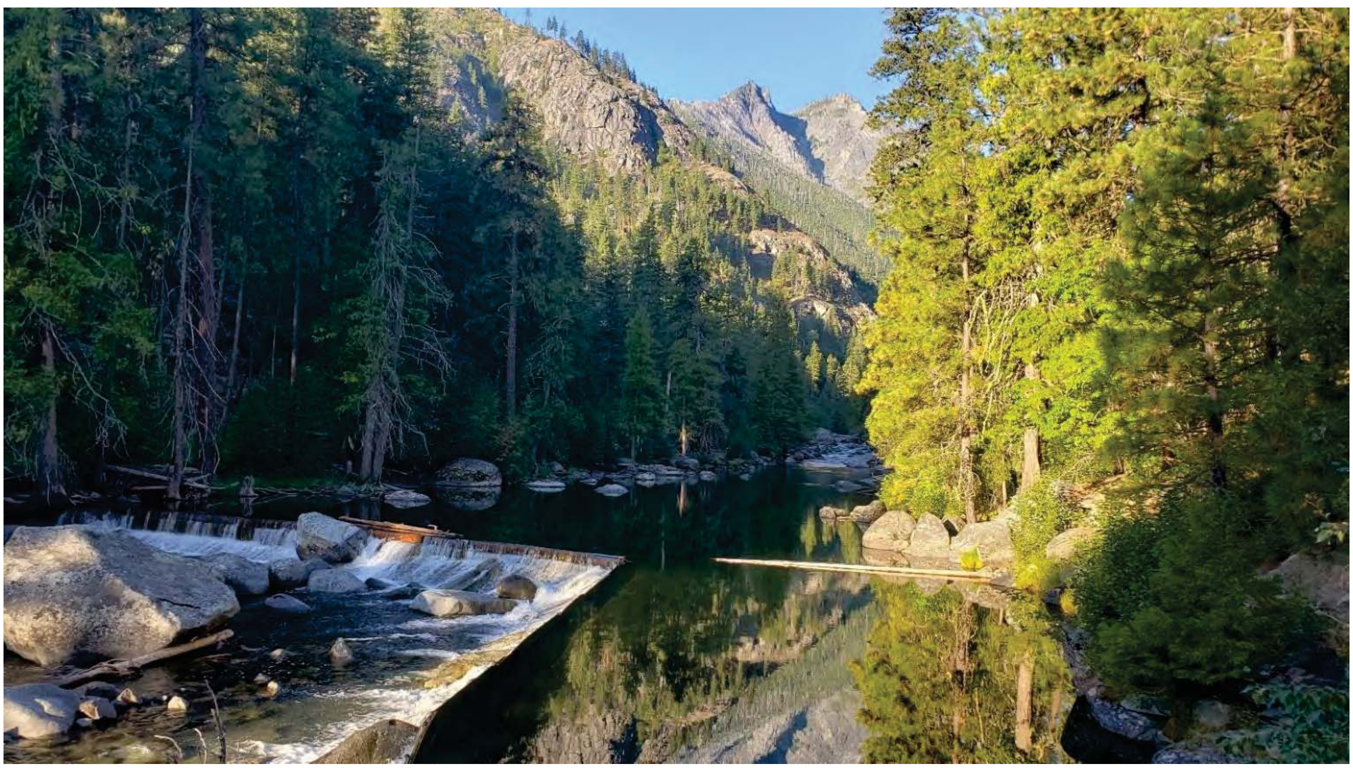
BUREAU OF RECLAMATION

# Surface Water Intake Screening and Fish Passage 2D Hydraulic Modeling

## Leavenworth National Fish Hatchery



U.S. Department of the Interior

July 2020

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# Surface Water Intake Screening and Fish Passage 2D Hydraulic Modeling

**Technical Report No. ENV-2020-046**


**BUREAU OF RECLAMATION**
**Technical Service Center, Denver, Colorado**
**Sedimentation and River Hydraulics Group, 86-68240**

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# Acronyms and Abbreviations

| | |
|---|---|
| LNFH | Leavenworth National Fish Hatchery |
| USFWS | U.S. Fish and Wildlife Service |
| NMFS | National Marine Fisheries Service |
| L-SWISP | LNFH Surface Intake Screening and Fish Passage |
| NAVD88 | North American Vertical Datum 1988 |
| ft | feet |
| cfs | cubic feet per second |
| Reclamation | Bureau of Reclamation |
| $yds^3$ | cubic yards |
| $m^3$ | cubic meters |
| mm | millimeter |
| 2D | two-dimensional |
| WDFW | Washington Department of Fish and Wildlife |
| WSE | water surface elevation |
| XS | cross-section |
| LiDAR | Light Detection and Ranging |
| GIS | Geographic Information System |

# Contents

Page

**1.0 Introduction ... 1**

**2.0 Setting ... 5**

2.1 Hydrology ... 7
2.2 Icicle Creek Sediment Characteristics ... 10
2.3 Summary of Site-Specific Challenges ... 12

**3.0 Design Considerations ... 13**

3.1 Hydraulic and Sediment Objectives ... 13
3.2 Intake, Fishway, and Weir Options ... 14
3.3 Final Design ... 14
3.2 Cofferdam Construction Plan ... 17

**4.0 Fish Screen and Passage Criteria ... 20**

4.1 Fish Migration and Design Discharges ... 20
4.2 Fish Screen Hydraulic Requirements ... 22
4.3 Fish Passage Hydraulic Requirements ... 23
4.4 Roughened Channel Design Requirements (NFMS) ... 24

**5.0 Hydraulic Model Results ... 25**

5.1 Upstream Passage: Low Discharges ... 26
5.2 Upstream Passage: High Discharges ... 32
5.3 Fish Screen Operations ... 41
5.4 Flood Protection ... 43
5.5 Sediment Deposition at Intake ... 44
5.6 Construction Cofferdam ... 47

**6.0 Discussion ... 48**

6.1 Sediment Management to Maintain Fish Screen Submergence Criteria ... 48
6.2 Fish Screen Criteria ... 49
6.3 Upstream Adult Fish Passage Criteria ... 49
6.4 Roughened Channel Rocks and Grouting Needs ... 50
6.5 Large Wood and Debris ... 51

**References ... 53**

**Appendix A – 2010 Sediment analysis at hatchery channel ... 55**

**Appendix B – Sediment sample results from laboratory analysis (Hardee and Bountry, 2019) ... 59**

**Appendix C - Hydraulic Model Development ... 61**

Topographic Data ... 61
Mesh Generation ... 64
Hydraulic Roughness ... 65
Boundary Conditions ... 67
Calibration/Sensitivity ... 67
Model Limitations ... 68

**Appendix D – Construction Cofferdam Results ... 69**

Cofferdam 1 for Phase 1 ... 70
Cofferdam 2 for Phase 2 ... 77
Cofferdam 3 for Phase 3 ... 82

## Tables

Table 1. Monthly flow duration analysis results for the adjusted flow record for Icicle Creek above the LNFH intake. The 0.05 and 0.95 exceedance flows are highlighted (Clarkin, 2019) ......... 8

Table 2. Annual flow duration analysis results for the adjusted flow record for Icicle Creek above the LNFH intake........ 9

Table 3. Peak discharge estimates for annual exceedance probabilities for Icicle Creek ........ 10

Table 4. Bed-material samples in Icicle Creek providing indication of bed-load sediment sizes in millimeters (mm) at various locations ........ 12

Table 5. Adult upstream migration and foraging timing in Icicle Creek for ESA listed species Bull Trout and Steelhead/Rainbow Trout. Typical upstream migration times are shown in grey and peak migration times are shown as dark grey for fish migrating upstream to spawning areas. Bull trout timing in Icicle Creek for foraging shown in yellow. The 95% and 5% exceedance discharge in units of cfs are shown for each period........ 21

Table 6. Peak juvenile downstream migration during spring and fall freshets with the 95% and 5% exceedance value for those periods (Wydoski and Whitney, 2003)........ 21

Table 7. Modeled discharges for design analysis. ........ 25

Table 8. Summary of hydraulic conditions for juvenile downstream Bull Trout and Steelhead passage based on MPOR. Sweeping velocity and exposure time are averaged over the total length in front of the intake fish screens ........ 42

Table 9. Summary of hydraulic conditions for juvenile downstream Bull Trout and Steelhead passage based on MPOR. Sweeping velocity and exposure time are averaged over the total length of the intake fish screens (~21.4 ft). ........ 43

Table 10. Locations and elevations of the large, roughened channel boulders. ........ 64

## Figures

Figure 1. Plan view of the project area on Icicle Creek near Leavenworth, Washington. Water is diverted for LNFH at the diversion location and through a pipeline. The main access to the site is along Icicle Creek Road, visible on river left in the photo. The pipeline runs west to east, just north of and parallel to Icicle Creek. ........ 1

Figure 2. View of low-head diversion structure looking upstream. This photo highlights the rectangular concrete sill, the grouted channel, stop logs, and large boulders downstream. Direction of flow moves towards camera and left of the photo frame. Photograph taken August 2019. ........ 2

Figure 3. Existing fish ladder that was originally intended to assist with sediment sluicing. Sediment piles up in channel upstream of structure (near blue arrow) as it enters the existing intake diversion channel. The blue arrow indicates flow direction across the sluiceway. The yellow line highlights the natural boulder drop downstream. Photograph taken August 2019. ..... 3

Figure 4. Looking upstream at current unscreened entrance from Icicle Creek through trash rack before entering gate house where water is diverted into a pipeline system and transported downstream to the hatchery. Photograph taken April 2019. 3

Figure 5. Sand settling basin at end of diversion pipeline (Photo A), sand removed from settling basin (Photo B), and litterfall removed from settling basin (Photo C). Photograph taken April 2019. 4

Figure 6. Looking upstream at the confined channel and steep hillslopes at existing diversion site. Direction of flow from right to left across the photo frame. 5

Figure 7. Photo looking upstream at the backwater pool and steep, natural rapid upstream (background) that extends approximately 1,000 ft from current diversion structure. Note the large boulders in the rapid upstream and along the banks. Photograph taken August 2019. 6

Figure 8. Downstream of the existing diversion structure a natural boulder drop of 2 to 3 ft exists (photo looking upstream) with a deep scour hole immediately downstream. Additional large boulders are present in this photo that range in diameter from 5 to 15 ft. Photograph taken August 2019. 6

Figure 9. Typical cobble and boulder dominated channel with vegetated banks upstream of hatchery. Photograph taken approximately 1,500 ft upstream of the diversion structure by Lucy Piety, August 19, 2009. 7

Figure 10. Photo looking upstream at the existing intake diversion at high flow at approximately 4,500 cfs. Photograph taken by Hayley Muir, USFWS on December 9, 2015. 8

Figure 11. Photo looking upstream at the project site in winter during ice conditions from December 2, 2019, courtesy Carlo Aguon, LNFH. 9

Figure 12. Proposed design at the intake area site plan and design components. 15

Figure 13. Cross-section showing the modeled bed elevation of the roughened channel and low-flow fishway. The roughened channel is located between stations 75ft to 125ft, which creates a cross slope up the natural channel top-of-bank. Note the large scattered boulders and the side slope towards the banks. Note: vertical scale is exaggerated. 17

Figure 14. Cofferdam layout for Phase 1, 2 and 3 of construction of new intake and roughened channel. 19

Figure 15. Maximum allowable average culvert velocity guidance used to set criteria for fish passage in roughened channels in NMFS (2011). 23

Figure 16. Modeled depth (top) and velocity (bottom) in the low-flow fishway at 75 cfs show 1 ft and 1 ft/s contours, respectively. Flow depth through the low-flow fishway is greater than 1 ft, except on the margins and the crest at the fishway exit (shown as dark blue). Velocity through the low-flow fishway is below 3 ft/s for the vast majority of the fishway, except between boulders and at the crest. Note: the hydraulic conditions of the natural boulder drop downstream of the low-flow fishway (circled in yellow). 27

Figure 17. Modeled depth (top) and velocity (bottom) in the low-flow fishway at 75 cfs show contours based on criteria. Flow depth through the low-flow fishway is greater than 1 ft, except on the margins and the crest at the fishway exit (shown as dark blue). Velocity through the low-flow fishway is below 3 ft/s for the vast majority of the fishway, except between boulders and at the crest. Note: the hydraulic conditions of the natural boulder drop downstream of the low-flow fishway (circled in yellow)........ 28

Figure 18. WSE through low-flow fishway shows drop height through the fishway. Note: bed elevation of actual boulder weirs not shown to highlight through swimming between the boulders. Note: vertical scale is exaggerated........ 29

Figure 19. Cross-section profile at approximately mid-point of roughened channel showing the bed elevation (brown) and modeled WSE for 75 cfs (blue), 100 cfs (green), and 401 cfs (red). Note: vertical scale is exaggerated. ........ 29

Figure 20. Modeled depth (left) and velocity (right) for discharges 100, 298, and 401 and 298 cfs shown with 1 ft and 1 ft/s intervals, respectively. The natural boulder drop directly downstream of the proposed roughened channel is circled (yellow) for reference to natural conditions in Icicle Creek........ 30

Figure 21. Contours showing the modeled depth (left) and velocity (right) for discharges 100, 298, and 401 and 298 cfs based on criteria. The natural boulder drop directly downstream of the proposed roughened channel is circled (yellow) for reference to natural conditions in Icicle Creek........ 31

Figure 22. Modeled depth (left) and velocity (right) for discharges 401 and 586 cfs shown with 1 ft and 1 ft/s intervals, respectively. The natural boulder drop directly downstream of the proposed roughened channel is circled (yellow) for reference to natural conditions in Icicle Creek........ 33

Figure 23. Contours showing the modeled depth (left) and velocity (right) for discharges 401 and 586 cfs based on criteria. The natural boulder drop directly downstream of the proposed roughened channel is circled (yellow) for reference to natural conditions in Icicle Creek. ........ 34

