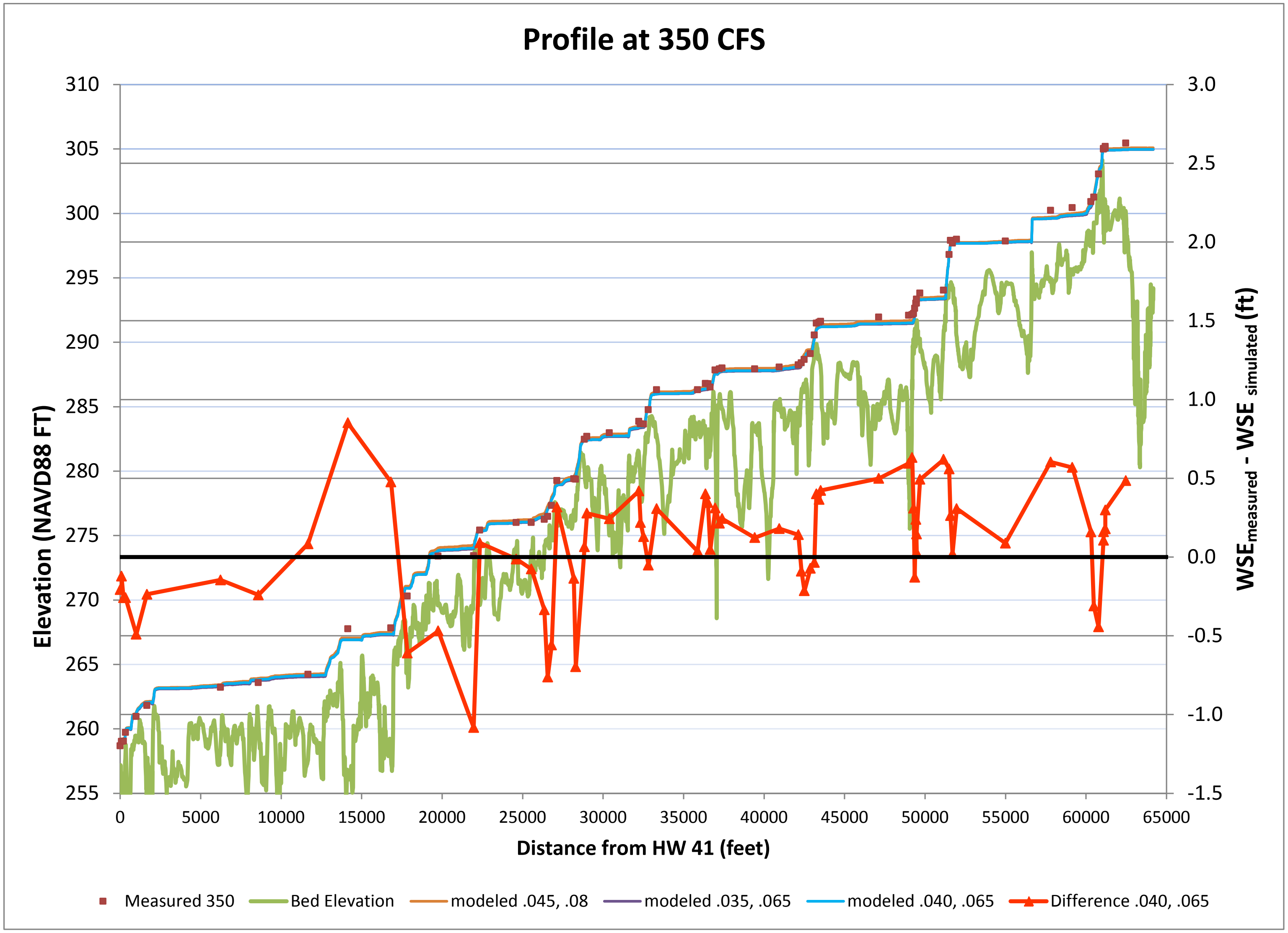

Figure 7. Comparison of measured versus simulated water surface elevation at 350 cfs along the Reach 1A_01 channel centerline. The secondary axis shows the difference in the measured and simulated (roughness values of .04 and .065) water surface elevation (ft). See Figure 12 for model sensitivity to roughness variation.

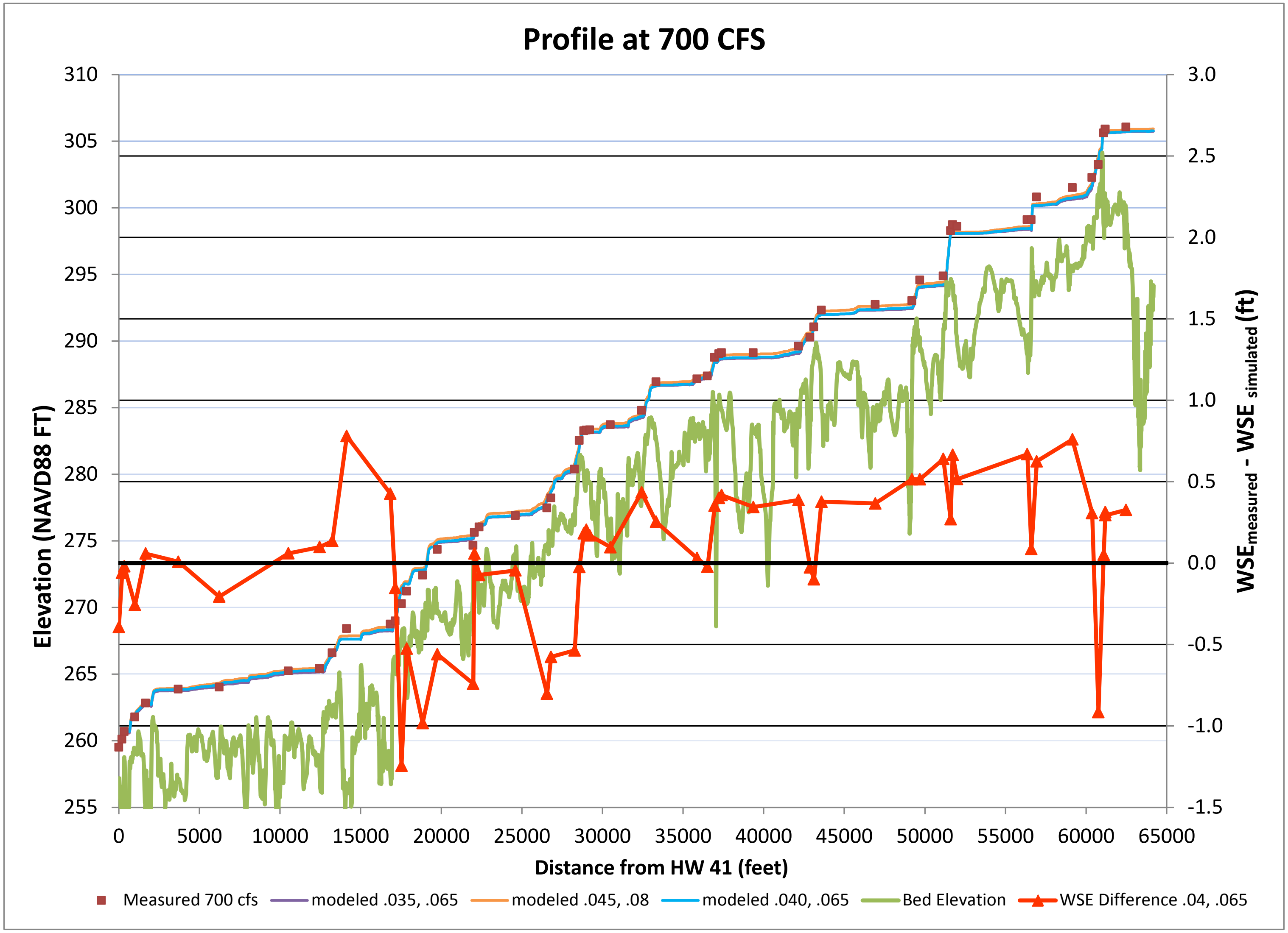

Figure 8. Comparison of measured versus simulated water surface elevation at 700 cfs along the Reach 1A_01 channel centerline. The secondary axis shows the difference in the measured and simulated (roughness values of .04 and .065) water surface elevation (ft). See Figure 12 for model sensitivity to roughness variation.

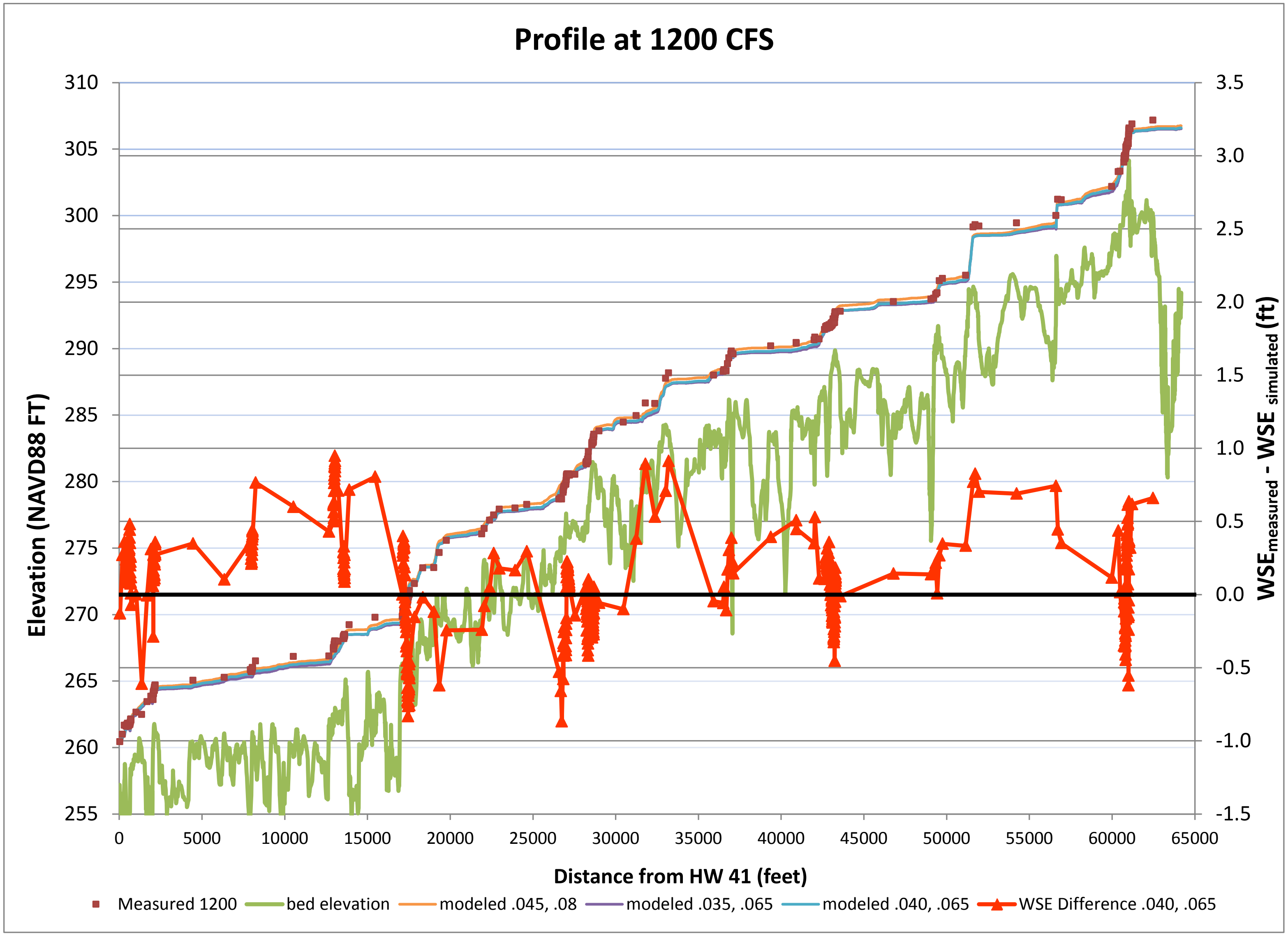

Figure 9. Comparison of measured versus simulated water surface elevation at 1200 cfs along the Reach 1A_01 channel centerline. Secondary axis shows the difference in the measured and simulated (roughness values of 0.04 and 0.065) water surface elevation (ft). See Figure 12 for model sensitivity to roughness variation.