Figure 24. Modeled depth (left) and velocity (right) contours 906 and 1,600 cfs shown with 1 ft and 1 ft/s intervals, respectively. The natural boulder drop directly downstream of the proposed roughened channel is circled (yellow) for reference to natural conditions in Icicle Creek. ........ 35

Figure 25. Contours showing the modeled depth (left) and velocity (right) for discharges 906 and 1,600 cfs based on criteria. The natural boulder drop directly downstream of the proposed roughened channel is circled (yellow) for reference to natural conditions in Icicle Creek. ........ 36

Figure 26. Modeled depth (left) and velocity (right) contours 2,671 and 3,002 cfs shown with 1 ft and 1 ft/s intervals, respectively. The natural boulder drop directly downstream of the proposed roughened channel is circled (yellow) for reference to natural conditions in Icicle Creek. ........ 37

Figure 27. Contours showing the modeled depth (left) and velocity (right) for discharges 2,671 and 3,002 cfs based on criteria. The natural boulder drop directly downstream of the proposed roughened channel is circled (yellow) for reference to natural conditions in Icicle Creek. ........ 38

Figure 28. Modeled velocities were sampled along the cross-section locations shown. Three roughened channel cross-sections (XS-upper, XS-middle, and XS-lower) and two reference (XS-boulders and XS-riffle)....... 39

Figure 29. Comparison of modeled velocity between proposed design and natural channel sampled along five cross-sections. The XS-upper, XS-middle, and XS-lower are located within the proposed designed roughened channel at the upstream end, the middle, and downstream end, respectively. These are compared to two natural reference cross-sections: XS-boulders and XS-riffle. The line represents the median velocity, the X is the mean velocity, the box represents the upper and lower quartile range, the whiskers show the upper and lower extremes, and outliers are shown in as circles. The black dashed line shows the velocity criteria of 3 ft/s. ....... 40

Figure 30. Contours showing the modeled WSE at 1 ft increments for the 100-yr flood (13,300 cfs). The WSE is highest at the upstream side of the intake structure (1,205 to 1,206 ft) and drops about 1 ft in front of the fish screens (1,204 ft). Weir crest location is shown with black line. Inundation beyond the black line on river right is along the steep hillslope. ....... 44

Figure 31. Potential sediment mobility based on dimensionless shear stress for 4,100 cfs (2-yr flood). Contours show areas of mobility for fines (dark blue), sand (light blue, 0.063 to 2 mm), very-fine to coarse gravel (teal, 2 to 32 mm), coarse-gravel to very-coarse gravel (green, 32 to 64 mm), cobbles (light green, 64 to 256 mm), small boulders (orange, 256 to 512 mm), and large boulders (512 mm and up). New weir location shown with black line. ....... 46

Figure 32. Potential sediment mobility based on dimensionless shear stress for 7,500 cfs (10-yr flood). Contours show areas of mobility for fines (dark blue), sand (light blue, 0.063 to 2 mm), very-fine to coarse gravel (teal, 2 to 32 mm), coarse-gravel to very-coarse gravel (green, 32 to 64 mm), cobbles (light green, 64 to 256 mm), small boulders (orange, 256 to 512 mm), and large boulders (512 mm and up). New weir location shown with black line. ....... 47

Figure 33. Location map of Icicle Creek and Leavenworth National Fish Hatchery (LNFH) on 2009. ....... 57

Figure 34. Approximate locations of test pits excavated upstream of fish hatchery in August 2009. Locations are from waypoints taken with a hand-held GPS unit....... 58

Figure 35. Location and rock height above existing bed (ft) for placed boulders on ramp. Letters designate label that corresponds to Table 10 and numbers represent rock height. ....... 63

Figure 36. Computational mesh developed in SMS on proposed modeled bed elevation at the project site. ....... 65

Figure 37. Model roughness values at the project site....... 66

Figure 38. Representation of existing conditions terrain and Cofferdam 1 during phase 1 of construction. Letters A to E are provided for reference locations in the discussion. Flow moves from left to right across the image. ....... 71

Figure 39. 2D results at 298 cfs with Cofferdam 1 for water depth (ft) and velocity (ft/s) in top and bottom images, respectively. Contour interval is in 1-ft (ft/s) increments for this figure and all following figures. Flow is from left to right in this figure and all subsequent figures. ....... 72

Figure 40. 2D results at 906 cfs with Cofferdam 1 for water depth (ft) and velocity (ft/s) in top and bottom images, respectively. 73
Figure 41. 2D results at 1,600 cfs with Cofferdam 1 for water depth (ft) and velocity (ft/s) in top and bottom images, respectively. 74
Figure 42 2D results at 3,400 cfs with Cofferdam 1 for water depth (ft) and velocity (ft/s) in top and bottom images, respectively. 75
Figure 43. 2D water surface elevation (NAVD88 ft) results for Cofferdam 1 at 1,600 (top) and 3,400 cfs (bottom). Contour interval is in 1-ft increments. 76
Figure 44. Representation of existing conditions terrain and Cofferdam 2 during phase 2 of construction. Letters A to E are provided for reference locations in the discussion. 77
Figure 45. 2D results at 298 cfs with Cofferdam 2 for water depth (ft) and velocity (ft/s) in top and bottom images, respectively. 78
Figure 46. 2D results at 906 cfs with Cofferdam 2 for water depth (ft) and velocity (ft/s) in top and bottom images, respectively. 79
Figure 47. 2D results at 1,600 cfs with Cofferdam 2 for water depth (ft) and velocity (ft/s) in top and bottom images, respectively. 80
Figure 48. 2D water surface elevation (NAVD88 ft) results for Cofferdam 2 at 1,600 (top) and 3,400 cfs (bottom). 81
Figure 49. Representation of existing conditions terrain and Cofferdam 3 during phase 3 of construction. Letters A to E are provided for reference locations in the discussion. 82
Figure 50. 2D results at 298 cfs with Cofferdam 3 for water depth (ft) and velocity (ft/s) in top and bottom images, respectively. 83
Figure 51. 2D results at 906 cfs with Cofferdam 3 for water depth (ft) and velocity (ft/s) in top and bottom images, respectively. 84
Figure 52. 2D results at 1,600 cfs with Cofferdam 3 for water depth (ft) and velocity (ft/s) in top and bottom images, respectively. 85
Figure 53. 2D water surface elevation (NAVD88 ft) results for Cofferdam 3 at 906 (top) and 1,600 cfs (bottom). 86

# 1.0 Introduction

Leavenworth National Fish Hatchery (LNFH) was built as fish mitigation for the construction of Grand Coulee Dam in the late 1930s. Reclamation and the Bonneville Power Administration (BPA) fund the operations and maintenance, while the U.S. Fish and Wildlife Service (USFWS) owns, manages, and operates LNFH. The LNFH obtains most of its water from its shared water intake on Icicle Creek (Figure 1). The water is diverted through an open channel and into a 6,500-foot long buried pipeline. The pipeline passes through an existing maintenance easement on private property prior to entering LNFH property. In 2017, the National Marine Fisheries Service (NMFS) issued a biological opinion requiring LNFH to provide fish entrainment protection by May 31, 2023 (NFMS, 2017). The LNFH Surface Intake Screening and Fish Passage (L-SWISP) project was developed to meet those mandates.

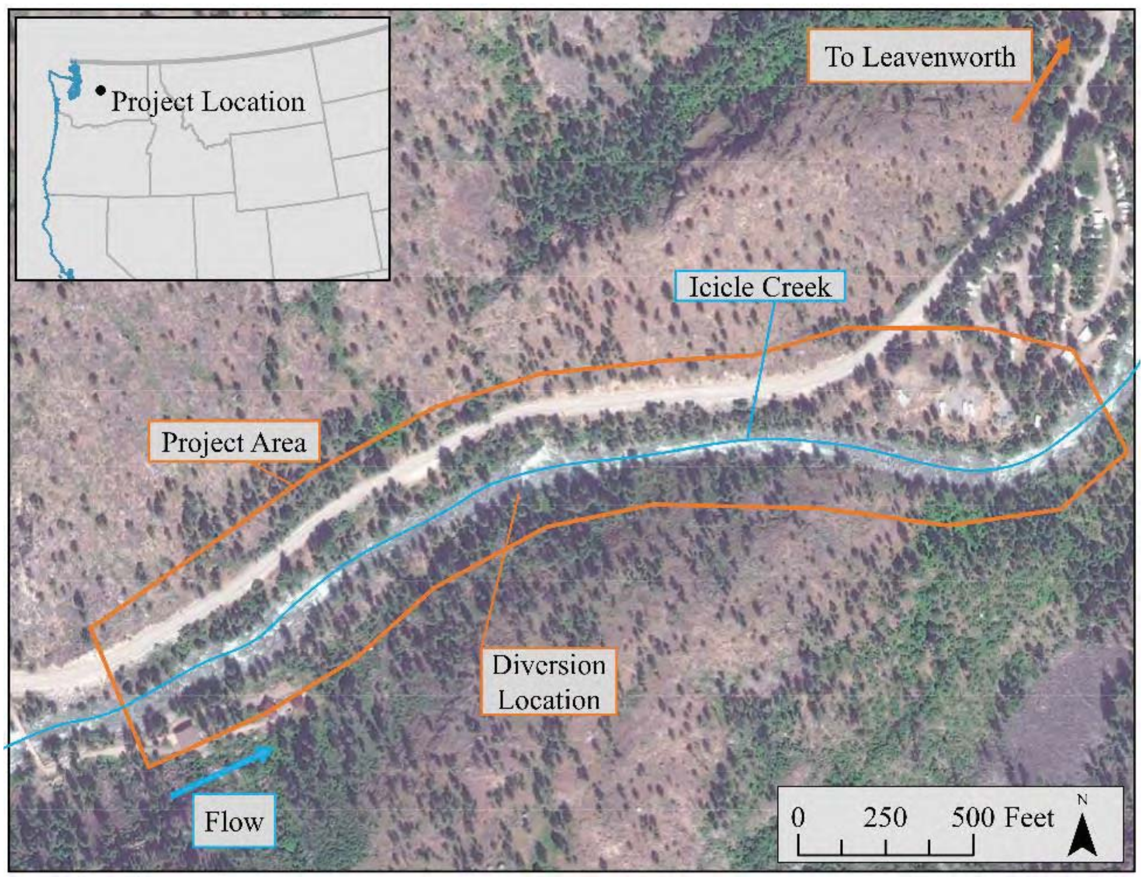


Figure 1. Plan view of the project area on Icicle Creek near Leavenworth, Washington. Water is diverted for LNFH at the diversion location and through a pipeline. The main access to the site is along Icicle Creek Road, visible on river left in the photo. The pipeline runs west to east, just north of and parallel to Icicle Creek.

The existing low-head diversion structure is approximately 80 years old and consists of three vertical sections: 1) a grouted crest at elevation 1192 feet (ft; North American Vertical Datum 1988[1]), 2) an additional 1 ft rectangular concrete cap raising the control to 1193 ft, and 3) additional wood stop logs that raise the control to 1194 ft, which are difficult to remove or manage (Figure 2). When constructed, portions of the floodplain and hillslope were excavated to create a channel for diverted water. A small sediment sluiceway was constructed to clean out sediment in front of the trash rack (Figure 4); however, the sluiceway provided only marginal sediment sluicing to the downstream channel because of its perpendicular alignment to flow and narrow width relative to Icicle Creek. Instead of the desired effect, sediment transport generally occurs through an unscreened trash rack into the gravity-fed intake pipeline that leads to LNFH (Figure 4). The sediment is then routed through the pipeline, collected in a sand settling basin at the LNFH, which is periodically removed with heavy excavation equipment (Figure 5). Sediment particles routed through the pipeline erode and damage the existing pipeline. During periods of fish migration, the sediment sluiceway is converted to operate as a fish ladder, with wood boards creating 1 ft drops in water stage. The last documented use of the sediment sluiceway to sluice sediment was in 2012 (Anglin et al., 2013).

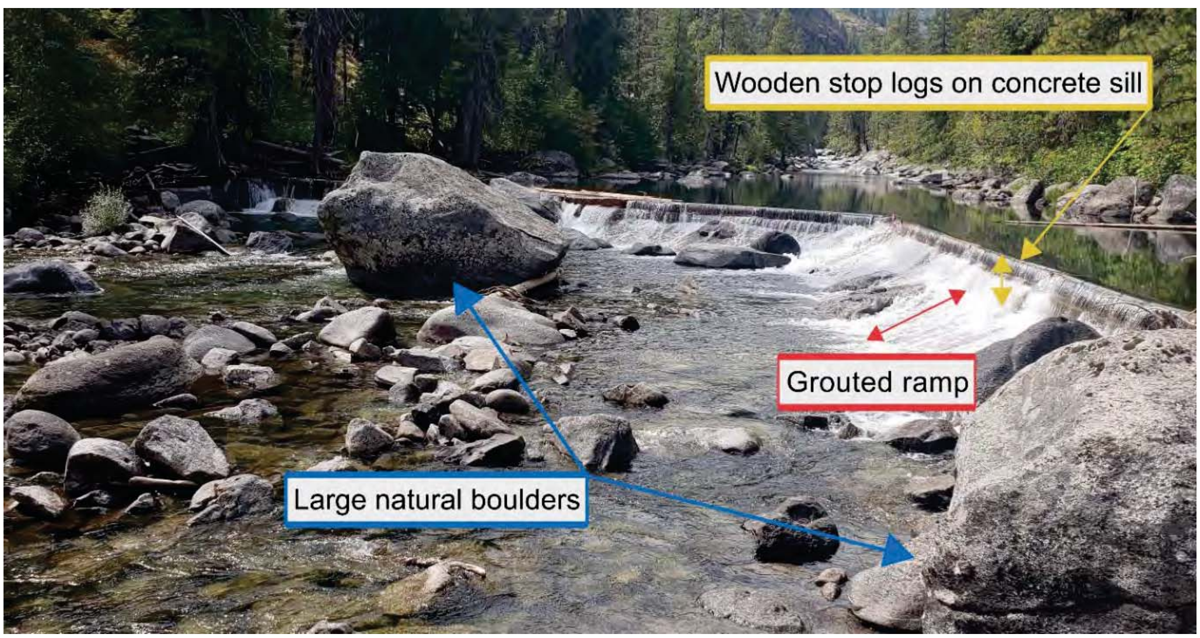


Figure 2. View of low-head diversion structure looking upstream. This photo highlights the rectangular concrete sill, the grouted channel, stop logs, and large boulders downstream. Direction of flow moves towards camera and left of the photo frame. Photograph taken August 2019.

[1] Unless otherwise noted, all elevations mentioned in this report are presented in North American Vertical Datum 1988 (NAVD88).


Figure 3. Existing fish ladder that was originally intended to assist with sediment sluicing. Sediment piles up in channel upstream of structure (near blue arrow) as it enters the existing intake diversion channel. The blue arrow indicates flow direction across the sluiceway. The yellow line highlights the natural boulder drop downstream. Photograph taken August 2019.

Figure 4. Looking upstream at current unscreened entrance from Icicle Creek through trash rack before entering gate house where water is diverted into a pipeline system and transported downstream to the hatchery. Photograph taken April 2019.


Figure 5. Sand settling basin at end of diversion pipeline (Photo A), sand removed from settling basin (Photo B), and litterfall removed from settling basin (Photo C). Photograph taken April 2019.

A new design was required to deliver a consistent 42 cubic feet per second (cfs) of gravity-fed water supply to the LNFH year-round, improve operator safety, and meet fish screening and fish passage regulatory criteria based on the NMFS biological opinion (NFMS, 2017) for species of concern. This report details the project site setting, proposed design, and fish criteria as it relates to the hydraulics and sediment analysis conducted to inform the design process. This report is written as a supplement to a more comprehensive basis of design report completed by Reclamation (Reclamation, 2020 draft in progress).

# 2.0 Setting

The hatchery is located about four river miles upstream of the confluence of Icicle Creek and the Wenatchee River, and the existing diversion structure is located at river mile 4.6. Upstream of the hatchery Icicle Creek has a gravel and cobble bed with bedrock and large boulders exposed in several locations. Vegetated islands and woody debris are present intermittently along the creek, and the banks are generally vegetated with large trees and light undergrowth. In the project reach the channel is generally confined and bound by steep hillslopes on either side (Figure 6). The typical channel slope downstream of LNFH is 0.003 (ft/ft) (Lorang, 2005 based on total station measurements), while upstream of the hatchery in the project reach the average slope is 0.025 (ft/ft based on Lidar data). A steep rapid (~0.030 ft/ft) exists about 1,000 ft upstream of the diversion pool that creates a natural break in the extent of the backwater pool (Figure 7). Immediately downstream of the existing diversion structure, a natural boulder drop of about 2 to 3 ft is present with a deep 3 ft scour hole formed from the hydraulic drop over the boulders (Figure 8). The channel profile consists of numerous runs and riffles with occasional shallow pools (Figure 9). The channel bed consists of large boulders and bedrock armor with sand, gravel and cobble deposits. The following sections provide more details on the hydrology and sediment characteristics of the project area.

Figure 6. Looking upstream at the confined channel and steep hillslopes at existing diversion site. Direction of flow from right to left across the photo frame.


Figure 7. Photo looking upstream at the backwater pool and steep, natural rapid upstream (background) that extends approximately 1,000 ft from current diversion structure. Note the large boulders in the rapid upstream and along the banks. Photograph taken August 2019.


Figure 8. Downstream of the existing diversion structure a natural boulder drop of 2 to 3 ft exists (photo looking upstream) with a deep scour hole immediately downstream. Additional large boulders are present in this photo that range in diameter from 5 to 15 ft. Photograph taken August 2019.

Figure 9. Typical cobble and boulder dominated channel with vegetated banks upstream of hatchery. Photograph taken approximately 1,500 ft upstream of the diversion structure by Lucy Piety, August 19, 2009.

## 2.1 Hydrology

The Icicle Creek basin is located on the eastern slope of the Cascade Mountains. There is a U.S. Geological Survey (USGS) gage (Station 12458000) at river mile 5.8, about 1.3 miles upstream of the hatchery diversion structure that was used to characterize discharge to the project site. Clarkin (2019) conducted a detailed hydrologic analysis for the project site, accounting for various diversions and reintroduction of water in the intervening drainage area. Approximately 87 percent of the basin above the USGS gage is predominantly owned and managed by the U.S. Forest Service. From the crest of the Cascades to the basin outlet, there is a wide range of average annual precipitation, from 120 inches at approximately 9,000 feet to 20 inches at approximately 1,100 feet. The Icicle Creek basin is approximately 205 square miles at the existing intake structure (Clarkin, 2019).

Mean daily flows peak during snowmelt months in late spring and can drop quite low in fall and winter months (Table 1). The maximum recorded discharge at the USGS gage was 19,800 cubic feet per second (cfs) in 1995 and the minimum recorded discharge was 44 cfs in November 1936. Another large flood occurred in 2006 with a reported peak of 15,700 cfs. Hatchery personnel noted that another large flood occurred in 1990 but a measured peak value is not available. During high flows the river is turbulent and the natural boulders provide hydraulic roughness visible in a photograph taken when the gage measured 4,500 cfs (Figure 10). During the winter months, frazil ice often forms in Icicle Creek and requires manual labor to break up and keep diversion operations going (Figure 11).

Using average mean-daily flows, exceedance probabilities were developed by Clarkin (2019) as shown in Table 2. Peak flow frequency from annual peaks were developed to estimate flood frequency values by Clarkin (2019) as shown in Table 3.

Table 1. Monthly flow duration analysis results for the adjusted flow record for Icicle Creek above the LNFH intake. The 0.05 and 0.95 exceedance flows are highlighted (Clarkin, 2019)

| Exceedance Probability (%) | Discharge (cfs) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Jan** | **Feb** | **Mar** | **Apr** | **May** | **Jun** | **Jul** | **Aug** | **Sep** | **Oct** | **Nov** | **Dec** |
| 5 | 773 | 855 | 747 | 1,489 | 3,494 | 3,478 | 2,082 | 513 | 295 | 651 | 1,210 | 898 |
| 50 | 233 | 213 | 253 | 572 | 1,442 | 1,641 | 578 | 140 | 109 | 171 | 268 | 274 |
| 95 | 102 | 96 | 126 | 219 | 572 | 599 | 129 | 60 | 54 | 70 | 76 | 94 |

Figure 10. Photo looking upstream at the existing intake diversion at high flow at approximately 4,500 cfs. Photograph taken by Hayley Muir, USFWS on December 9, 2015.

Figure 11. Photo looking upstream at the project site in winter during ice conditions from December 2, 2019, courtesy Carlo Aguon, LNFH.

Table 2. Annual flow duration analysis results for the adjusted flow record for Icicle Creek above the LNFH intake

| **Exceedance Probability (%)** | **Flow (cfs)** | **Exceedance Probability (%)** | **Flow (cfs)** |
|---|---|---|---|
| 0.1 | 5,343 | 60 | 232 |
| 0.2 | 4,747 | 70 | 183 |
| 0.5 | 3,949 | 80 | 140 |
| 1 | 3,435 | 85 | 119 |
| 2 | 2,906 | 90 | 97 |
| 5 | 2,219 | 95 | 75 |
| 10 | 1,561 | 98 | 63 |
| 15 | 1,189 | 99 | 57 |
| 20 | 906 | 99.5 | 49 |
| 30 | 586 | 99.8 | 45 |
| 40 | 401 | 99.9 | 39 |
| 50 | 298 | | |

Table 3. Peak discharge estimates for annual exceedance probabilities for Icicle Creek

| Annual Exceedance Probability (%) | Return Period (years) | Estimated Discharge | Lower (5%) | Upper (95%) |
|---|---|---|---|---|
| 95 | 1.05 | 2,200 | 1,800 | 2,400 |
| 90 | 1.11 | 2,500 | 2,200 | 2,700 |
| 80 | 1.25 | 2,900 | 2,600 | 3,200 |
| 70 | 1.43 | 3,300 | 3,000 | 3,600 |
| 67 | 1.50 | 3,400 | 3,100 | 3,800 |
| 50 | 2 | 4,100 | 3,700 | 4,500 |
| 20 | 5 | 6,100 | 5,400 | 6,900 |
| 10 | 10 | 7,500 | 6,700 | 8,900 |
| 5 | 20 | 9,100 | 7,900 | 11,300 |
| 2 | 50 | 11,400 | 9,500 | 15,400 |
| 1 | 100 | 13,300 | 10,800 | 19,300 |

Clarkin (2019) reviewed available predictions on climate change relative to stream flow on Icicle Creek. The available information suggests that spring flows will happen earlier in the year with drier summers and peak flows and droughts will be wetter and drier, respectively. Current streamflow in Icicle Creek during low flow periods is too low for fish passage and habitat availability and projected to worsen with climate change impacts. An Icicle Work Group has been setting goals to improve the instream flow at the historical channel adjacent to LNFH. Members of the Icicle Creek Work Group include: Native American Tribes, environmental groups, county and city government officials, irrigation distractors, recreational interest groups, State and Federal Agencies, as well as LNFH. If implemented, these goals would set a metric of an instream flow in drought years of 60 cfs, in non-drought years of 100 cfs, and a long-term goal of increasing this to 250 cfs (NMFS, 2017). Therefore, the incoming flow to the diversion weir site prior to pulling 42 cfs would be estimated at 102 cfs in drought years, 142 cfs in non-drought years, and a long-term goal of increasing to 292 cfs.

## 2.2 Icicle Creek Sediment Characteristics

There is no measured sediment load data, but literature, bed-material samples, and anecdotal observations can be used to characterize sediment in Icicle Creek in the project area (Appendix A). Lorang (2005) estimated the mean annual sediment load on Icicle Creek incoming to LNFH ranges from 3,900 to 5,900 yds$^3$ (3,000 to 4,500 m$^3$) per year, about the size of an Olympic-sized swimming pool. This estimate assumed that measured sediment deposition behind constructed dams at LNFH represents the total incoming sediment load, which may under-represent the actual load particularly for fine-grained sediment (silt and clay). Lorang (2005) also assumed the sediment volume used for load computation was fully deposited between 1938-40 and either 1983 or 2003, and once full any additional incoming sediment load passed over the structures. The range from 1983 to 2003 has to do with the uncertainty in when the measured sediment behind the structures was deposited because detailed records are not available. If the filling of pools upstream of the structures reached an equilibrium earlier than 1983, the estimate for annual load would increase due to the shorter timeframe. The gates in the structures historically have been opened, which would have initiated some erosion of the deposited sediment and then refilling once shut. Although the load estimate has uncertainty and may be on the low side, it is currently the only estimate available. Sediment load estimates here are reported to provide context for potential sediment deposition at the proposed intake structure in the future.

The largest portion of the incoming sediment load to the diversion structure is estimated to be sand to fine gravel, with a small portion being larger gravels and cobbles. The channel bed is visibly composed of large cobbles and boulders in rapids, with sand and gravels present in pools and on sediment bars and low floodplain. Channel margins often contain pockets of fine sediment (silt and clay) and fine sand deposited in between the exposed boulders.

The sizes of sediment transported by Icicle Creek (within the sand to cobble range) can be characterized by visible deposits: in the pool upstream of the diversion structure, in the hatchery channel upstream of a constructed spillway, and upstream of the small dams in the historical channel at LNFH used for operations (Table 4). A sample collected in front of the existing trash rack immediately upstream of the structure had a $d_{50}$ of 5 mm (coarse sand) with the sizes ranging from sand to fine gravel (Hardee and Bountry, 2019; Appendix A). The sediment trapped in the LNFH sand settling basin contain smaller particles because of a second set of grates that are 1 ½" in diameter that prevent larger material from entering the intake pipe. Test pits conducted in 2009 in a channel at the hatchery site revealed historical river sediment that had deposited since the 1930s (when constructed) was generally also sand to gravel sizes (Appendix B).

LNFH personnel in 2009 noted that sediment filling at the diversion structure was greater in years following upstream fires that initiate debris flows into the channel (Bountry, 2010). One of the largest fires noted in the area occurred in 1994 (Rat Creek-Hatchery Fire; Lorang, 2005), only one year prior to the 1995 flood of record which would have generated large amounts of erosion and sediment load to the stream. Additional fires have occurred in 2001, 2008, 2012, and 2017 in the basin (Washington Geospatial Open Data Portal, accessed April 14, 2020).

Hatchery personnel have historically had to clean sediment out of the existing diversion structure pool after large floods (verbal communication with Steve Croci, August 20, 2009). The sediment removed upstream of the diversion structure was noted to range from sand to cobbles. Softball-sized cobbles have been observed moving over the top of the diversion structure during higher flows, but hatchery personnel note that the percentage within the total volume removed is small, possibly 5 to 10% (Steve Croci, personal communication August 20, 2009). The last account of removing the fishway weirs (wood boards in current fish ladder) to sluice sediment occurred at a discharge of 2,663 cfs in June 2012 (Anglin et al., 2013).