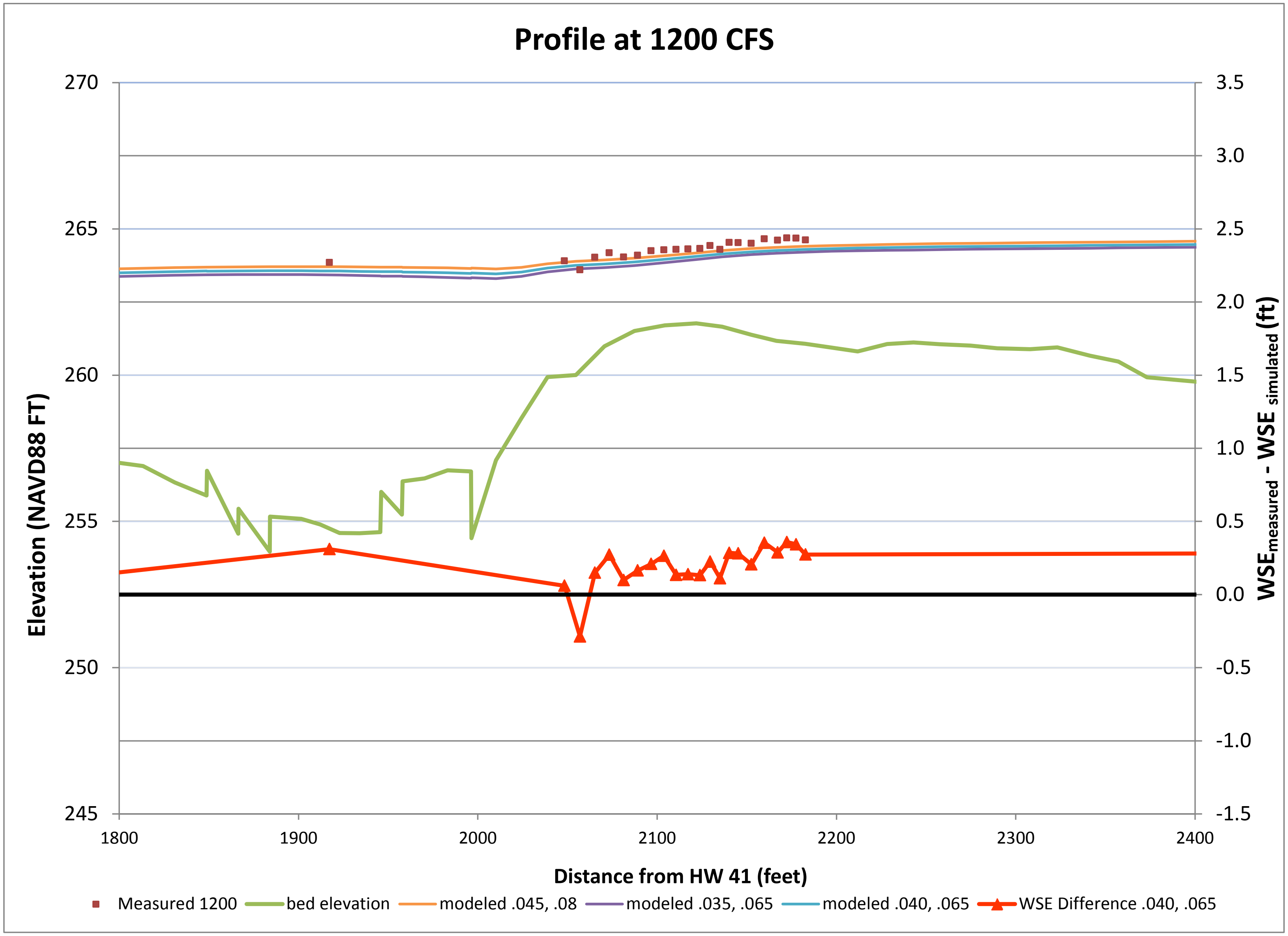

Figure 10. Comparison of measured versus simulated water surface elevation at 1200 cfs along a riffle near MP 260.7. Secondary axis shows the difference in the measured and simulated (roughness values of 0.04 and 0.065) water surface elevation (ft).

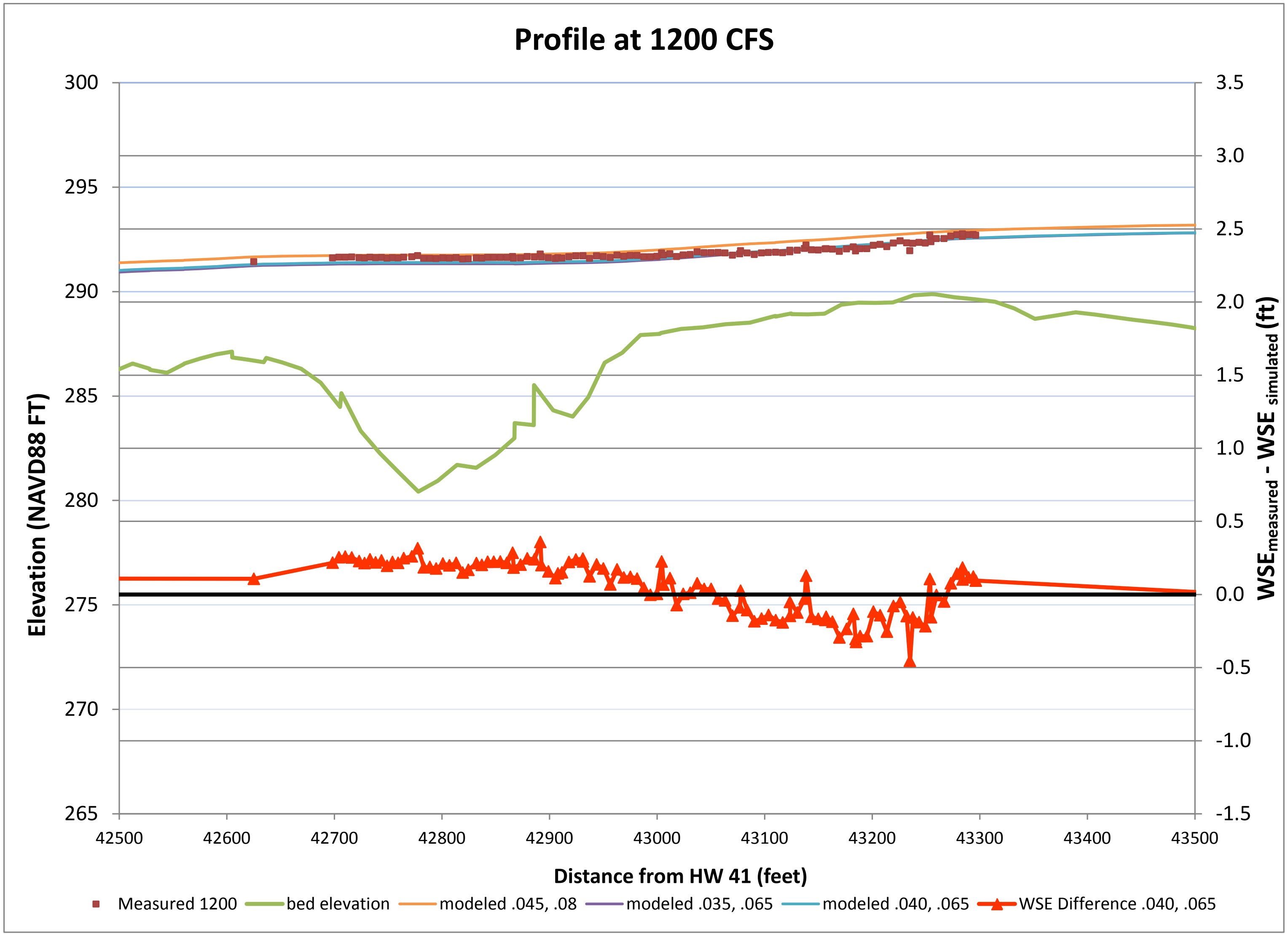

Figure 11. Comparison of measured versus simulated water surface elevation at 1200 cfs along a riffle near MP 263.3. Secondary axis shows the difference in the measured and simulated (roughness values of 0.04 and 0.065) water surface elevation (ft).

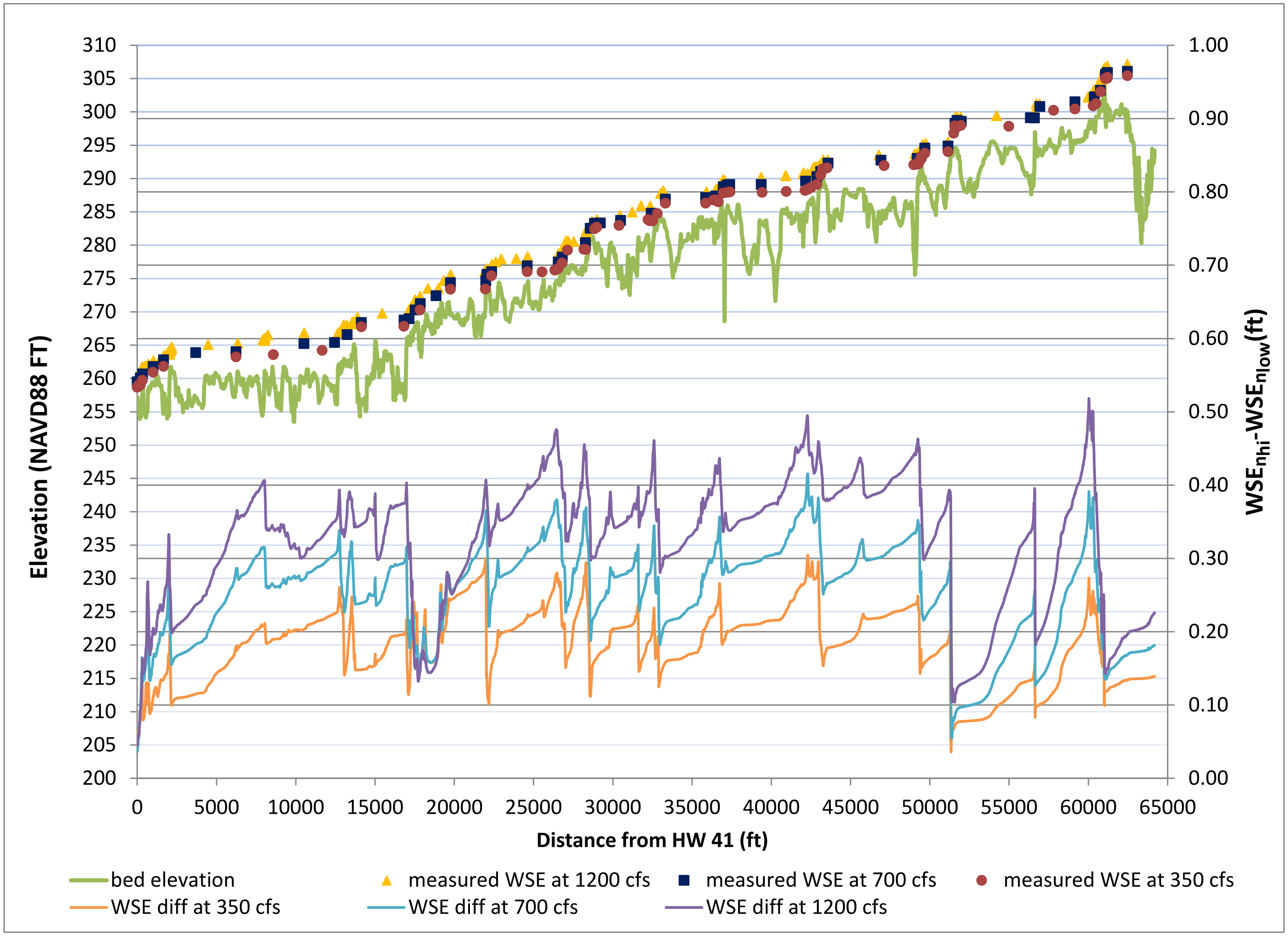

Figure 12. Influence of variation in roughness on predicted water surface elevation along Reach 1A_01 channel centerline for the in-channel calibration. Primary axis illustrates measured water surface and bed elevation. Secondary axis illustrates the difference in water surface elevation using the high roughness combination (n_{hi} = 0.045, 0.08) and the low roughness combination (n_{low} = 0.035, 0.065).