Table 4. Bed-material samples in Icicle Creek providing indication of bed-load sediment sizes in millimeters (mm) at various locations

| Date | Location | $d_{50}$ | Description | Source |
|---|---|---|---|---|
| 2009 | Diversion channel immediately downstream of existing structure and trash rack | 9 mm (coarse sand) | Size limited by 1.5 in. (38 mm) trash rack openings | Bountry (2010) |
| 2009 | Hatchery channel upstream of spillway | 2 mm | Primarily loose sand or unconsolidated sandy gravel | Bountry (2010) |
| 2009 | Gravel bars at upstream end of hatchery channel and in Icicle Creek immediately downstream | 20 to 26 mm | Bed composed of a mix of sand, gravel and cobbles | Bountry (2010) |
| 2019 | Sediment pile excavated from LNFH sand settling basin | 0.35 mm (fine sand) | Contained litterfall | Hardee and Bountry (2019) |
| 2019 | Diversion pool immediately upstream of existing structure and trash rack | 5 mm (coarse sand) | Sand to fine gravel deposit with larger gravels | Hardee and Bountry (2019) |

## 2.3 Summary of Site-Specific Challenges

Several site-specific challenges were important in understanding design options, as described above:

- The project site is in a confined canyon and channel width is limited.
- The slope of the natural channel is steep (approximately 0.025 ft/ft) with sections of steeper riffles (0.030 ft/ft).
- Large natural boulders create hydraulic controls and very complex hydraulic conditions throughout the reach.
- There is uncertainty in the hydrologic input, in part because of several diversions upstream of the site. Furthermore, water use and management may change in the future, particularly during low flows.
- Large variability in the hydrology during migratory periods of record requires designing for very low discharges (tens of cfs) as well as large flows (thousands of cfs).
- Winter conditions can develop frazil ice in the channel.

# 3.0 Design Considerations

The following sections discuss design considerations for the proposed design, which includes an intake-structure, roughened channel, and low-flow boulder weir fishway. Design considerations for temporary coffer dams to aid construction are also discussed.

## 3.1 Hydraulic and Sediment Objectives

The following hydraulic and sediment design objectives were established by the design team for the proposed intake modifications:

1. Maintain existing crest height and structure base to create enough water depth (head) to meet gravity fed delivery of 42 cfs year-round.

2. Meet the requirements of the biological opinion to install fish screens and address regulatory requirements for submergence and sweeping velocity at the fish screens.

3. Improve fish passage for native adult and juvenile fish during periods of migration.

4. Reduce sediment loads diverted into the intake to reduce future damage to the underground pipeline delivery system and limit maintenance needed at the sand settling basin at the LNFH.

5. Manage sediment deposition to prevent burial of the fish screens at the intake location, using best practices to protect native fish when present.

6. Manage debris including large logs that may be transported into the site and impact fish passage or intake operations.

7. Develop alternative operation protocols for periods when frazil ice is present.

8. Improve safety for LNFH personnel when performing operations and maintenance at the diversion site

9. Build infrastructure that is protected from erosion and remains safely accessible during a 100-yr flood event.

10. Develop an annual monitoring plan to ensure functionality of new infrastructure and if needed identify any required adaptive management components.

## 3.2 Intake, Fishway, and Weir Options

Several alternatives for the fish screen intake structure, roughened channel, and low-flow boulder weir fishway were evaluated between the initial, 30, and 60 and 90 percent design stages. The initial design concept used the existing diversion dam alignment and placed the new intake screens at the location of the trash rack where flow enters the canal leading to the gravity fed pipe system. The existing fish ladder and low-flow fishway on river right was still utilized. Fish screens were oriented perpendicular to flow, increasing the risk of sediment and debris accumulation. Further, at low flows only a small portion of water was going past the screen because the rest was either diverted or routed into the low-flow fishway. This resulted in sweeping velocity being the same as or less than approach velocity at the screen location.

For the 30 percent stage, the design team evaluated alternate locations for the fish screens to orient the screens parallel to the flow and increase sweeping velocity. The preferred location was to shift the screens just upstream of the weir, simplify the weir to a single cross-channel section perpendicular to flow, and move the low-flow fishway near the screens. The reasoning for shifting the fishway near the screen was to locate both the screens and the fishway in the thalweg to optimize submergence and opportunity for fish to follow the dominant flow path directly into the low-flow fishway for downstream migration.

Between the 60 and 90 percent designs, the number of boulder weirs within the low-flow fishway were optimized with modeling to meet depth and hydraulic drop criteria for lower discharges (10s to 100s of cfs). Between the 90 percent and final design, the weir alignment, longitudinal slope, cross-slope, and number and spacing of boulders on the roughened channel outside the low-flow fishway were optimized to meet upstream passage and sweeping velocity criteria for larger flows.

## 3.3 Final Design

In order to accomplish the hydraulic and sediment objectives stated above, the design team's preferred option is to construct a roughened channel with a low-flow boulder weir fishway and in-stream cylindrical fish screen intake oriented parallel to flow (Figure 12; Reclamation, 2019).

Design highlights important to 2D modeling, such as fish screen location and orientation, weir structure geometry and materials, and the roughened channel geometry and slope are presented in the paragraphs below. Additional design details can be found in the companion basis of design report being prepared by Reclamation and published in June 2020.

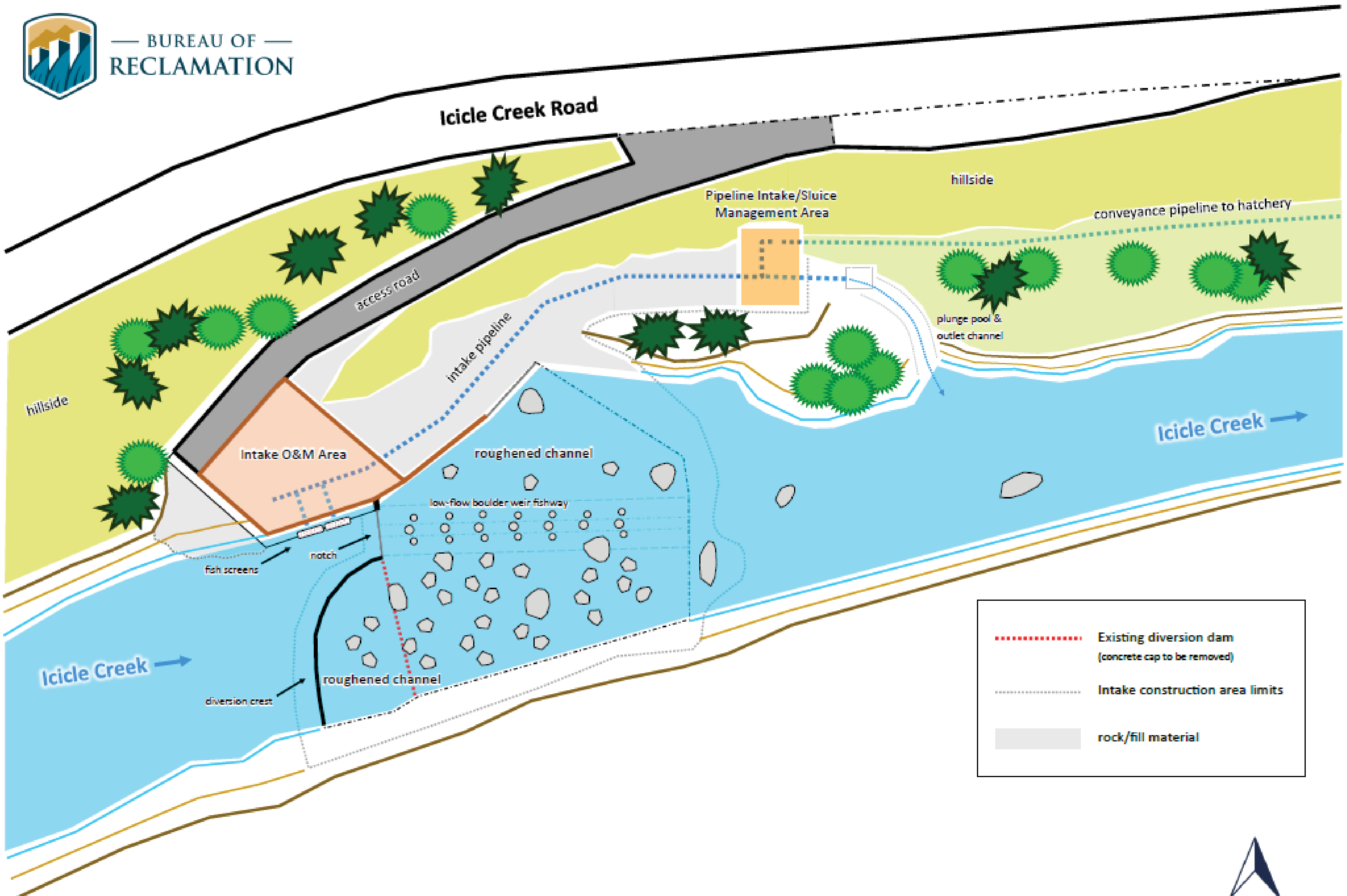


Figure 12. Proposed design at the intake area site plan and design components.

At the intake structure, two 10-foot-long, 30-inch diameter, brushed cylinder fish screens with a screen surface area of 55 square feet, will be utilized to meet the design goal of diversion of 42 cfs. Both intake screens will be placed on river left in the deepest portion of the natural channel and oriented parallel to the natural flow path. The screens will be mounted over a concrete pad constructed at elevation 1,188 ft; the screens can be mechanically lifted out of the water for maintenance. A training wall constructed of large rock will be built upstream of the intake structure on river left to minimize recirculation of flow. Debris deflectors will be incorporated to protect screens from incoming large wood during floods. A retaining wall will be tied into the hillslope to prevent water from flowing around the intake structure away from the active channel. A pipeline will be placed and buried along the path of existing diversion channel (north of the proposed intake structure) and will be filled in to create an access road and intake operations and management area.

The upstream extent of the proposed roughened channel crest will be approximately 30 ft upstream of the existing diversion. Therefore, the roughened channel will be approximately 150 ft long with a 4.7 % slope (ft/ft). The roughened channel crest height will be at constant elevation of 1,194 ft, the same as the existing diversion structure with stop logs. The existing 1-ft wooden stop logs and 1-ft concrete cap will be removed, to lower the height of the existing diversion structure and the remaining diversion structure will be buried beneath the roughened channel. The roughened channel crest will be gradually sloped both upstream and downstream to create a smooth transition and grouted to increase stability and limit seepage. Because of the high velocities present on Icicle Creek, the downstream end of the roughened channel was tied into the natural boulder drop to prevent potential toe scour and headcutting that could erode the roughened channel. Numerous large 5 to 8 ft rocks will be placed in the roughened channel, outside of the low-flow fishway, to create additional hydraulic roughness and increase resting areas for fish (Figure 13). Large natural boulders present in the existing channel will remain, except for one large 15-ft boulder that is currently within the proposed fishway. This boulder will need to be removed or it will create a hydraulic barrier for fish passage during low flows. Another section of natural rock will need to be excavated in the downstream-third of the fishway to create the necessary flow depths for fish passage.

The low-flow boulder weir fishway will be a grouted trapezoidal channel inset into the roughened channel (Figure 13). At the crest, the invert of the low-flow fishway will be notched into the existing diversion structure at an elevation of 1,193 ft with the sides sloping up to an elevation of 1194 ft to match the rest of the crest. The purpose of the notch is to encourage low flows to enter the fishway to maintain adequate depths for upstream passage (rather than spilling over the entire crest and creating shallow depths). The low-flow fishway is approximately 130 ft long with a 4.6% slope (ft/ft). The boulder weirs within the fishway comprises seven series of 2.5-ft to 3.5-ft rocks with 2.5-ft gaps in between to facilitate improved fish passage without requiring jumping over a weir (Mefford, 2009). Downstream of the crest, the right top-of-bank of the low-flow fishway is approximately 1 ft lower than the left top-of-bank to further focus flows toward the center of the channel, increasing flow depths at low discharges. This drop in bank height also increases the cross-slope between the edge of the fishway to the natural top-of-bank on river right of the roughened channel (Figure 13). The elevation of the roughened channel matches that of the natural channel top-of-bank to prevent running material up the natural hillslope, which would be unstable during floods.

The location of the fishway entrance was slightly offset from the intake screens to increase sweeping velocities past the screen during low flows. The fishway was also located on river left so that during low flows, fish will be following the dominant downstream flow vectors in the creek with the fastest velocities to encourage quick transition into the fishway past the screens. The downstream end of the fishway is in a backwater created by the natural boulder drop.

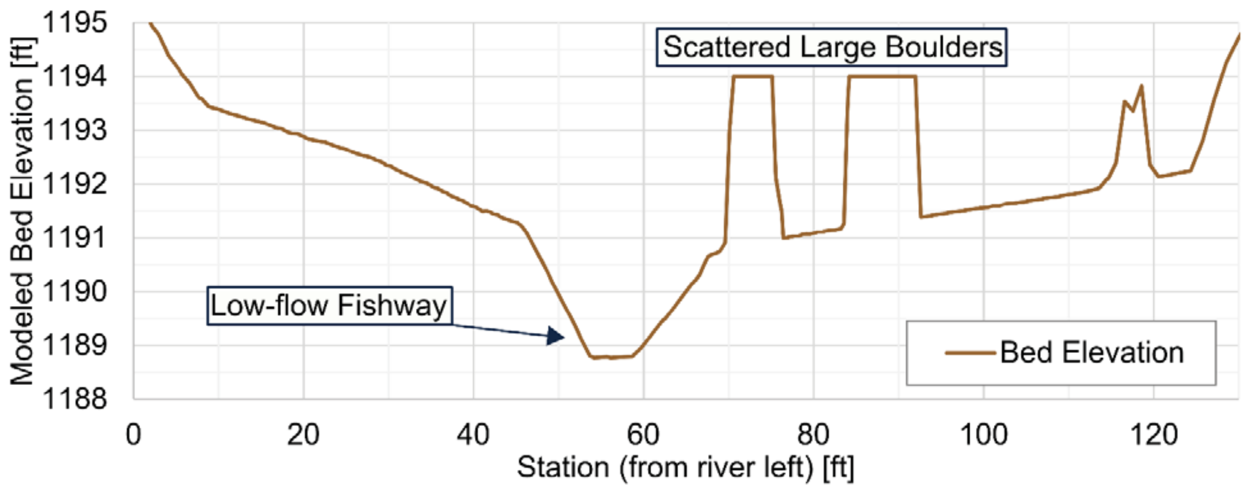


Figure 13. Cross-section showing the modeled bed elevation of the roughened channel and low-flow fishway. The roughened channel is located between stations 75ft to 125ft, which creates a cross slope up the natural channel top-of-bank. Note the large scattered boulders and the side slope towards the banks. Note: vertical scale is exaggerated.

## 3.2 Cofferdam Construction Plan

To effectively work in “the dry”, cofferdams will be used to isolate constuction areas redirect flow around the construction site. The government construction plan involves three consecutive phases, each requiring a unique cofferdam alignment (Figure 14). The propsoed government construction plan may differ from the actual contractor proposals. The objectives of the three phases as defined by the Reclamation design team are:

Cofferdam 1

- Block off the left side (looking downstream, north-side) of the active channel and accomplish construction of the new intake structure and diversion facilitites.

- Perform work that opens up the most usable space first on the right (south) hillslope. Once the access road is built and the intake structure platform is available for use, the roughened channel and south side of creek will be easier to access.

- The work involved with the intake structure is complicated (excavations, formwork, concrete placement, etc.). therefore Due to chances of large rain events in Novermber, the work with the highest chance for delay during construction is scheduled first, so as not to risk be delayed into that time period. a

Cofferdam 2

- Accomplish construction of the low-flow fishway and a portion of the roughened channel on river left (north).

- Perform phase 2 construction as soon as the intake work is complete to begin fish passage construction.

Cofferdam 3

- Complete construction of the roughened channel on river right (south-side).

- Most difficult part of this phase is going to be the access. May involve the construction of a temporary bridge to shift the equipment over to the site in the morning, then removing it every night.

- If possible, this phase can be finished at the end of the first season, or the contractor can remobilze the next summer to complete this phase.

This report documents the hydraulic analysis conducted to determine water surface elevation (WSE) for the three cofferdam configurations to minimize risk of overtopping during construction or cofferdam failure due to high velocity and shear stress values.

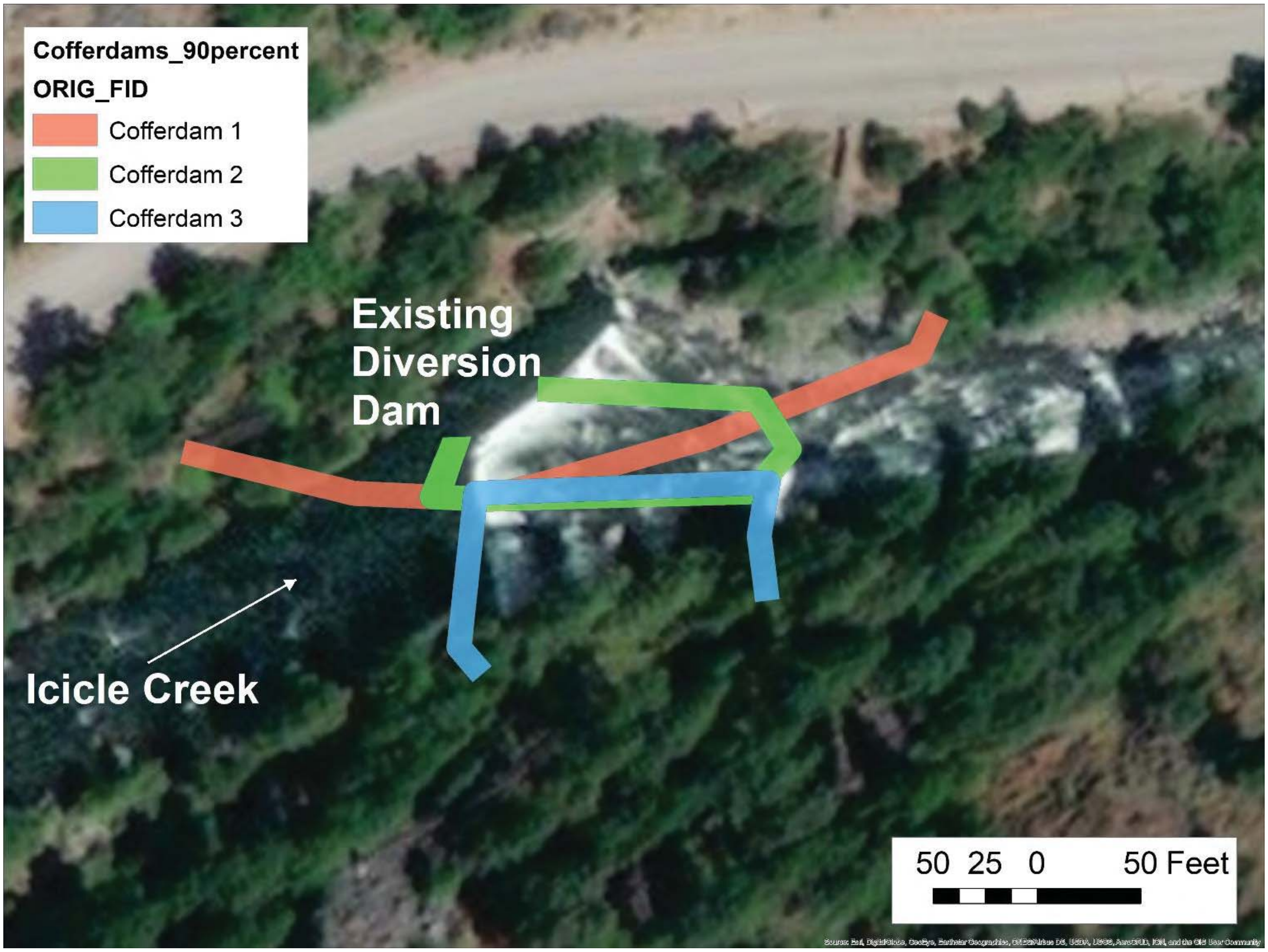


Figure 14. Cofferdam layout for Phase 1, 2 and 3 of construction of new intake and roughened channel.

# 4.0 Fish Screen and Passage Criteria

Under the biological opinion (NFMS, 2017), LNFH is required to provide entrainment protection (fish screens) and fish passage for Bull Trout and Steelhead. Fish screen hydraulics and fish upstream and downstream fish passage criteria are summarized in the following sections as they were used in the hydraulic analysis. Washington Department of Wildlife (WDFW) and NFMS will be reviewing the design.

## 4.1 Fish Migration and Design Discharges

To compute design discharges for evaluating fish criteria, the peak upstream adult ( Table **5**) and peak downstream juvenile (Table 6) migration were documented for Bull Trout and Steelhead/Rainbow Trout. Bull Trout upstream migration typically occurs on the falling limb of the spring snowmelt hydrograph. The peak hydrograph typically occurs between May and June. Specifically, Nelson (2008) found that during an 8-year study, mean peak upstream migration occurred June 22 to August 2, between 28 and 62 days after peak discharge. Steelhead/Rainbow Trout typically migrate upstream in early spring, with peak migration in March and April (written communication Jim Craig, LFC, USFWS, April 27, 2020). Adult and subadult Bull Trout also use Icicle Creek to forage during April to December (Anglin, 2013) and would be expected to migrate upstream through the project site during this time period.

Downstream juvenile migration of Bull Trout and Steelhead/Rainbow Trout typically occurs on the rising limb of the spring (May – June) and fall (September – October) freshets (Wydoski and Whitney, 2003). Adult and subadult Bull Trout may also migrate downstream after foraging during April to December (Anglin, 2013).

The design low flow for fish passage is based on NMFS (2011) criteria using the mean daily average streamflow that is exceeded 95% of the time during periods when migrating fish are normally present at the site. The design high flow is based on NMFS (2011) criteria using the mean daily average streamflow that is exceeded 5% of the time during periods when migrating fish are normally present at the site. Design discharges for adult upstream migration are presented in Table **5** to evaluate passage criteria in the fishway and roughened channel. Design discharges are presented in Table 6 for downstream juvenile migration to evaluate sweeping velocities and exposure times along the fish screens. USFWS expressed an interest in evaluating hydraulics on a monthly basis, particularly for peak migration months, monthly 95 and 5% exceedance values. Additionally, sweeping velocities across the screens are analyzed using the annual 95 and 5% flow exceedance values (75 and 2,219 cfs) for potential aquatic species in Icicle Creek throughout the year. In the results section of this report, the fish passage flows are compared with model output over a range of flows to get a representation of how well criteria are met.

Table 5. Adult upstream migration and foraging timing in Icicle Creek for ESA listed species Bull Trout and Steelhead/Rainbow Trout. Typical upstream migration times are shown in grey and peak migration times are shown as dark grey for fish migrating upstream to spawning areas. Bull trout timing in Icicle Creek for foraging shown in yellow. The 95% and 5% exceedance discharge in units of cfs are shown for each period

| Species and Discharge Exceedance (cfs) | J | F | M | A | M | J | J | A | S | O | N | D |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Bull Trout Adult Migration*** ****1, 2*** **(95% / 5%) cfs** | | | | | | 73 / 3,002 | | | | | | |
| ***Bull Trout Adult/Subadult Foraging*** ****5*** **(95% / 5%) cfs** | | | | 71 / 2,458 | | | | | | | | |
| ***Steelhead/Rainbow Trout*** ****3, 4*** **(95% / 5%) cfs** | | | | 163 / 2,671 | | | | | | | | |
| **Monthly (95% / 5%) cfs** | 102 / 773 | 96 / 855 | 126 / 747 | 219 / 1,489 | 572 / 3,494 | 599 / 3,478 | 129 / 2,082 | 60 / 513 | 54 / 295 | 70 / 651 | 76 / 1,210 | 94 / 898 |

*1: Nelson, 2008; 2: Wydoski and Whitney. 2003; 3: Hall, et al., 2014; 4: written communication Jim Craig, LFC, USFWS, April 27, 2020); 5: Anglin et al., 2013

Table 6. Peak juvenile downstream migration during spring and fall freshets with the 95% and 5% exceedance value for those periods (Wydoski and Whitney, 2003)

| Species and Discharge Exceedance (cfs) | J | F | M | A | M | J | J | A | S | O | N | D |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Bull Trout (95%/5%) cfs** | | | | | 581 / 3,483 | | | | 64 / 523 | | | |
| **Steelhead /Rainbow Trout (95%/5%) cfs** | | | | | 581 / 3,483 | | | | 64 / 523 | | | |
| **Monthly (95%/5%) cfs** | | | | | 572 / 3,494 | 599 / 3,478 | | | 54 / 295 | 70 / 651 | | |

## 4.2 Fish Screen Hydraulic Requirements

The NMFS guidance (2011), state the following criteria with regards to fish screen criteria:

- The approach velocity must not exceed 0.40 ft/s for active screens.

- End of pipe screens must be submerged to a depth of at least one screen radius (1.25 ft) below the minimum water surface, with a minimum of one screen radius clearance between screen surfaces and natural or constructed features.

- Screens longer than 6 feet (design includes two 10 ft screens) must be angled more parallel with the flow and have sweeping velocity greater than the approach velocity. This angle may be dictated by site-specific geometry, hydraulic, and sediment conditions. Optimally, sweeping velocity should be between 0.8 ft/s and 3 ft/s. Sweeping velocity must not decrease along the length of the screen.

- The screen should be constructed at the point of diversion with the screen face generally parallel to river flow. For screens constructed at the bankline, the screen face must be parallel with the adjacent bankline and the bankline must be shaped to smoothly match the face of the screen structure to minimize turbulence and eddying in front, upstream, and downstream of the screen.

- Structural features must be provided to protect the integrity of the fish screens from large debris, and to protect the facility from damage if overtopped by flood flows.

The NMFS draft guidance (2018) additionally state:

- All screen facilities must be designed to function properly and protect fish from being entrained into the water diversion under the full range of location specific hydrologic conditions (low flow to 100-yr recurrence interval). .In situations where streambank overtop before the 100-yr flood event, the screen may be designed to overtop at flows equivalent to main channel capacity.

WDFW also require the following criteria/information regarding fish screen hydraulics (written communication Amanda Barg, WDFW habitat biologist, February 27, 2020):

- Minimize exposure time along the screens (sweeping velocity times length of screen) for juvenile downstream fish passage

- Provide an overlay of out migration to sweeping velocity timing

- Fish-friendly sediment removal and management plan (salmon, steelhead, bull trout, resident fish and pacific lamprey)

## 4.3 Fish Passage Hydraulic Requirements

The NFMS (2011) criteria state the following with regards to upstream fish passage hydraulic requirements:

- Minimum water depth at the low fish passage design flow should be: 1.0 feet for adult steelhead, Chinook, coho, and sockeye salmon; 0.75 feet for pink and chum salmon; and 0.5 feet for all species of juvenile salmon.

- Pool head differential should be less than 1 ft.

- No criteria are available for maximum velocity values for upstream fish passage. Culvert velocity criteria are applied. Maximum average water velocity for a 100 to 200 ft culvert length is 4 ft/s for Chinook, Steelhead, and Coho adults, 3 ft/s for pink and Chum adults, and 1 ft/s for juvenile salmonids.

**Table 7-1.** Maximum Allowable Average Culvert Velocity

| Culvert Length (ft) | Maximum Average Velocity (ft/s) | | |
|---|---|---|---|
| | Chinook, Steelhead, Sockeye, and Coho Adults | Pink and Chum Adults | Juvenile Salmonids |
| <60 | 6.0 | 5.0 | 1.0 |
| 60-100 | 5.0 | 4.0 | 1.0 |
| 100-200 | 4.0 | 3.0 | 1.0 |
| 200-300 | 3.0 | 2.0 | 1.0 |
| >300 | 2.0 | 2.0 | 1.0 |

Figure 15. Maximum allowable average culvert velocity guidance used to set criteria for fish passage in roughened channels in NMFS (2011).

The Washington Administrative Code (WAC 220-660-200) states the following criteria for fish passage improvement structures:

- Minimum water depth at any location within a hydraulic design passage structure without a natural bed must be at least 0.8 ft.

- The hydraulic drop within the culvert or at the culvert inlet or outlet may not exceed 0.5 ft. When a drop has a submerged jet (the lowest part is below the downstream water surface) or is part of a natural or roughened channel design, the department may approve an exception to this criterion.