Figure 13. 2007 aerial photo of the location 13,500 feet upstream from HW41, where artificial features are used to create a backwater condition for a gravel mining operation. The topography and mesh do not represent the artificial features or the mid-channel bar well.

6.2 Reach 1A_02 Model

In-channel roughness calibration for the Reach 1A_02 model (HW41 to HW99) was performed analogously to the Reach 1A_01 model. The calibration flows of 270 cfs, 700 cfs, and 1150 cfs are the estimated discharges at the time water surface elevation was measured in October 2009, November 2009, and April 2010, respectively. Combinations of roughness values used to calibrate the model to measured water surface elevation are shown in Table 4. Similar to the Reach 1A_01 model, modifications to the in-channel roughness zones at riffles and rough areas (e.g., log jams or vegetation encroachment) were necessary to capture notable drops and rises in the water surface across these features.

Table 4. Combinations of roughness values used for in-channel calibration of the Reach 1A_02 model.

Land Use	DWR (2010)	In-Channel Calibration Combinations		
Main Channel Bed	0.035	0.035	0.04	0.045
In-channel Riffles/Rough areas	NA	0.065	0.065	0.08

Comparisons of measured and simulated water surface elevations for the calibration flows are illustrated in Figure 14 to Figure 16. Simulated water surface elevation is generally within 1 ft of measured water surface elevation for all combinations of flow and roughness values. The sensitivity of the model to variation in channel roughness is visible in Figure 17. In general, the greatest sensitivity occurs at riffle tail and pools, which also tend to be the locations where water surface elevation prediction is best. Differences in the predicted water surface elevations between the highest roughness combination (0.045 channel and 0.08 riffle) and the lowest roughness combination (0.035 channel and 0.065 riffle) are less than 0.5 feet. The calibrated roughness values for the in-channel and rough areas were selected as 0.040 and 0.065, respectively. Differences between the simulated and measured results at these discharges could be related to differences in simulated and actual discharges. Based on Table 1, flows do not appear to have been steady, particularly at the lowest measured discharge in October 2009. River flow interactions with the gravel pits likely contribute to variations in the measured flows and make calibration efforts at low flow challenging.

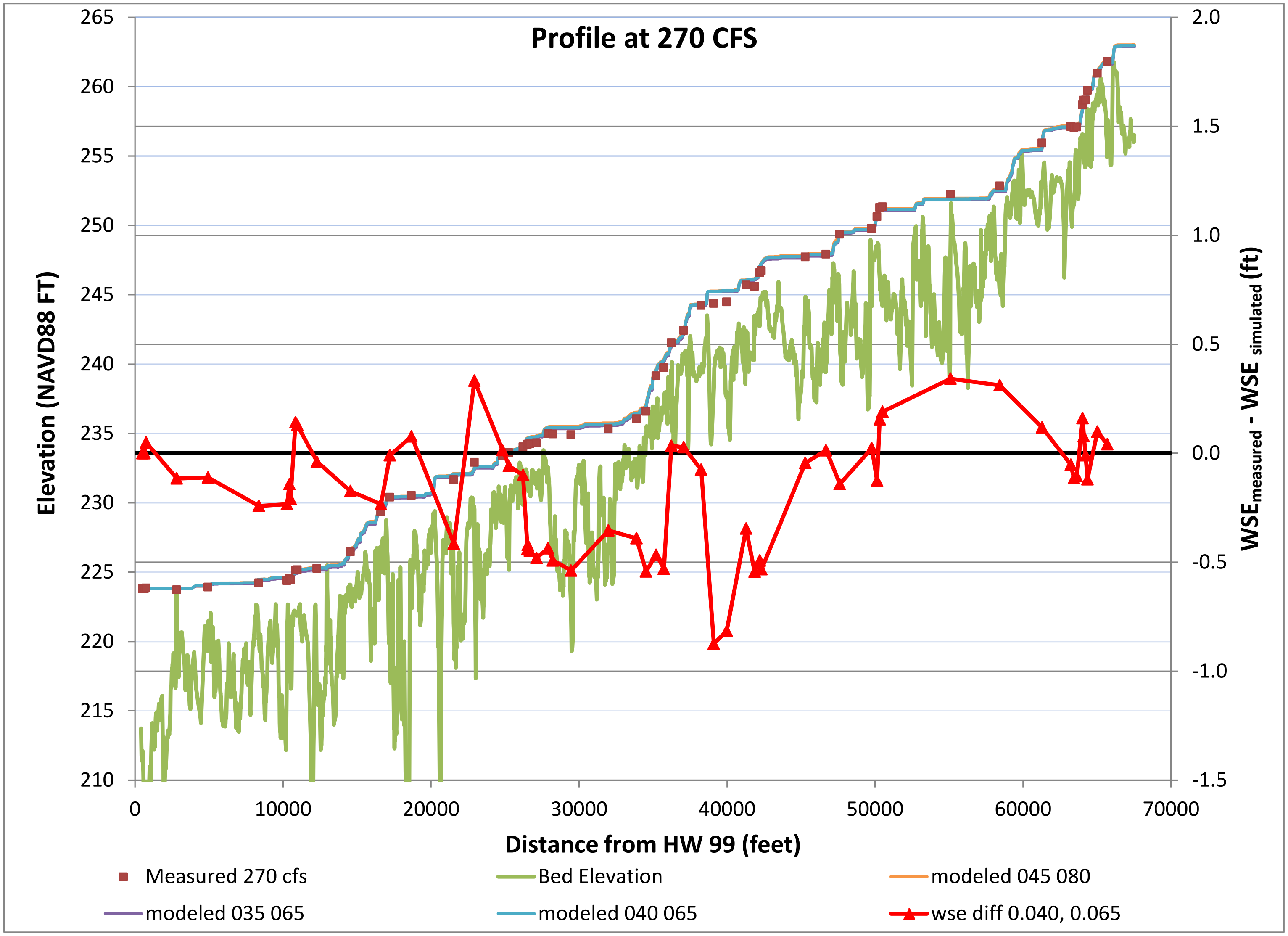

Figure 14. Comparison of measured versus simulated water surface elevation at 270 cfs along the Reach 1A_02 channel centerline. The secondary axis shows the difference in the measured and simulated (roughness values of .04 and .065) water surface elevation (ft). See Figure 17 for model sensitivity to roughness variation.

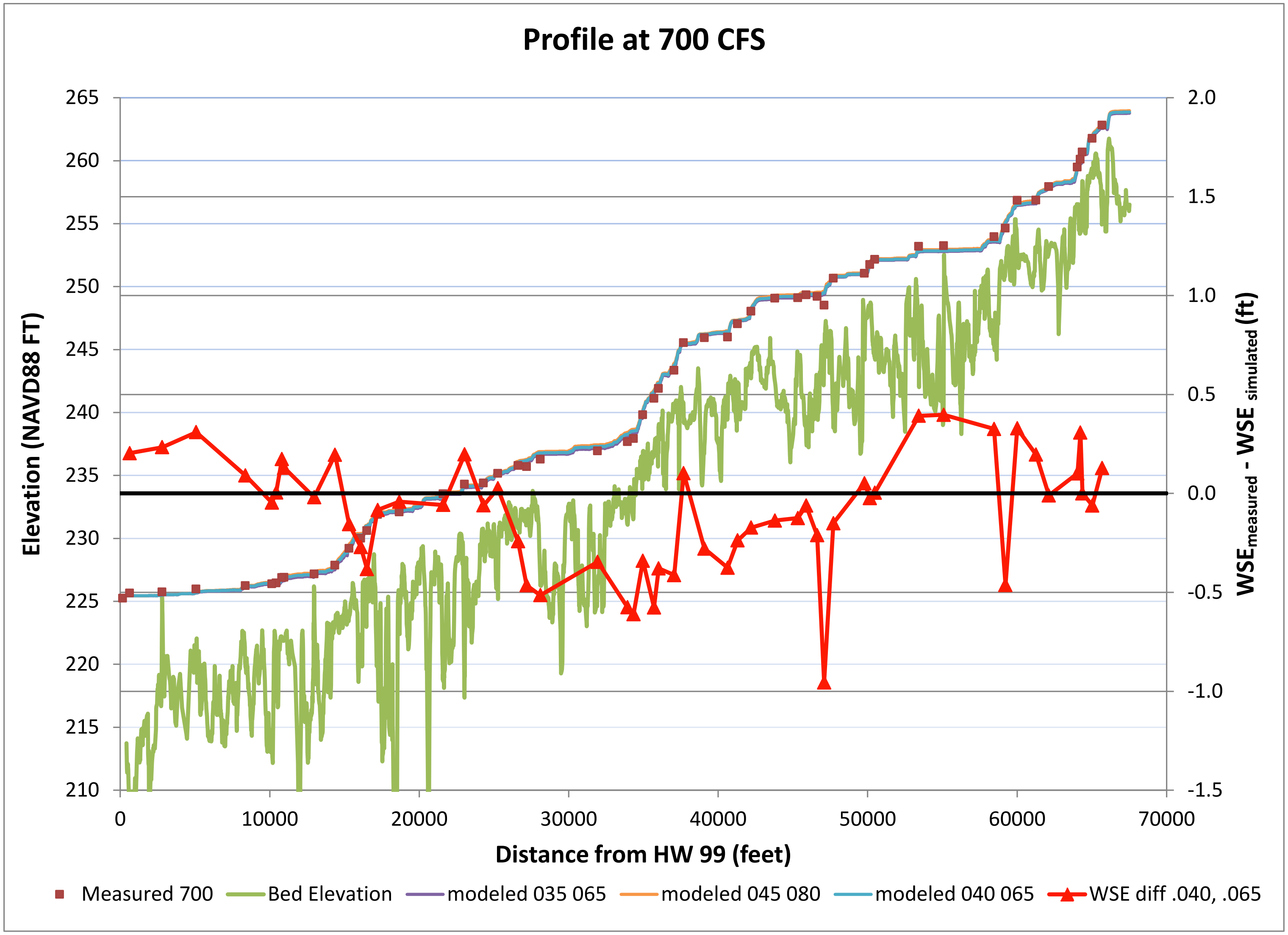

Figure 15. Comparison of measured versus simulated water surface elevation at 700 cfs along the Reach 1A_02 channel centerline. The secondary axis shows the difference in the measured and simulated (roughness values of .04 and .065) water surface elevation (ft). See Figure 17 for model sensitivity to roughness variation.

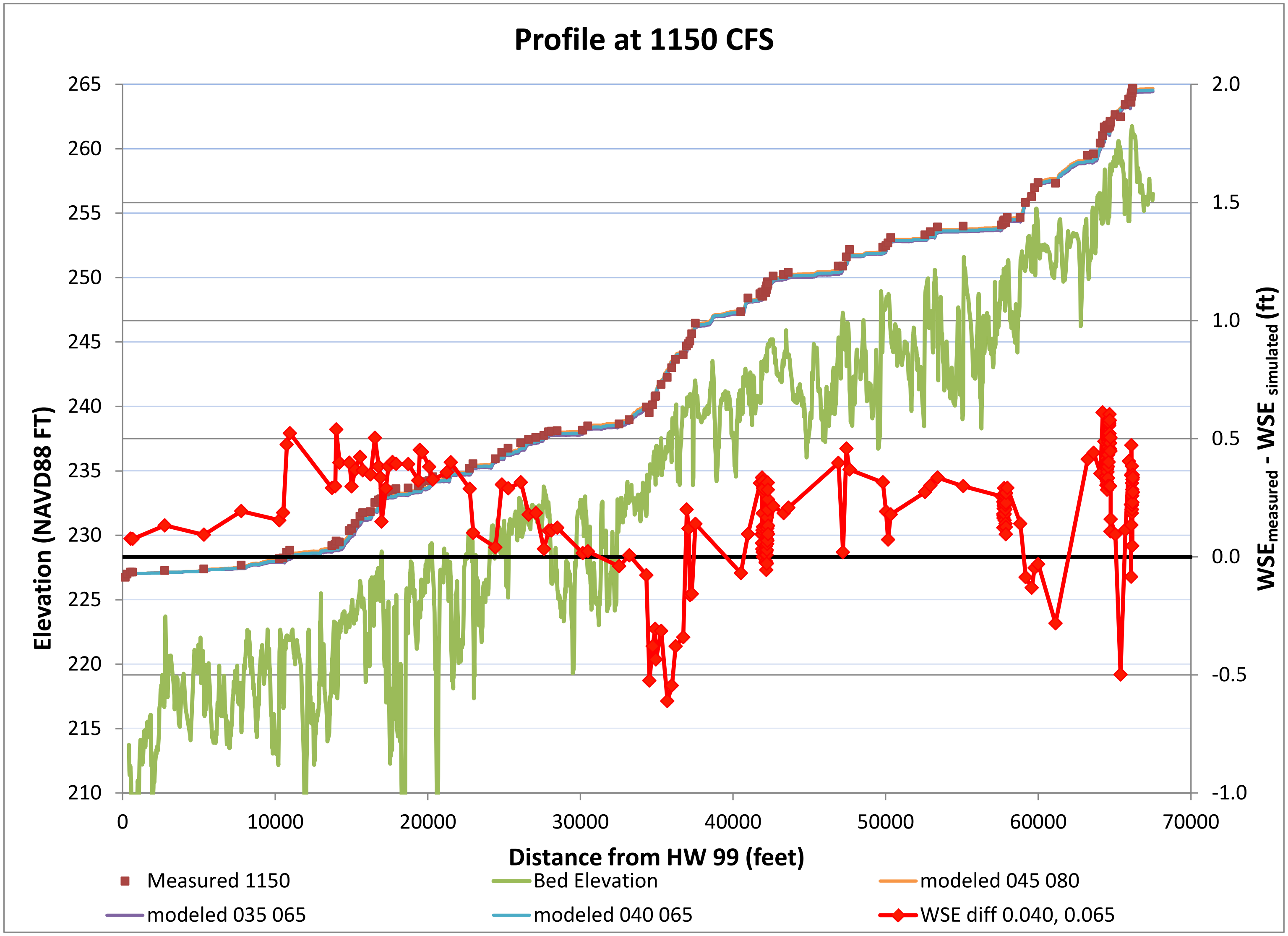

Figure 16. Comparison of measured versus simulated water surface elevation at 1150 cfs along the Reach 1A_02 channel centerline. The secondary axis shows the difference in the measured and simulated (roughness values of .04 and .065) water surface elevation (ft). See Figure 17for model sensitivity to roughness variation.

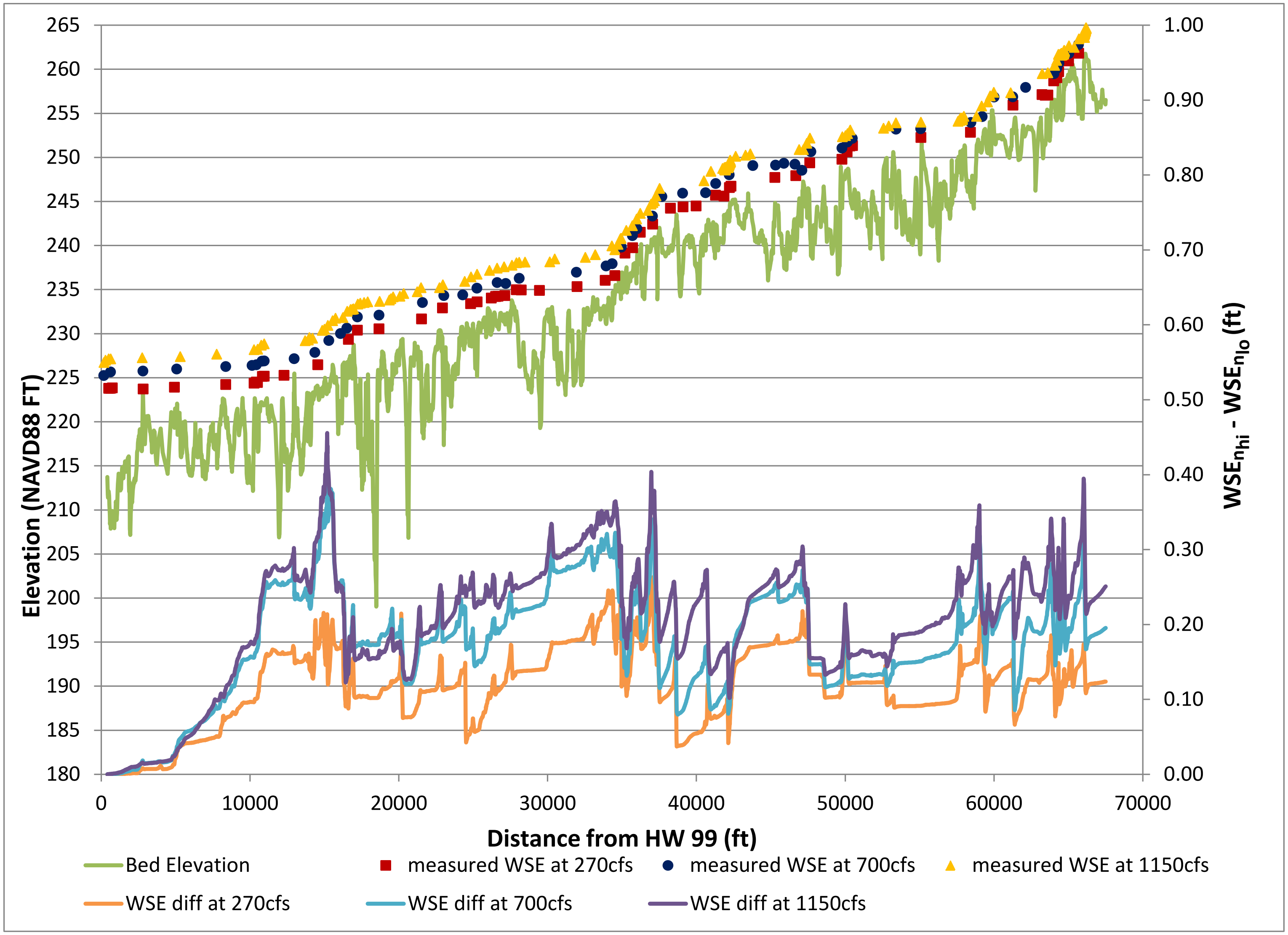

Figure 17. Influence of variation in roughness on predicted water surface elevation along Reach 1A_02 channel centerline for the in-channel calibration. Primary axis illustrates measured water surface and bed elevation. Secondary axis illustrates the difference in water surface elevation using the high roughness combination (n_{hi} = .045, .08) and the low roughness combination (n_{low} = .035, .065).

7 Floodplain Calibration

7.1 Reach 1A_01

Calibration of the roughness values in the floodplain (outside the channel) was accomplished using simulated discharges of 4,500 cfs and 7,650 cfs. The combinations of roughness values used for calibration are illustrated in Table 5. In order to isolate the influence of floodplain roughness on water surface elevation, the in-channel roughness values were held at 0.040 for the main channel bed and 0.065 for riffles and in-channel rough areas. Profiles of simulated water surface elevation for varying roughness values compared to measured water surface elevations are illustrated in Figure 18 and Figure 19. Although there is some variation through the reach, simulated water surface elevation is generally insensitive to variation in floodplain roughness values (Figure 20). Differences in simulated water surface elevations using the “High *n*” and “Low *n*” floodplain roughness combinations (Table 5) were less than 0.5 feet. The “Middle *n*” roughness values produced water surface elevations that were within about 0.5 ft of the measured water surface elevation for 4500 cfs and within 1 ft of the measured water surface elevation for 7650 cfs.

Table 5. Roughness values used in floodplain calibration for the Reach 1A_01 model. The “Middle *n*” values were taken as the calibrated roughness values.

		Floodplain Calibration Combinations		
Land Use	**DWR (2010)**	**Low *n***	**Middle *n***	**High *n***
Open /Bare Ground/ Scattered Brush	0.045	0.035	0.045	0.055
Scattered Trees	0.06	0.05	0.06	0.07
Medium Density Trees/Brush	0.08	0.07	0.08	0.09
Dense Trees/ Brush	0.1	0.09	0.1	0.11
Agriculture	0.045	0.035	0.045	0.055