- Roughened channels must create an average cross-section velocity within the limits of fish-passage design criteria and the hydraulic design option. WDFW uses culvert design criteria to set goals for velocities in roughened channel designs. Maximum water velocity may not exceed 3 ft/s for 100 to 200 ft culvert length or 4 ft/s for 10 to 100 ft culvert length at any point. Further velocity criteria guidance was provided via written communication (Amanda Barg, WDFW habitat biologist, February 27, 2020) "In a larger river it would be acceptable if only a portion of the roughened channel width, perhaps 10-20%, meets the velocity and depth criteria during high flows. Those sections would need to meet the criteria for the full length of the channel (downstream to upstream). The velocity criteria don't have to be met at the low-flow boulder weir fishway, just within the cross-section of the roughened channel."

## 4.4 Roughened Channel Design Requirements (NFMS)

As noted in NMFS (2011), "Designs of roughened channels vary depending on the specific site conditions. Criteria for this type of passage design are evolving, and proposals for this type of ladder are assessed on a site-specific basis." NMFS (2011) provides the following guidance for roughened channels:

- Channel slope using stream simulation is less than 6%.
- Total length of passage is less than 150 feet.
- An appropriate mix of bed materials (from fines to boulder sized material) are used such that flow depths of at least 1 foot can be maintained for upstream adult salmonid passage.
- Sub-surface flow will be minimized by filling voids between larger materials with finer-sized material.
- Arrangement of bed materials should demonstrate similar channel complexity to the adjacent stream reaches.
- To minimize the potential for head-cutting to occur, discrete hydraulic drops across the entire width of the roughened channel should be avoided.
- Any site utilizing a constructed roughened channel must include an annual (at a minimum) monitoring plan at least until after a 50-year stream flow event has occurred.

# 5.0 Hydraulic Model Results

A 2D hydraulic model was developed to analyze and inform design considerations and better assess fish passage concerns. For more information on hydraulic model development, see Appendix C. Based on the hydrologic modeling from Clarkin (2019 and 2020), a subset of discharges were modeled (Table 7). For all discharges listed in this report, a constant 42 cfs is removed from the model at the location of the intake structure (e.g. for a modeled discharge of 75 cfs, only 33 cfs is passing the intake structure to the downstream boundary of the model). When flow magnitudes important for analysis were within 5%, the same flow value was applied to the model as results would not be significantly different.

The following sections highlight the hydraulic model results for the low-flow fishway, the roughened channel, and the intake structure focusing on fish passage and design criteria.

Table 7. Modeled discharges for design analysis

| Modeled Incoming Discharge (After intake diversion) (cfs) | Corresponding Hydrologic Analysis Method |
|---|---|
| 75 (33) | Bull trout upstream 95% migration flows (73 cfs) & foraging (71 cfs); minimum discharge modeled |
| 100 (58) | Future minimum flow in drought years per Icicle Work Group |
| 163 (121) | Stealhead/Rainbow trout upstream 95% migration flow |
| 298 (256) | 50% mean daily |
| 401 (359) | 40% mean daily |
| 523 (481) | Sept/Oct downstream 5% migration flow (both species) |
| 586 (544) | May/June downstream 95% migration flow (581 cfs, both species) |
| 906 (864) | 20% mean daily |
| 1,600 (1,558) | intermediate discharge |
| 2,219 (2,177) | 5% mean daily |
| 2,458 (2,416) | Bull Trout foraging 5% flow |
| 2,671 (2,408) | Steelhead/Rainbow trout upstream 5% migration flow |
| 3,002 (2,952) | Bull Trout upstream 5% migration flow |
| 3,483 (3,441) | May/June downstream 5% migration flow (both species) |
| 4,100 (4,058) | 50% peak discharge (2-yr) |
| 7,500 (7,458) | 10% peak discharge (10-yr) |
| 13,300 (13,258) | 1% peak discharge (100-yr) |
| 19,800 (19,758) | Peak discharge on record |

## 5.1 Upstream Passage: Low Discharges

The low-flow fishway is designed to provide depth and velocities at low discharges that meet the following upstream fish passage criteria: 1 ft depth (0.8 ft, per WDFW), less than 1 ft hydraulic drops between boulder weirs, and less than 3 ft/s velocity (4 ft/s for distances between 10 and 100 ft).

To analyze the low-flow fishway for depth and hydraulic drop criteria, the lowest design discharge of 75 cfs (inlet, 33 cfs through the fishway as 42 cfs is diverted) is presented (Figure 16, Figure 17). Flow through the fishway creates a continuous path of flow depths greater than 1 ft, deeper in the pools behind the weirs and in the backwater created by the natural boulder drops. At these low discharges when depth of flow over the crest is less than 1 ft, fish would need to jump over the crest to reach the upstream pool. Upstream fish passage through the low-flow fishway is limited by the velocity because depth is greater than 1 ft for all modeled discharges. Velocity in the low-flow fishway at 75 cfs is below 3 ft/s, except between the boulders and at the crest at the fishway exit. Recirculation zones (velocity vectors directed upstream) form along the outer edges of the low-flow fishway and boulder weirs. These zones provide resting areas as fish migrate upstream.

The natural boulder cluster directly downstream of the roughened channel and low-flow fishway creates a hydraulic control causing backwater at low flows (circled in Figure 16, Figure 17). Flow depth and velocity over the natural boulder drop are less than 1 ft and greater than 3 ft/s, respectively. The natural flow path through the boulder drop aligns with the main flow path of the low-flow fishway.

At 75 cfs, the hydraulic drop between the boulder weirs meets criteria, averaging 0.8 ft and not exceeding 1 ft (Figure 18). The low-flow boulder weir fishway is designed with 2 ft spacing between each boulder to provide through-swimming throughout the boulder weirs where depths exceed 1 ft. At the notch of the low-flow fish channel, there is insufficient depth for through-swimming; however, the hydraulic drop does not exceed 0.4 ft.

At approximately 100 cfs, flow begins to fill in the remaining areas of the low-flow fishway and spread out over the roughened channel (Figure 19). However, continuous paths of flow depth less than 1 ft on the roughened channel do not exist until 401 cfs.

As discharge increases beyond 100 cfs, flow spills out onto the roughened channel and the focus of upstream passage shifts to a combination of the low-flow fishway and the roughened channel. Velocities through the low-flow fishway are less than the required 3 ft/s for discharges between 100 cfs to 298 cfs (Figure 20, Figure 21). Continuous paths with flow depths of 1 ft or greater begin to form along the right edge of the low-flow fishway at approximately 298 cfs. By 401 cfs, considerable areas of flow depth greater than 1 ft are available for fish passage on the roughened channel. As discharge reaches 401 cfs, large portions of the low-flow fishway have velocity values greater than 3 ft/s. Potential swimming paths are available on the middle portion of the roughened channel where velocities are slower due to the boulders.

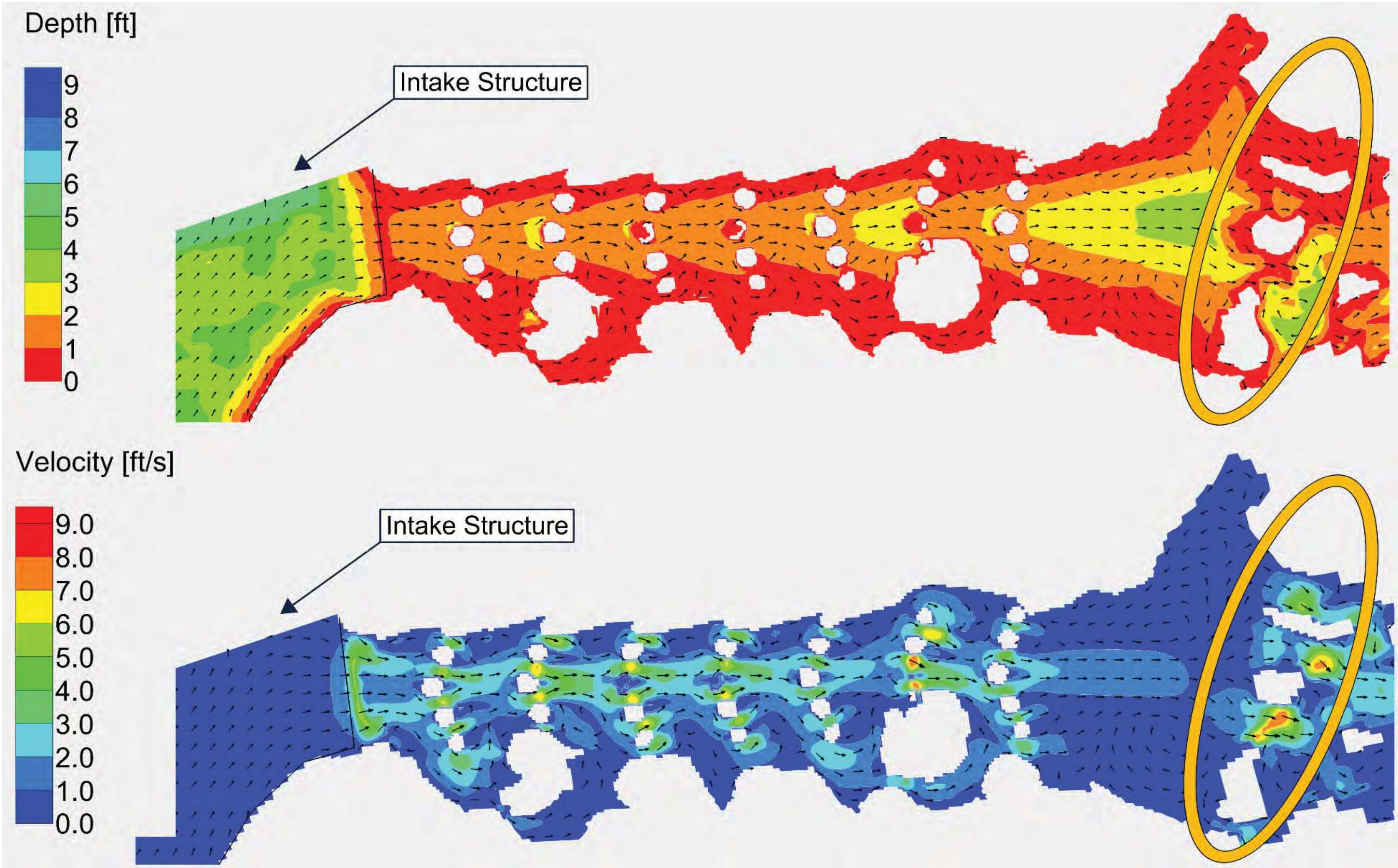


Figure 16. Modeled depth (top) and velocity (bottom) in the low-flow fishway at 75 cfs show 1 ft and 1 ft/s contours, respectively. Flow depth through the low-flow fishway is greater than 1 ft, except on the margins and the crest at the fishway exit (shown as dark blue). Velocity through the low-flow fishway is below 3 ft/s for the vast majority of the fishway, except between boulders and at the crest. Note: the hydraulic conditions of the natural boulder drop downstream of the low-flow fishway (circled in yellow).

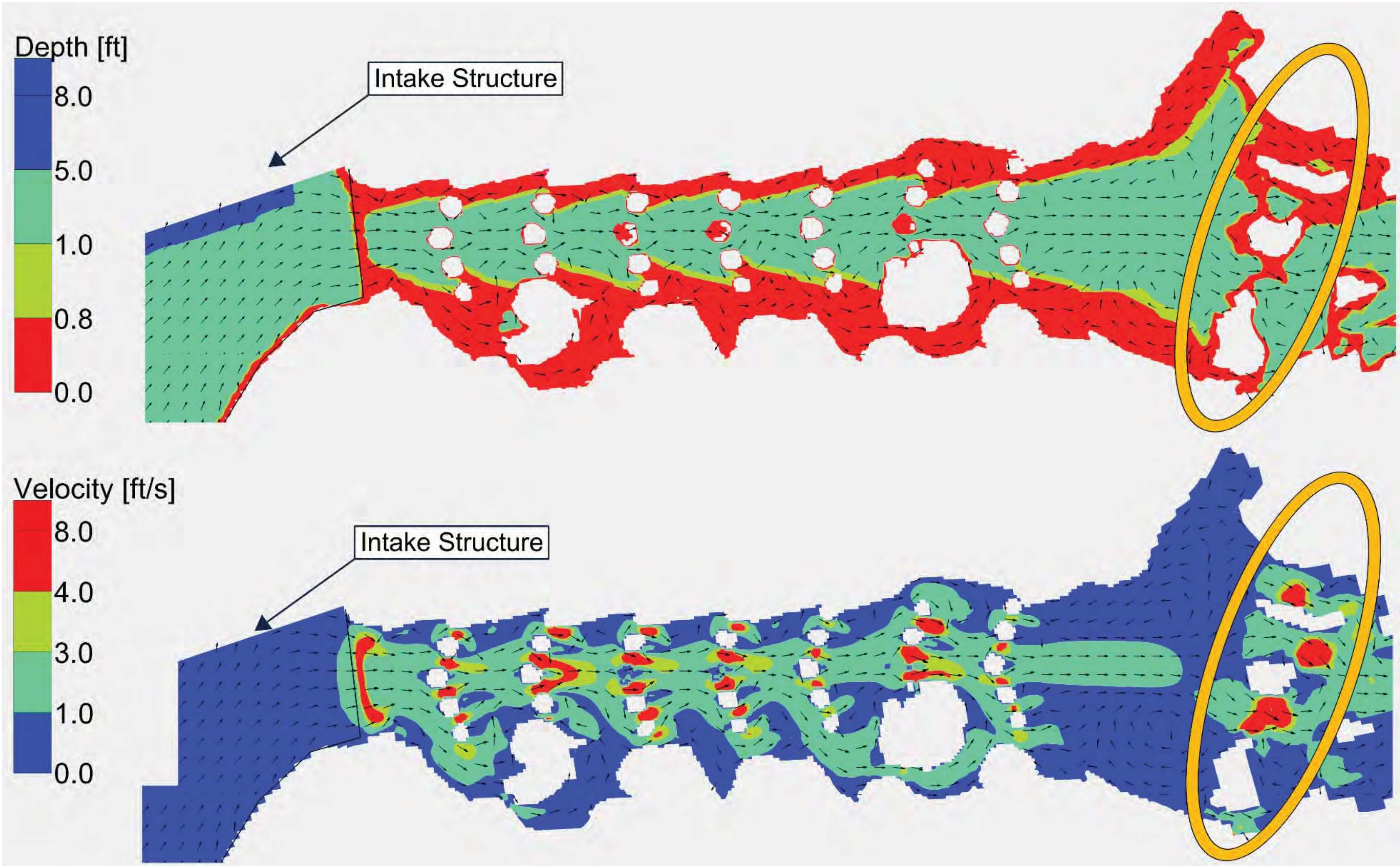


Figure 17. Modeled depth (top) and velocity (bottom) in the low-flow fishway at 75 cfs show contours based on criteria. Flow depth through the low-flow fishway is greater than 1 ft, except on the margins and the crest at the fishway exit (shown as dark blue). Velocity through the low-flow fishway is below 3 ft/s for the vast majority of the fishway, except between boulders and at the crest. Note: the hydraulic conditions of the natural boulder drop downstream of the low-flow fishway (circled in yellow).