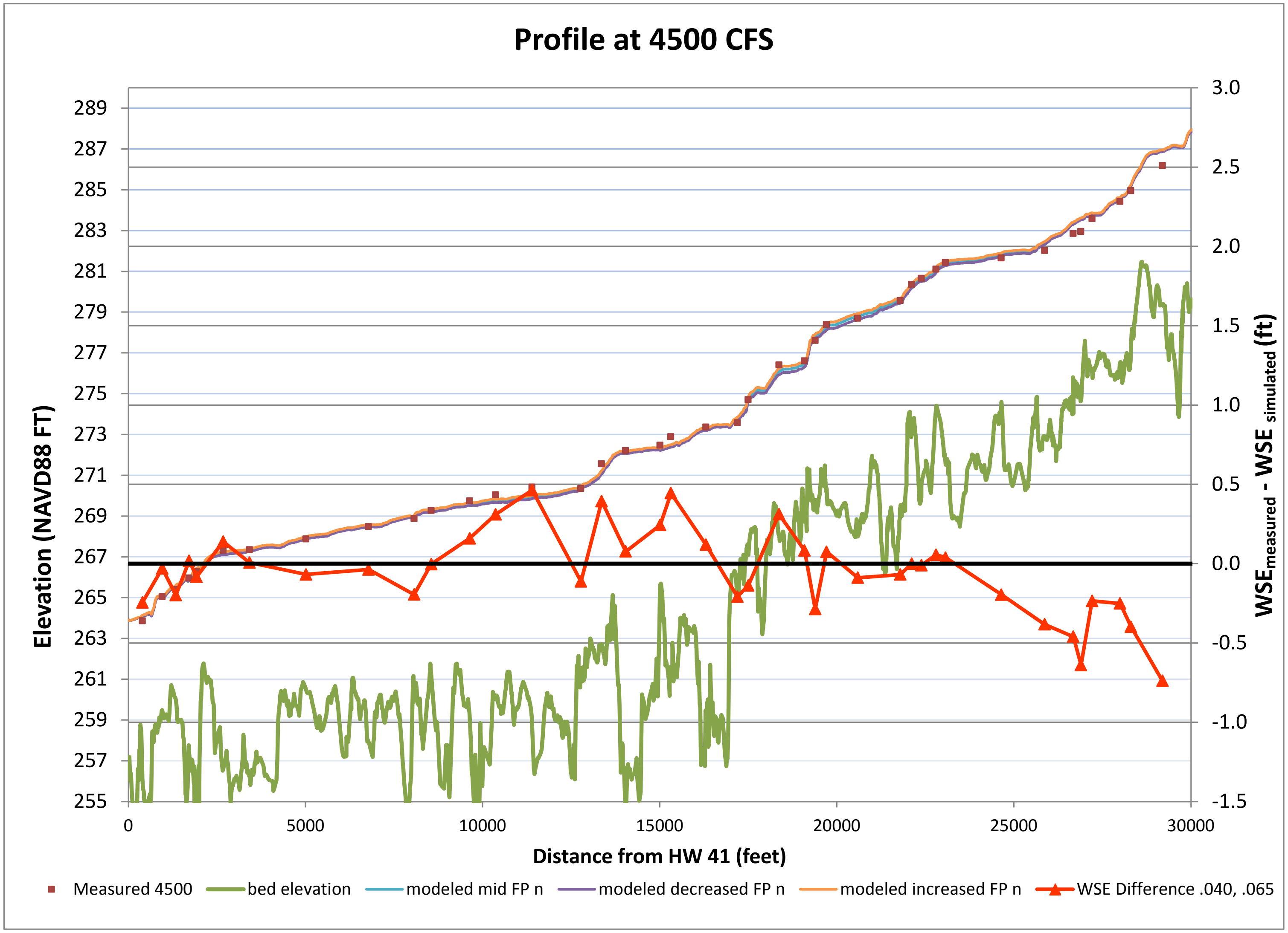

Figure 18. Comparison of measured versus simulated water surface elevation at 4500 cfs along the channel centerline in Reach 1A_01. Secondary axis shows the difference in measured and simulated (roughness values of .04 and .065) water surface elevation (ft). See Figure 20 for model sensitivity to roughness variation.

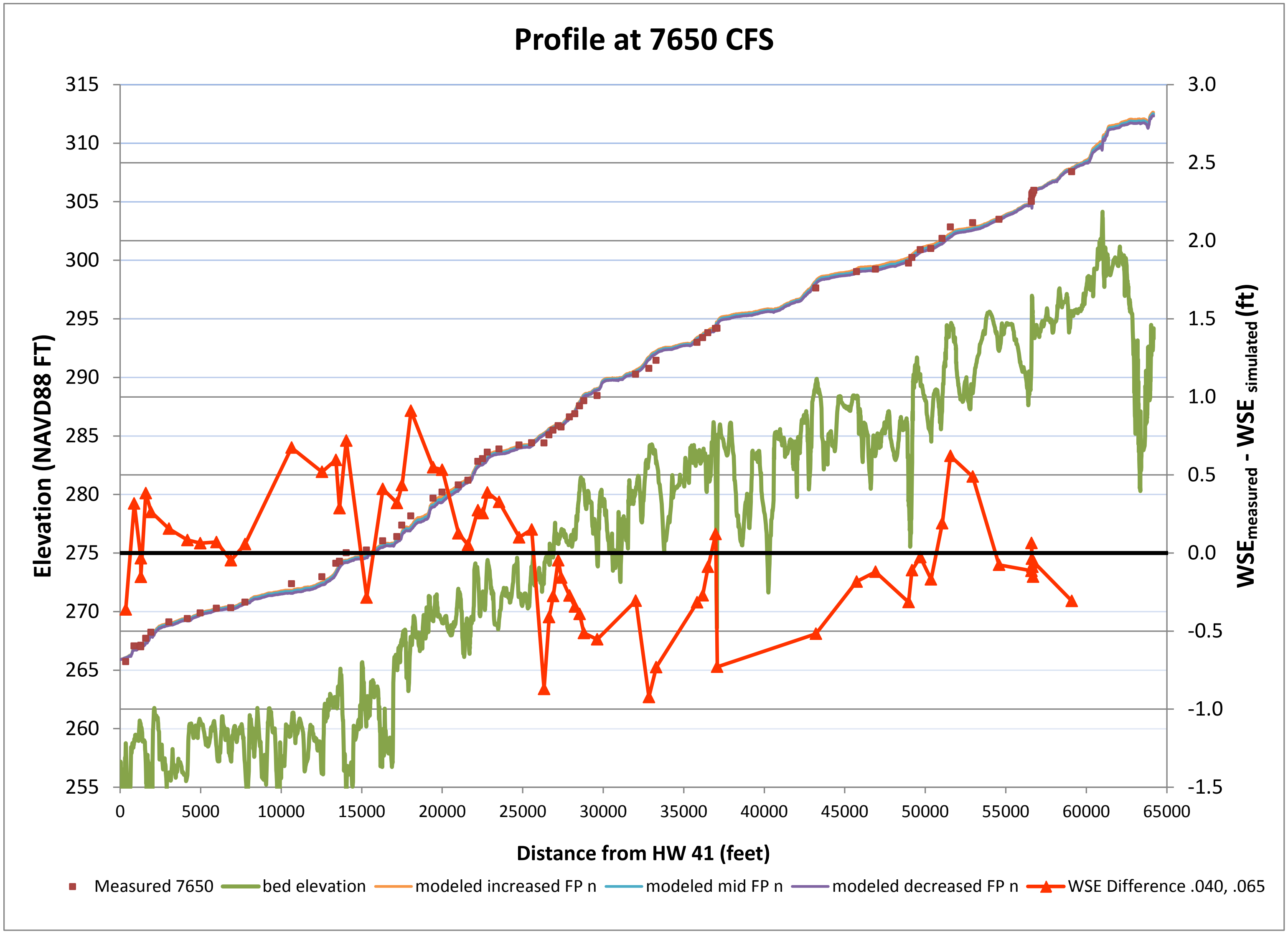

Figure 19. Comparison of measured versus simulated water surface elevation at 4500 cfs along the channel centerline in Reach 1A_01. Secondary axis shows the difference in measured and simulated (roughness values of .04 and .065) water surface elevation (ft). See Figure 20 for model sensitivity to roughness variation.

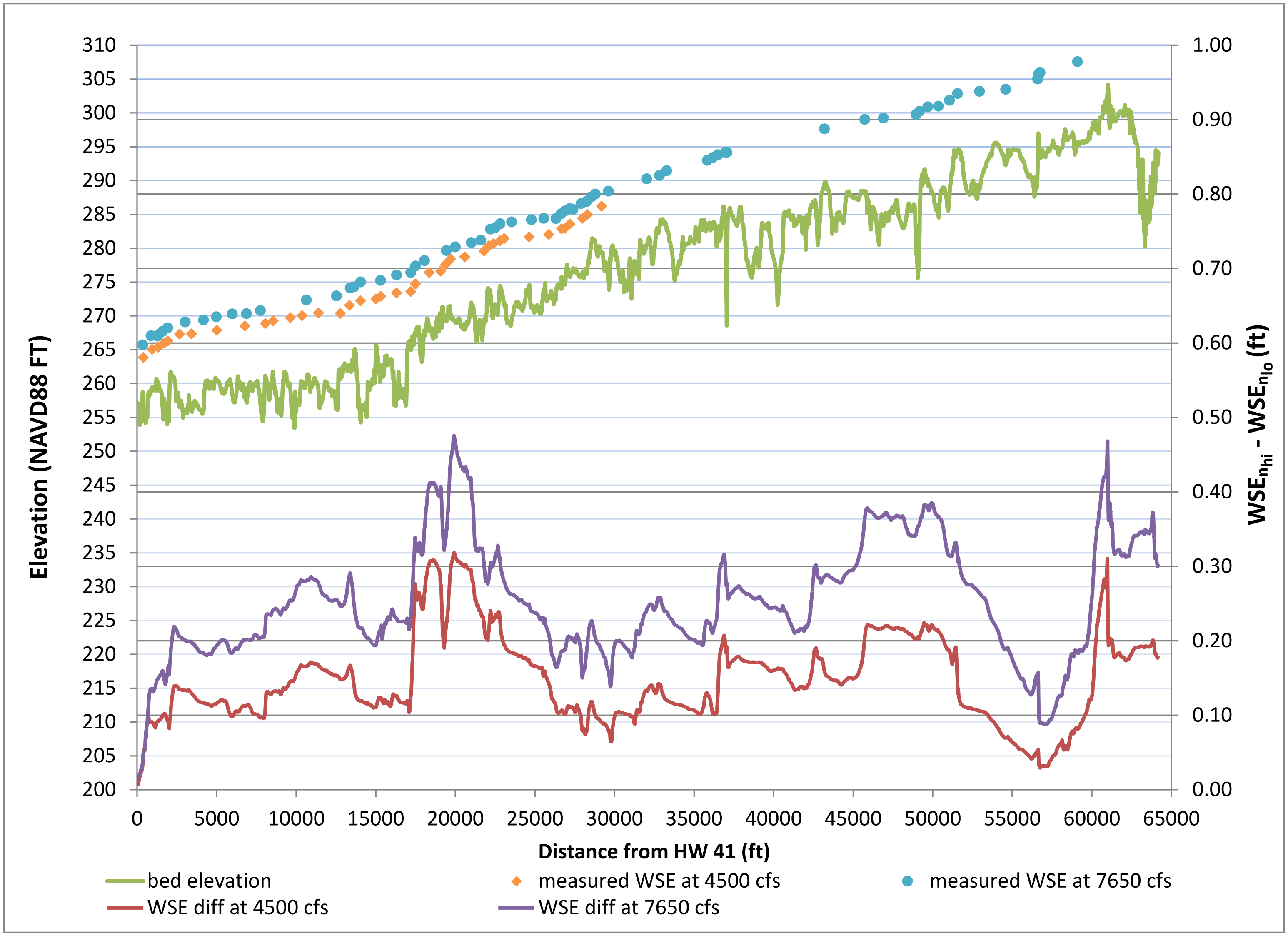

Figure 20. Influence of variation in roughness on predicted water surface elevation along Reach 1A_01 channel centerline for floodplain calibration. Primary axis illustrates measured water surface and bed elevation. Secondary axis illustrates the difference in water surface elevation using the high roughness combination (n_{hi} = high FP n) and the low roughness combination (n_{low} = low FP n).

7.2 Reach 1A_02

Calibrating floodplain roughness values for the Reach 1A_02 model was complicated by the following reach characteristics: (A) presence of large off-line gravel pits that become inundated at higher discharges, (B) fluctuations in measured and gaged discharges, and (C) side-channel and floodplain complexity. In order to improve the water surface elevation calibration, mesh land use zones were iteratively refined to better resolve high roughness features and low roughness areas. For example, stands of dense trees may be located within larger areas defined in the model as sparse, thus requiring improved resolution of features in order to capture the relevant hydraulics. In the vicinity of Milburn Pond, the mesh was refined to better capture the entrance conditions to the off-line gravel pit and the flow path through an adjacent side channel.

Discharges used in calibrating the floodplain roughness in the Reach 1A_02 model included 4500 cfs (May 2011) and 7650 cfs (March 2011). The combinations of roughness values used for calibration are illustrated in Table 6.

In order to isolate the influence of floodplain roughness on water surface elevation, the in-channel roughness values were held at 0.040 for in-channel and 0.065 for in-channel rough areas, respectively. Roughness values for agricultural areas (two small regions along model boundary) and off-channel wetted areas (side channels and gravel pits) were held at 0.055 and 0.045, respectively.

Profiles of simulated water surface elevation for varying roughness values compared to measured water surface elevations are illustrated in Figure 21 and Figure 22. An increase in floodplain roughness of approximately 50% above the baseline values was required to adequately match simulated and measured water surface elevations at flows above 4500 cfs. Figure 23 illustrates the sensitivity of the model to variation in floodplain roughness. The model is fairly sensitive to variation in floodplain roughness values, particularly in the middle third of the reach (MP 246 to MP252) where differences in the predicted water surface are greater than 1 foot between simulations using the baseline floodplain combination and increased 50% combination at a discharge of 7650 cfs.

Table 6. Roughness values used in floodplain calibration simulations for the Reach 1A_02 model.

		Floodplain Calibration Combinations		
Land Use Types	**DWR (2010)**	**Baseline**	**increased 25%**	**increased 50%**
Off-Channel Open Water	0.045	0.045	0.045	0.045
Open /Bare Ground/ Scattered Brush	0.045	0.045	0.056	0.068
Scattered Trees	0.06	0.06	0.075	0.090
Medium Density Trees/Brush	0.08	0.08	0.100	0.120
Dense Trees/ Brush	0.1	0.1	0.125	0.150
Agriculture	0.045	0.055	0.055	0.055

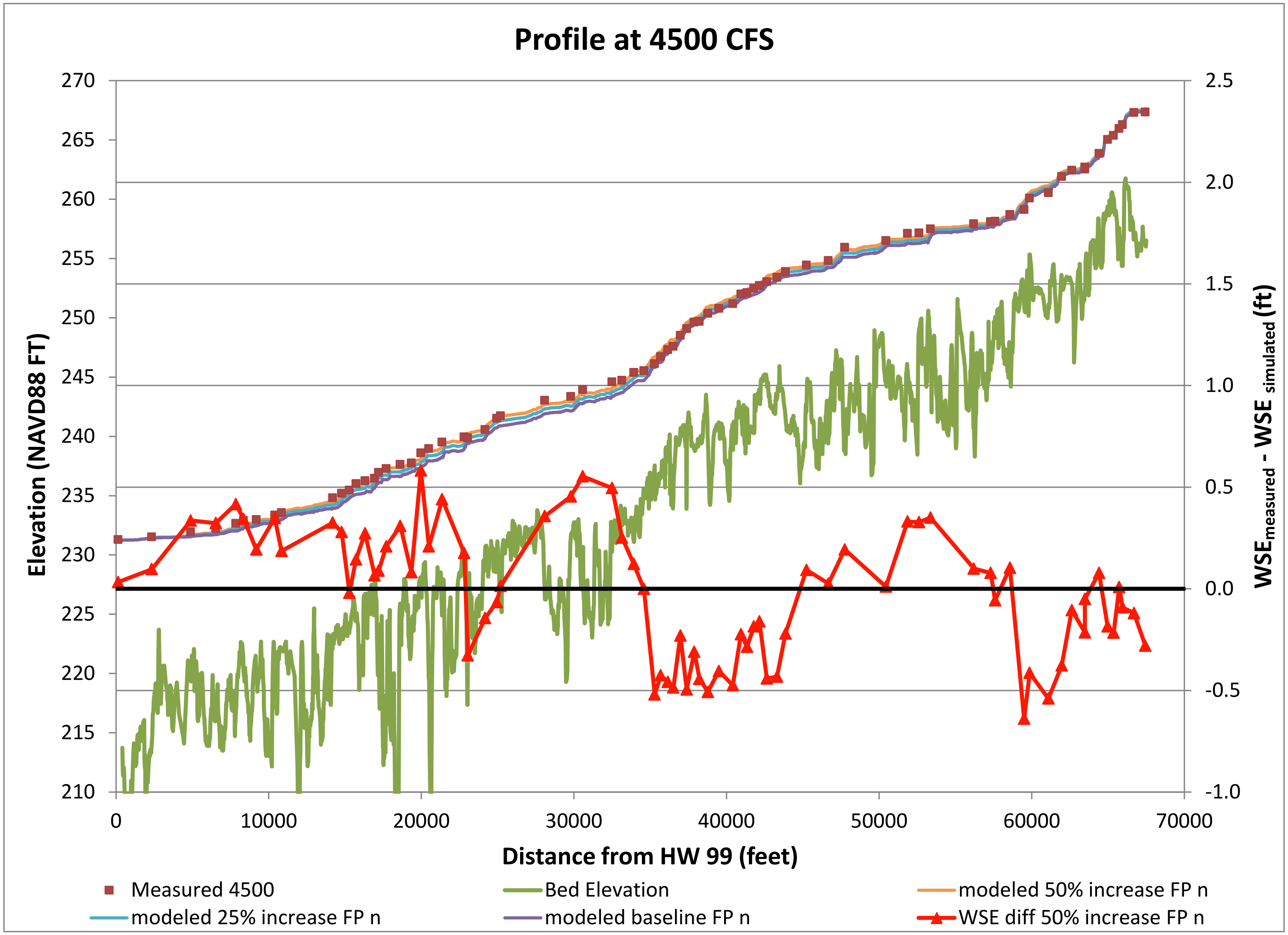

Figure 21. Comparison of measured versus simulated water surface elevation at 4500 cfs along the channel centerline in Reach 1A_02. Secondary axis shows the difference in measured and simulated water surface elevation (ft) for roughness values increase 50% above baseline values. See Figure 23 for model sensitivity to roughness variation.

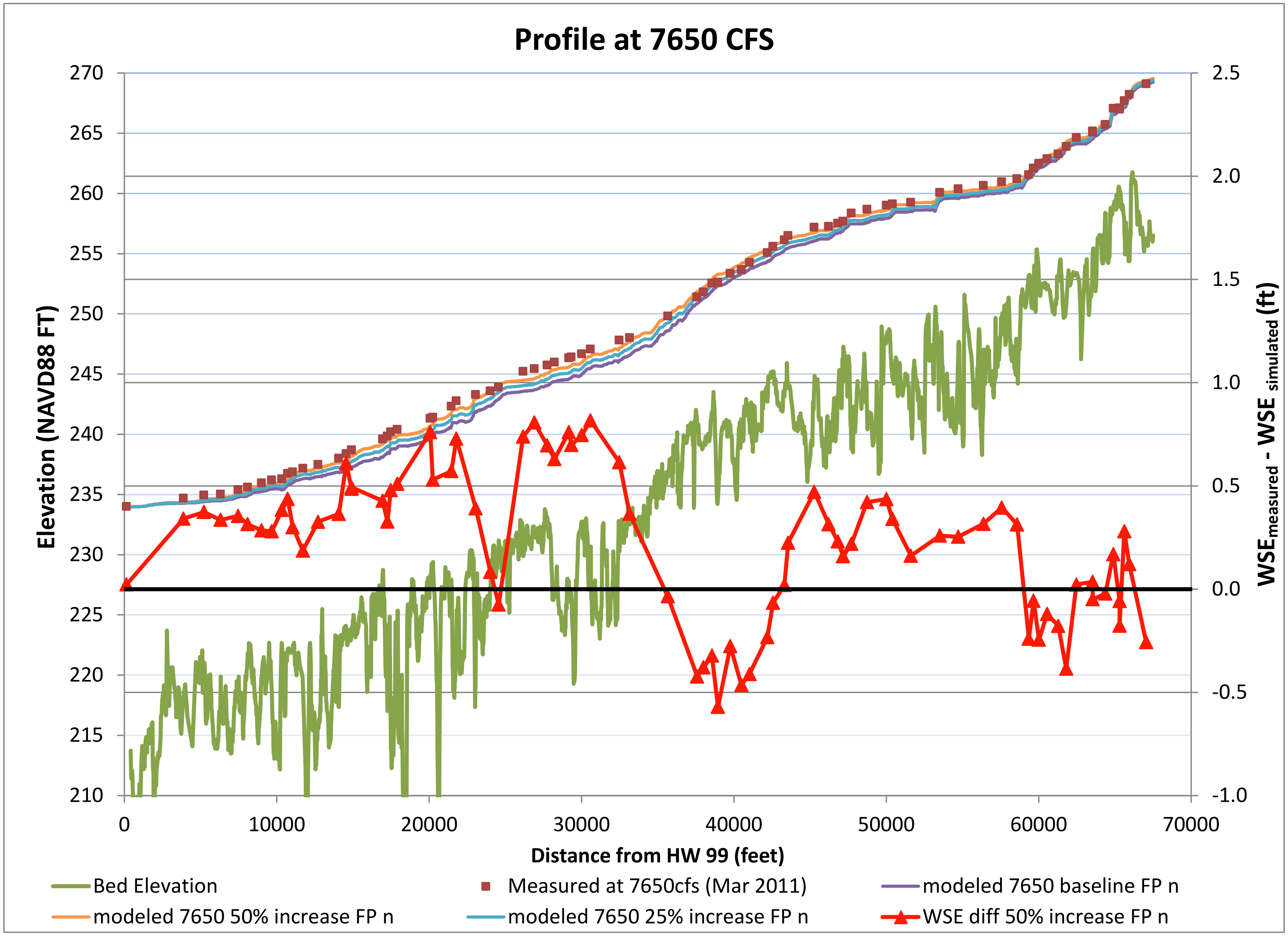

Figure 22. Comparison of measured versus simulated water surface elevation at 7650 cfs along the channel centerline in Reach 1A_02. Secondary axis shows the difference in measured and simulated water surface elevation (ft) for roughness values increased 50% above baseline values. See Figure 23 for model sensitivity to roughness variation.

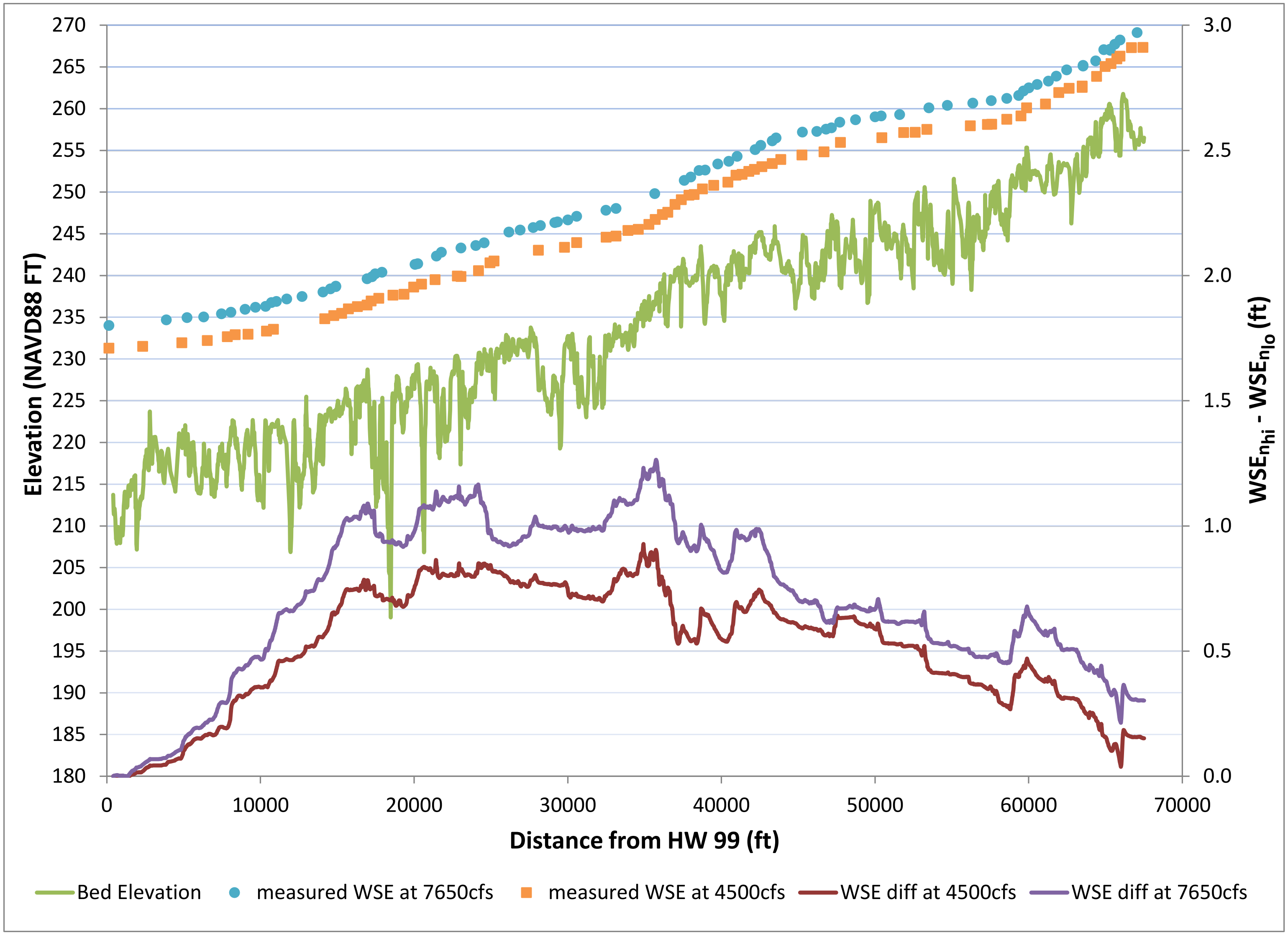

Figure 23. Influence of variation in roughness on predicted water surface elevation along Reach 1A_02 centerline for floodplain calibration. Primary axis illustrates measured water surface and bed elevation. Secondary axis shows the difference in water surface elevation using the high roughness combination (n_{hi} = 50% increase) and the low roughness combination (n_{low} = baseline FP n).