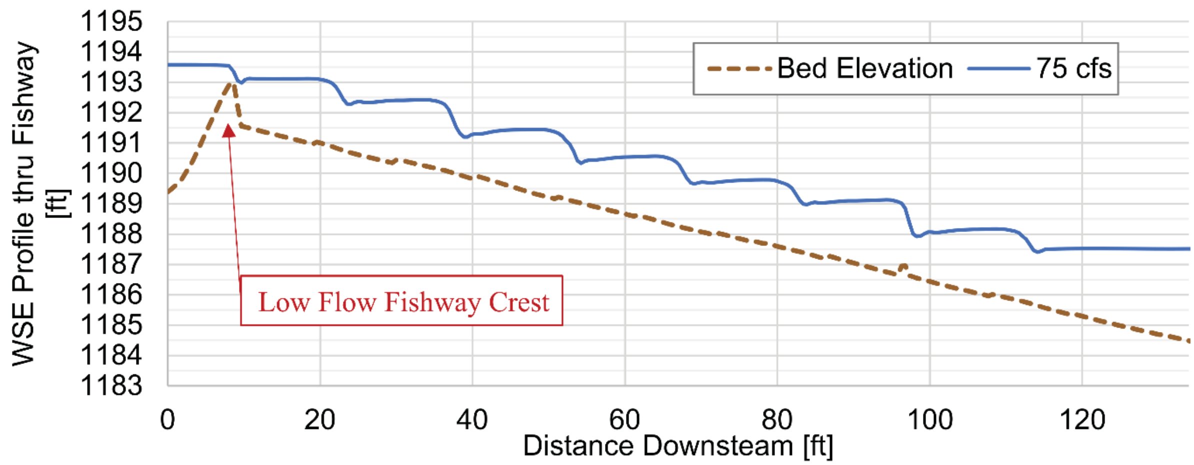


Figure 18. WSE through low-flow fishway shows drop height through the fishway. Note: bed elevation of actual boulder weirs not shown to highlight through swimming between the boulders. Note: vertical scale is exaggerated.

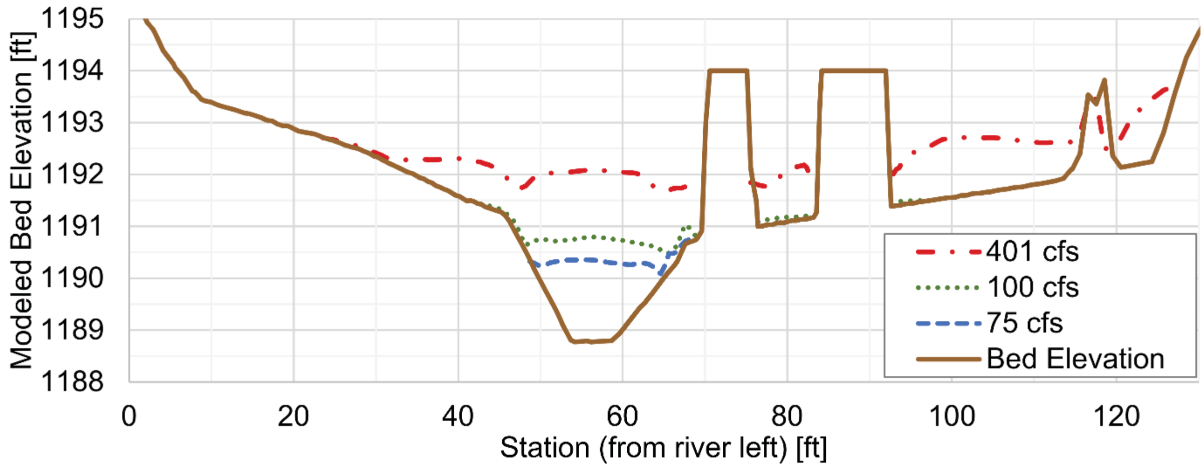


Figure 19. Cross-section profile at approximately mid-point of roughened channel showing the bed elevation (brown) and modeled WSE for 75 cfs (blue), 100 cfs (green), and 401 cfs (red). Note: vertical scale is exaggerated.

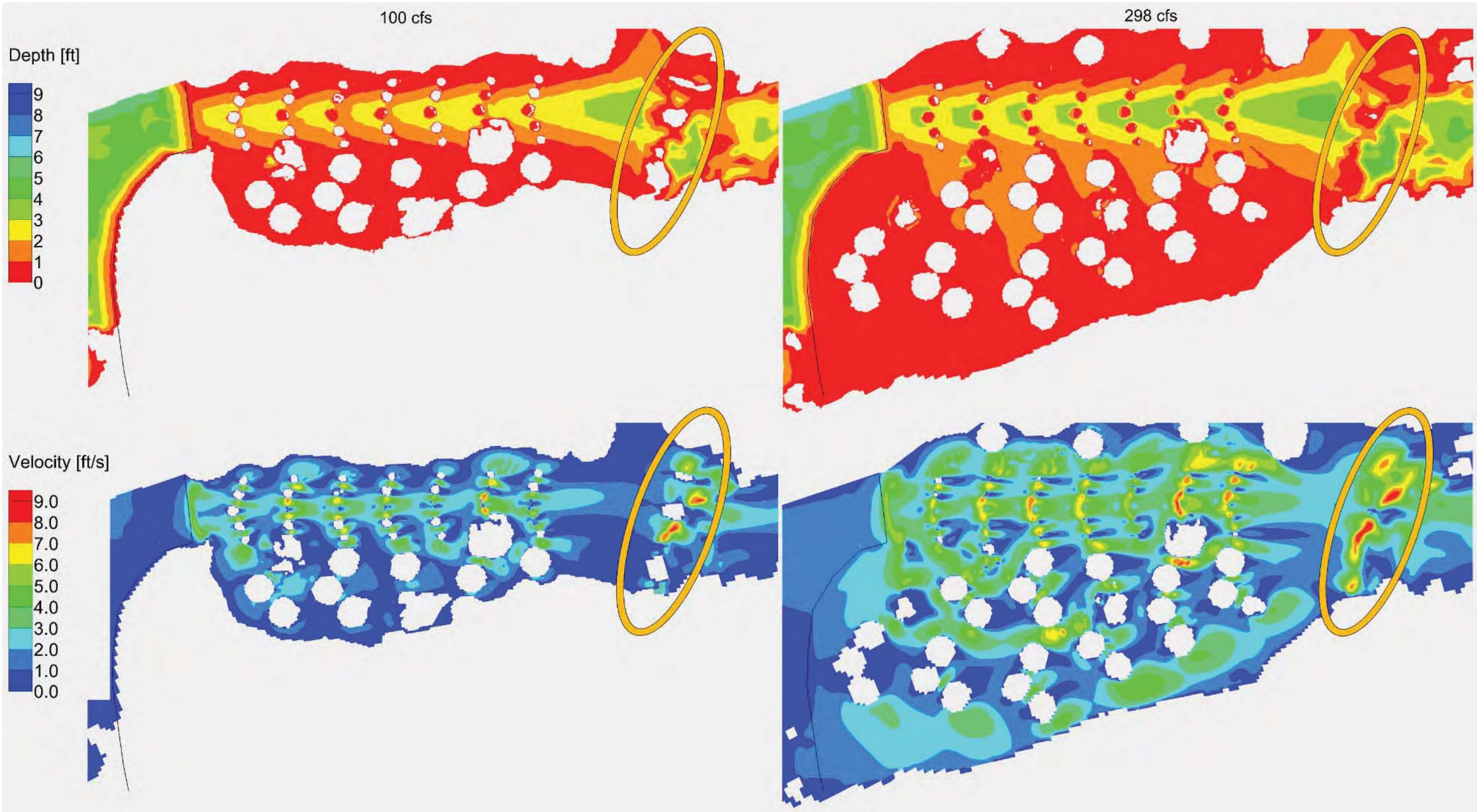


Figure 20. Modeled depth (left) and velocity (right) for discharges 100, 298, and 401 and 298 cfs shown with 1 ft and 1 ft/s intervals, respectively. The natural boulder drop directly downstream of the proposed roughened channel is circled (yellow) for reference to natural conditions in Icicle Creek.

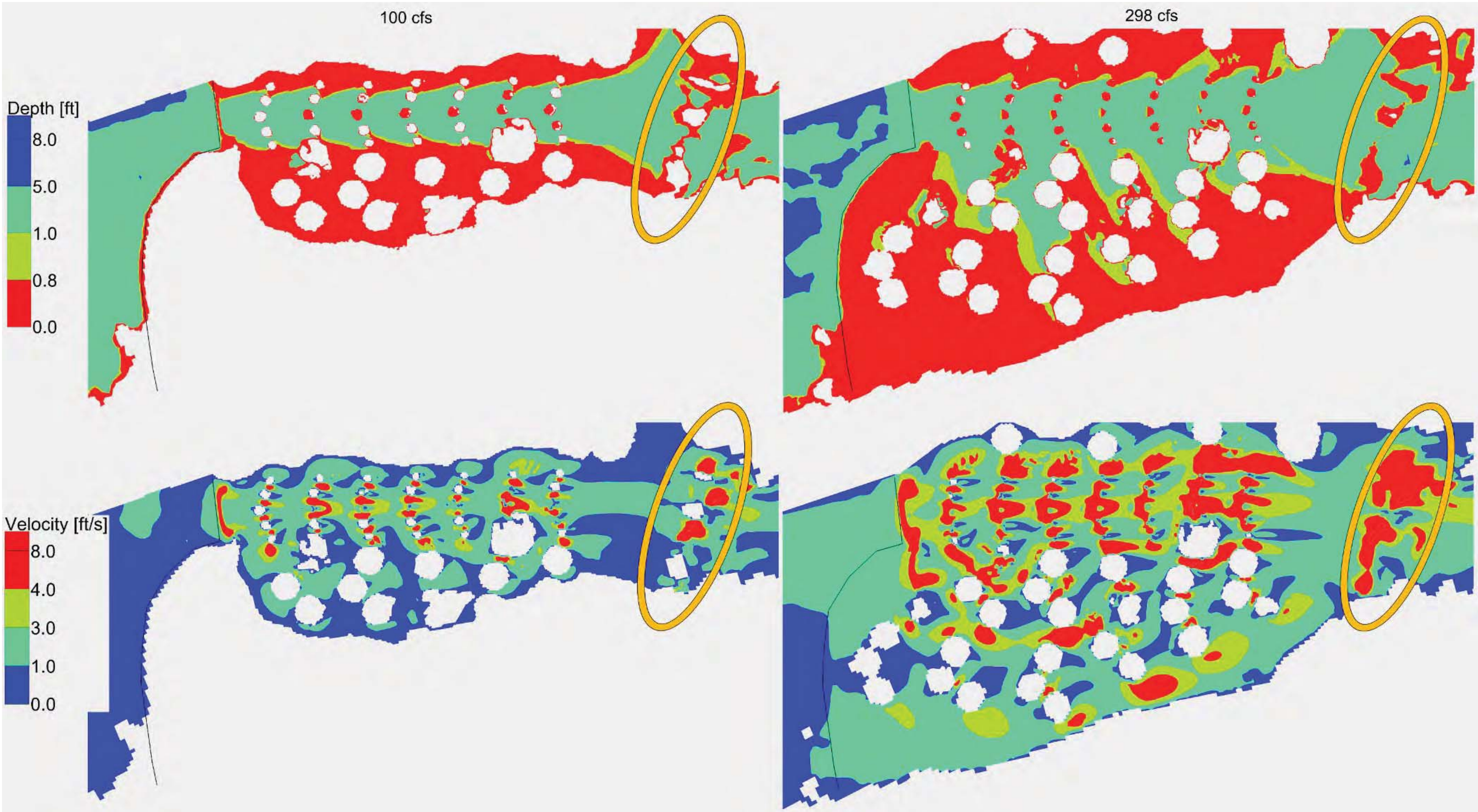


Figure 21. Contours showing the modeled depth (left) and velocity (right) for discharges 100, 298, and 401 and 298 cfs based on criteria. The natural boulder drop directly downstream of the proposed roughened channel is circled (yellow) for reference to natural conditions in Icicle Creek.

## 5.2 Upstream Passage: High Discharges

As discharge increases from 401 cfs, flow depths throughout the roughened channel are greater than 1 ft, also meeting the 0.8 ft depth criteria (Figure 22, Figure 23). Therefore, velocity becomes the dominant factor and focus of upstream fish passage shifts from the low-flow fishway to the roughened channel. At discharges ranging between 586 to 906 cfs, areas with velocity less than 3 ft/s decrease, but potential longitudinal pathways can still be observed (Figure 24, Figure 25). The distance between low-velocity zone through which fish may be expected to burst is approximately 5 to 10 ft. At approximately 1,600 cfs, zones of higher velocity over the low-flow fishway and along the right side of the boulder clusters become more defined and continuous. The boulder clusters on the roughened channel provide adequate low-velocity and recirculation zones throughout the length of the roughened channel. However, longitudinal paths become less defined. The distance fish are expected to burst swim between resting zones is approximately 10 to 15 ft.