8 Discussion of Results

8.1 Reach 1A_01

Calibrated roughness values for all land use zones in the Reach 1A_01 model are shown in Table 7. To calculate point differences between the measured and simulated water surface elevations, ArcGIS spatial join capabilities were utilized to map simulated points to measured points (60 ft search radius). Statistics on the differences between measured and simulated water surface elevations are shown in Table 8 and Figure 24. The root mean squared error (RMSE) is less than 0.5 feet for all simulated discharges, indicating that the model objectives were met. The histogram in Figure 24 shows that the majority of point differences are between -0.2 and 0.5 feet, demonstrating that the model performs well in predicting measured water surface elevation.

Table 7. Calibrated roughness values for SRH-2D hydraulic simulations using the Reach 1A_01 model between Friant Dam and HW 41.

Land Use	Roughness
Channel Bed/Open Water	0.04
In-channel Riffles/Rough areas	0.065
Open /Bare Ground/ Scattered Brush	0.045
Scattered Trees	0.06
Medium Density Trees/Brush	0.08
Dense Trees/ Brush	0.1
Agriculture	0.045

Table 8. Statistics on point differences between the measured and simulated water surface elevation (ft, NAVD 88) for the Reach 1A_01 model.

Statistic	350 cfs	700 cfs	1200 cfs	4500 cfs	7650 cfs
Mean	0.04	0.06	0.08	-0.06	0.08
Median	0.13	0.06	0.13	-0.03	0.02
Minimum	-1.69	-1.25	-0.87	-1.21	-0.92
Maximum	0.85	1.15	1.07	0.65	1.76
Count	90	74	534	58	120
Standard Deviation	0.43	0.44	0.33	0.35	0.48
Standard Error about the mean	0.05	0.05	0.01	0.05	0.04
RMSE	0.43	0.44	0.34	0.35	0.49

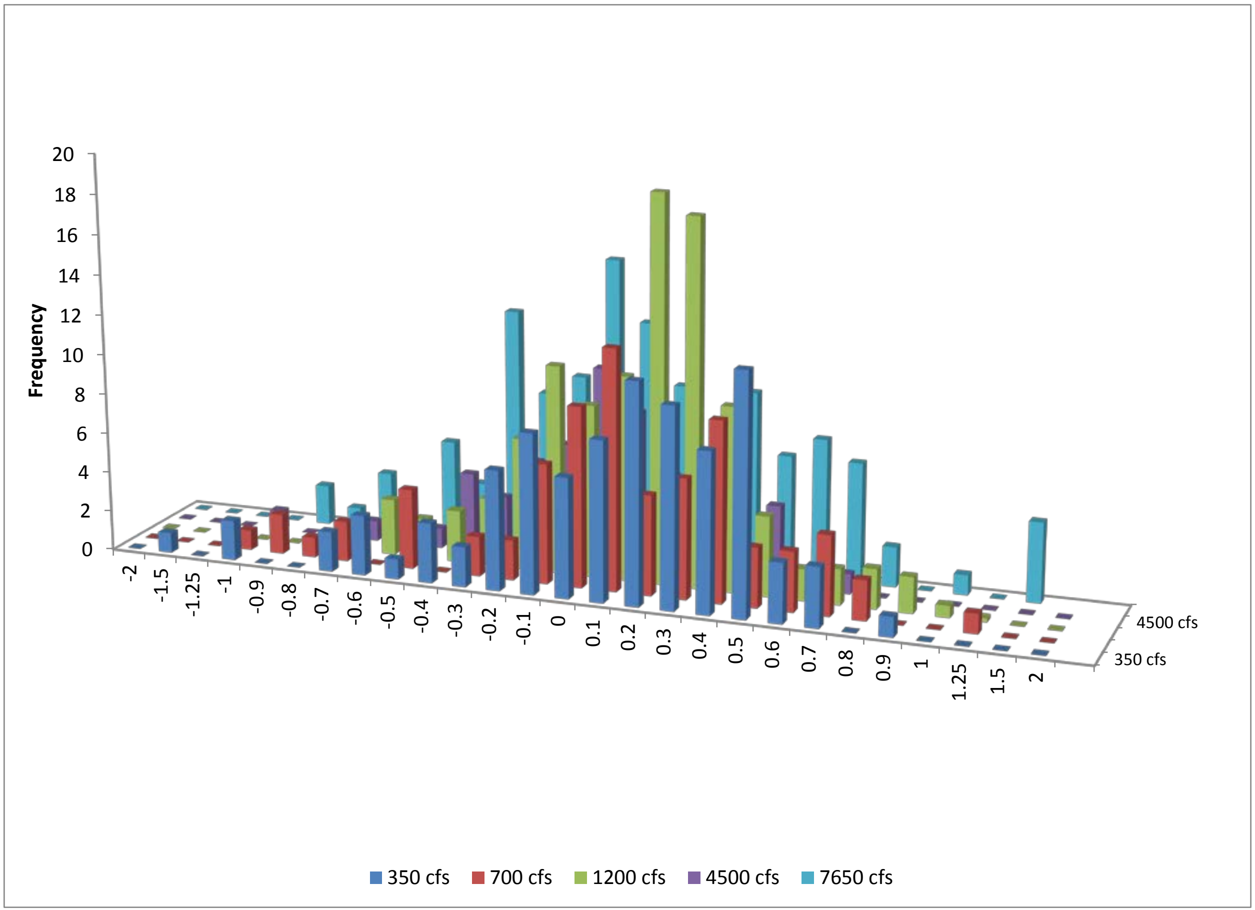

Figure 24. Histogram of point differences between measured and simulated water surface elevations (ft) at each discharge. A negative value indicates that the simulated value was higher than the measured value. Because 1200 cfs had 5 times more measured points than other flows, each frequency value was divided by 5.

Model sensitivity to roughness was examined during both in-channel and floodplain calibration for Reach 1A_01. The indicator used to evaluate sensitivity was the computed difference between the simulated water surface using the highest roughness values and the simulated water surface simulated using lowest roughness values. At discharges of 1200 cfs and lower, model sensitivity to roughness appears to be correlated to topography. Through locations of high topographic relief, such as riffle crests, model sensitivity to roughness is lowest. At low flow, riffle crests act as hydraulic controls where flow is supercritical and roughness has minimal influence on predicted water surface. Sensitivity increases in riffle tails and pools, where topographic relief is generally small. Sensitivity to roughness increases slightly with increasing discharge between 350 cfs and 1200 cfs (Figure 12). The analysis of sensitivity for in-channel calibration flows suggests that the differences in simulated and measured water surface are topographic in nature, and that variations in roughness have a small influence on simulated water surface relative to topography (Figure 25). Model sensitivity to roughness at high flows is not correlated with channel topography, but rather with channel and floodplain complexity. Although model sensitivity to roughness remains small at the floodplain calibration flows (less than 0.5 feet), the areas of greatest sensitivity to roughness are locations of split in-channel flows and floodplain flows, inundated vegetated islands, and inundated floodplains with dense bank vegetation.

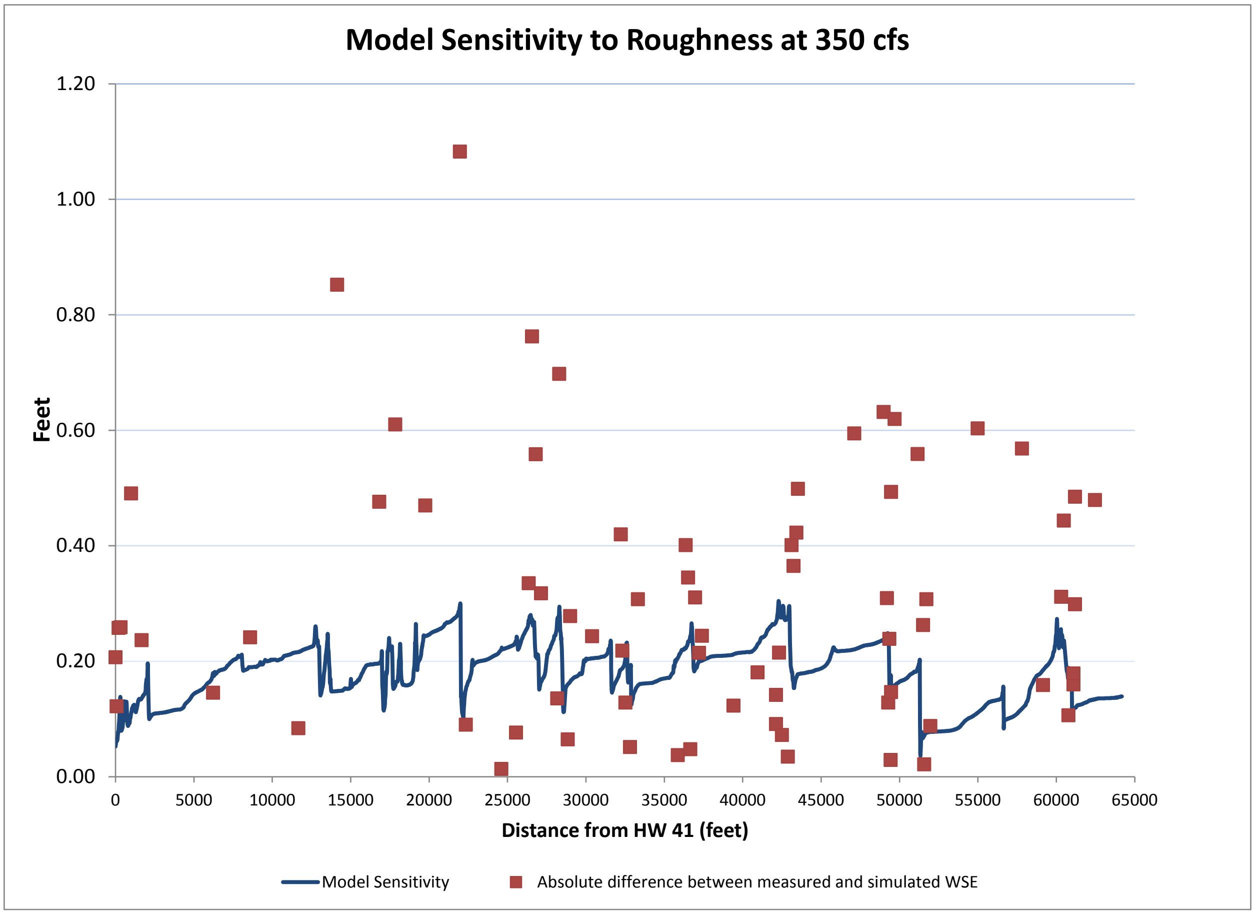

Figure 25. Comparison of model sensitivity to roughness and the absolute difference in measured and simulated water surface. Model sensitivity represents the difference in the simulated water surface using the highest roughness combination and the simulated water surface using the lowest roughness combination.

8.2 Reach 1A_02

Calibrated roughness values for all land use zones in the Reach 1A_02 model are shown in Table 9. Results were processed as described in section 8.1 to summarize statistical differences (Table 10 and Figure 26) between the measured and simulated water surface elevations. The statistical analysis demonstrates that the model predicts the water surface elevation well, with most differences between -0.5 and 0.5 ft. The RMSE for all discharges was 0.5 feet or less, which was the objective of the modeling effort. The model tends to slightly over predict water surface elevation at 270 cfs and tends to under predict water surface elevation at 1150 cfs. Several possible reasons for this include: (1) the use of 1150 cfs output as the initial conditions for the 270 cfs runs (required to inundate gravel pits), (2) fluctuating discharge during the acquisition of water surface elevations, which spanned multiple days at both 270 and 1150 cfs, (3) flow interaction with the gravel pits, and (4) need to define near-bank roughness in greater detail. However, multiple iterations of roughness zone refinement that were accomplished as part of the calibration effort resulted in small changes in the water surface elevations, indicating that additional efforts to further define near-bank vegetation may only result in small localized improvements in water surface prediction (0.1 to 0.2 feet).

Table 9. Calibrated roughness values for SRH-2D hydraulic simulations using the Reach 1A_02 model between HW 41 and HW 99.

Land Use Types	Roughness
Main Channel Bed	0.04
In-channel Riffles/Rough areas	0.065
Off-Channel Open Water	0.045
Open /Bare Ground/ Scattered Brush	0.068
Scattered Trees	0.090
Medium Density Trees/Brush	0.120
Dense Trees/ Brush	0.150
Agriculture	0.055

Table 10. Statistics on point differences between the measured and simulated water surface elevation (ft, NAVD 88) for the Reach 1A_02 model.

Statistic	270 cfs	700 cfs	1150 cfs	4500 cfs	7650 cfs
Mean	-0.14	-0.08	0.22	0.01	0.23
Median	-0.11	-0.05	0.23	0.05	0.27
Minimum	-0.87	-0.96	-0.61	-0.64	-0.57
Maximum	0.39	0.40	0.61	0.86	0.82
Count	68	60	257	100	111
Standard Deviation	-0.19	0.28	0.23	0.30	0.32
Standard Error about the Mean	-0.02	0.04	0.01	0.03	0.03
Root Mean Squared Error (RMSE)	0.46	0.29	0.30	0.30	0.39

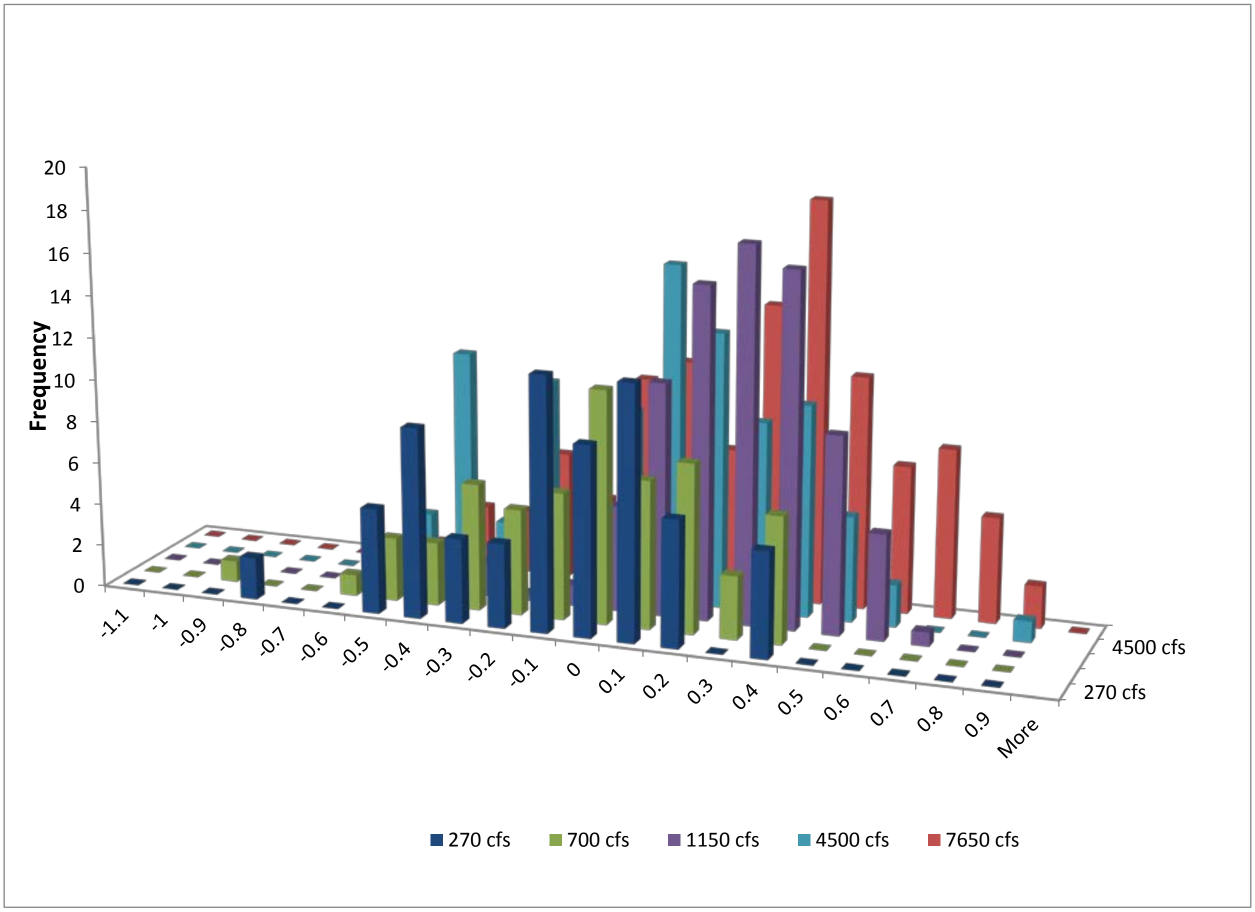

Figure 26. Histogram of point differences between measured and simulated water surface elevation (ft) at each discharge. A negative value indicates that the simulated value was higher than the measured value. Because 1150 cfs had 2.5-3 times more measured points than other discharges, each frequency value was divided by 3.

Model sensitivity to roughness for Reach 1A_02 was also examined at in-channel and floodplain calibration discharges. Similar to Reach 1A_01, sensitivity at the in-channel calibration flows in Reach 1A_02 is related to topography. While the magnitudes of the sensitivities are similar to those of Reach 1A_01, the variability in sensitivity throughout the reach is reduced compared with that of Reach 1A_01, which may be related to more subdued differences between pool and riffle slopes. Sensitivity to roughness at floodplain calibration flows in Reach 1A_02 is much greater than sensitivity at in-channel flows and greater than sensitivity to floodplain flows in Reach 1A_01. A wider range of roughness values was evaluated for floodplain calibration in Reach 1A_02 than Reach 1A_01, and therefore, the simulated water surface elevations had a wider range in values. Floodplain roughness was increased by 50% above the baseline values to achieve the model accuracy objective (RMSE < 0.5 ft) in Reach 1A_02. In addition, floodplain connectivity, including connections with gravel pit complexes, is much greater throughout most of Reach 1A_02 than within Reach 1A_01.

9 Future Model Use and Potential Model Improvements

The Reach 1A SRH-2D models covering Friant Dam to Highway 99 can be used in evaluation of spawning habitat. Results from model simulations presented herein or from additional simulations can be processed to identify areas meeting depth and velocity criteria determined to be suitable for spawning within the San Joaquin River (USBR, 2012b). Velocity, Froude number, and shear stress data may also be useful in evaluating fish passage, potential rearing habitat, and bed material mobilization.

Within the Reach 1A_01 model, caution should be applied utilizing the resulting hydraulics across the two Lost Lake rock weirs and the historic Friant Dam Bridge (RD 206) due to the localized changes in mesh cell elevations required for model calibration. If the model will be used to address questions regarding hydraulics through or within the backwater of these structures (e.g. fish passage velocities), it is recommended that additional bed and water surface elevations be collected. Within the Reach 1A_02 model, simulated results within close proximity (1000 ft) to the upstream boundary should not be used because the width of the simulated inlet may not be consistent with the width of the true flow path at all simulated discharges (i.e. high flows are conveyed within the channel at the model entrance but may actually be conveyed across the floodplain). The inlet boundary condition for the Reach 1A_02 model is located approximately 1 mile upstream from HW41 bridge (downstream boundary of the Reach 1A_01 model), and is therefore in an area of overlap with the Reach 1A_01 model. Results from the Reach 1A_01 model should generally be used in analysis of the overlap region due to the continuity with the upstream extent of the model.

The newly-developed Reach 1A_02 model improves representation of a side channel and entrance conditions at Milburn Pond (near MP 248). Additional model refinement may be necessary at gravel pit entrances if river and gravel pit interactions become an important model objective. In addition, if high accuracy solutions are necessary for high flows (over 4500 cfs), some additional calibration of near bank channel roughness may be necessary.

The Reach 1A terrain was generated from multiple surveys of differing types between 1999 and 2012. Due to localized changes in the river bathymetry, it is recommended that an updated comprehensive topographic and water surface elevation collection plan be developed for Reach 1A to improve the consistency of the data across time and space. An updated terrain could be reapplied to the existing mesh so that the model elevations represent current topography. Over the course of the last 15 years, localized changes within the channel have occurred, some of which can be attributed to gravel movement locally and sand movement through the reach. However, the changes that influence the hydraulics the most are likely attributable to anthropogenic activities, such as installation or movement of large boulders intended to divert flow or create backwater. Within Reach 1A_01, multiple locations were identified where the current terrain model does not adequately represent current topographic conditions, such as the in-channel features used in the gravel mining operation located approximately 13,500 feet upstream from HW 41. Additional survey information at these sites could be incorporated into the terrain model to improve model prediction capabilities at specific locations for short-term model prediction improvement. However, certain in-channel features may be regularly modified, which could present continued challenges in comparing with measured water surface elevations. Once the topography has been updated (either at specific sites or across the entire reach), the model could be run to evaluate the influence of the topographic changes on the predicted hydraulics and subsequently on the areas determined to meet the suitability requirements for spawning salmon.

The current models are intended to provide information on spatial patterns of hydraulic conditions across the entire length of the Reach 1A. Zones of increased roughness were added at riffles and rough areas to better match patterns across the entire reach. However, roughness was not varied across individual riffles to represent patch-scale (less than 1 meter) variations (e.g. smoother heads and rougher tails). The model can be further refined in the future as needed to address specific questions. If the area for potential spawning decreases in scale as physical and biological processes become further understood, the model length could be shortened and in-channel roughness could be defined for different geomorphic features, such as riffle heads and tails. Additional investigation into the patterns of model prediction capabilities across riffles could be accomplished to better understand how model cell sizes and topography may influence model accuracy. Further analysis of trends in model sensitivities and water surface prediction capability with respect to geomorphic features or meso-habitat units could be accomplished by overlaying the model errors and an indicator of model sensitivity on mapped features in a geospatial information system. This may clarify understanding of where model refinements would be most warranted given how sensitive the model is to changes in roughness.

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