The upper-end of the upstream passage discharges (2,671 and 3,002 cfs) shows the majority of the roughened channel with velocity greater than 3 ft/s (Figure 26, Figure 27). The distance between low-velocity zones behind the boulder clusters increases to approximately 15 to 30 ft in the center of the roughened channel. At these large discharges, fish are expected to navigate the low velocity zones along the margins of the channel, much like they would in the natural system.

To further analyze the velocity on the roughened channel at high discharges, cross-sections (XS) were selected at three locations along the roughened channel. Velocity was sampled along the length of the cross section. These were compared to two locations in the natural channel for reference: the natural boulder drop and natural riffle (Figure 28). Figure 29 shows modeled velocities sampled along each XS and grouped by discharge relevant to upstream fish migration. For example, at 586 cfs (30% mean daily), the average XS velocities within the roughened channel (2.4, 3.1, and 3.2 ft/s for XS-upper, XS-middle, and XS-lower, respectively) are lower than the average velocity along the two reference XSs (6.4 ft/s and 6.4 ft/s). The average velocity along all three roughened channel XSs are lower than those of the reference XSs. At higher discharges (1,600 cfs, 2,671 cfs, and 3,002 cfs), the majority of locations in the roughened channel XSs show modeled velocities greater than 3 ft/s. At 1,600 cfs, at least 16% of the points along the roughened channel XSs are less than 3 ft/s. For the same high discharges, velocity in the reference XSs never average below 8 ft/s and have no local areas below 3 ft/s.

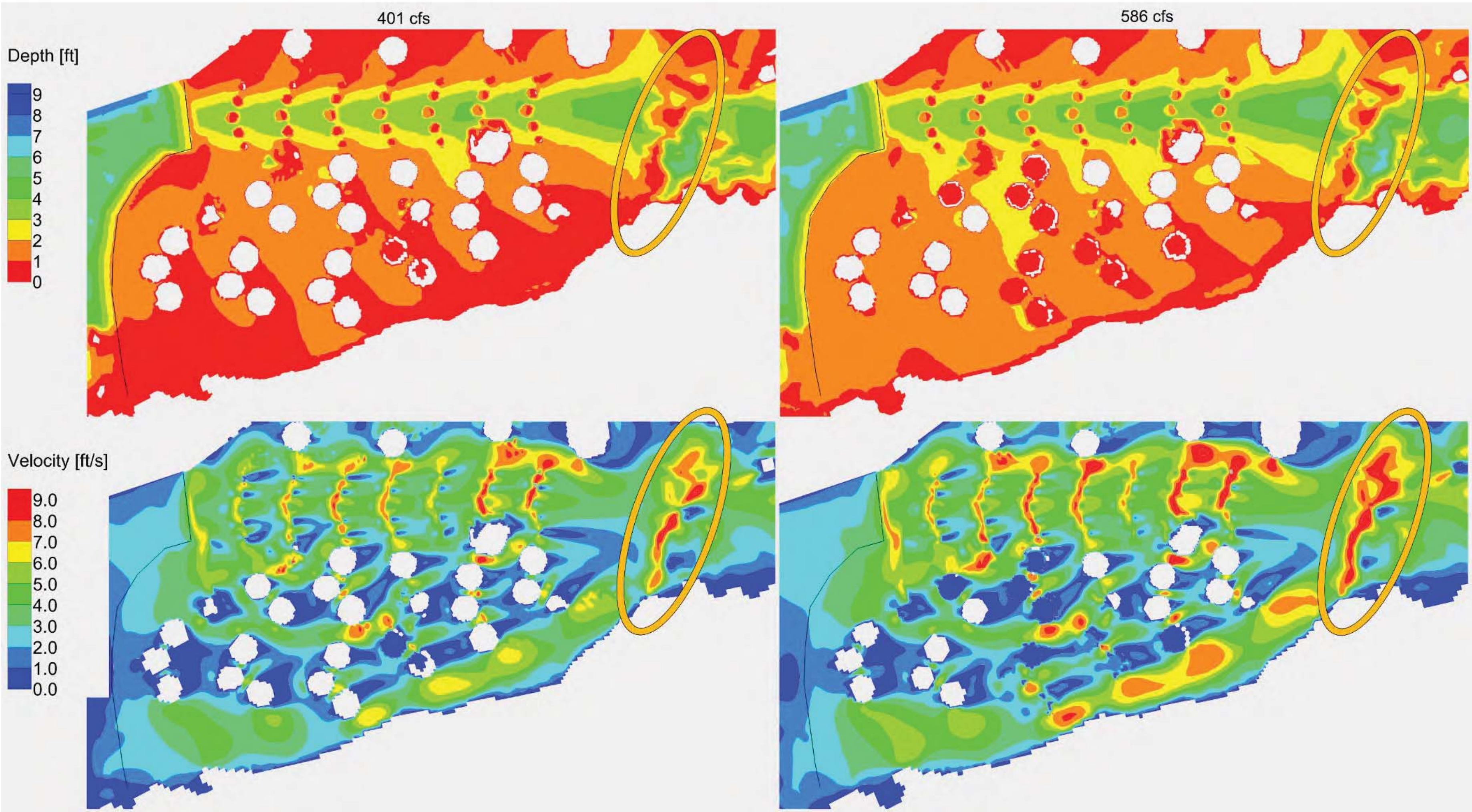


Figure 22. Modeled depth (left) and velocity (right) for discharges 401 and 586 cfs shown with 1 ft and 1 ft/s intervals, respectively. The natural boulder drop directly downstream of the proposed roughened channel is circled (yellow) for reference to natural conditions in Icicle Creek.

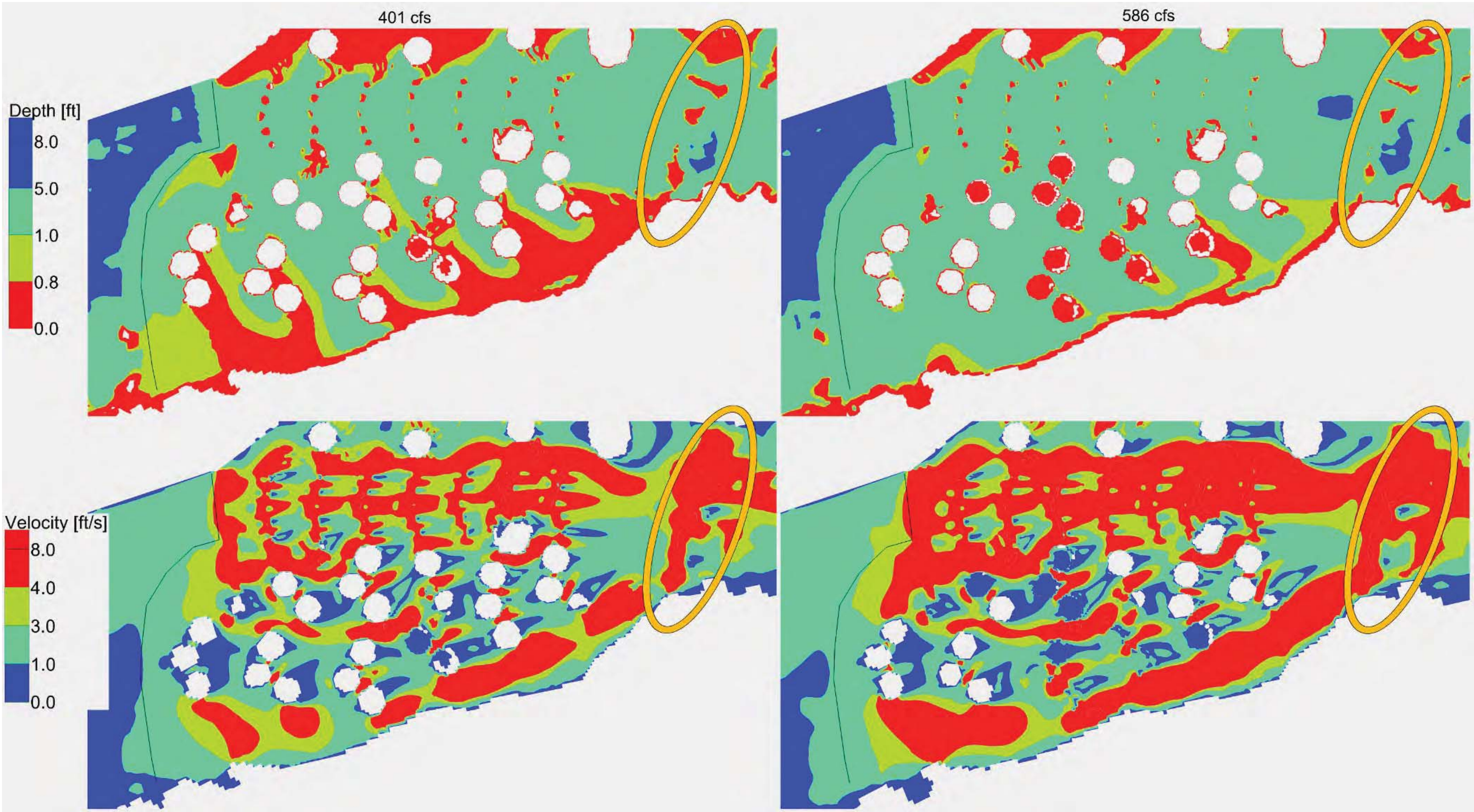


Figure 23. Contours showing the modeled depth (left) and velocity (right) for discharges 401 and 586 cfs based on criteria. The natural boulder drop directly downstream of the proposed roughened channel is circled (yellow) for reference to natural conditions in Icicle Creek.

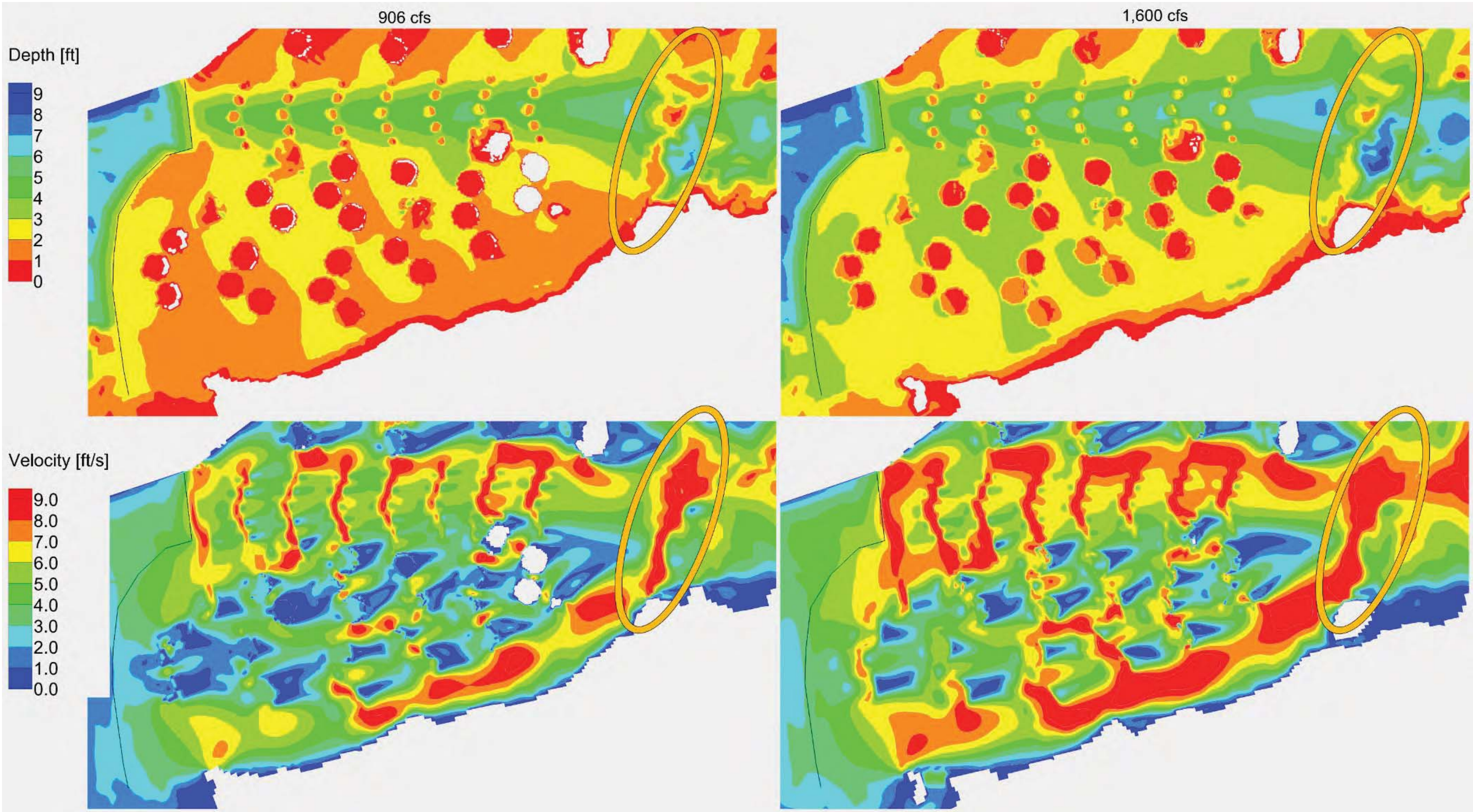


Figure 24. Modeled depth (left) and velocity (right) contours 906 and 1,600 cfs shown with 1 ft and 1 ft/s intervals, respectively. The natural boulder drop directly downstream of the proposed roughened channel is circled (yellow) for reference to natural conditions in Icicle Creek.

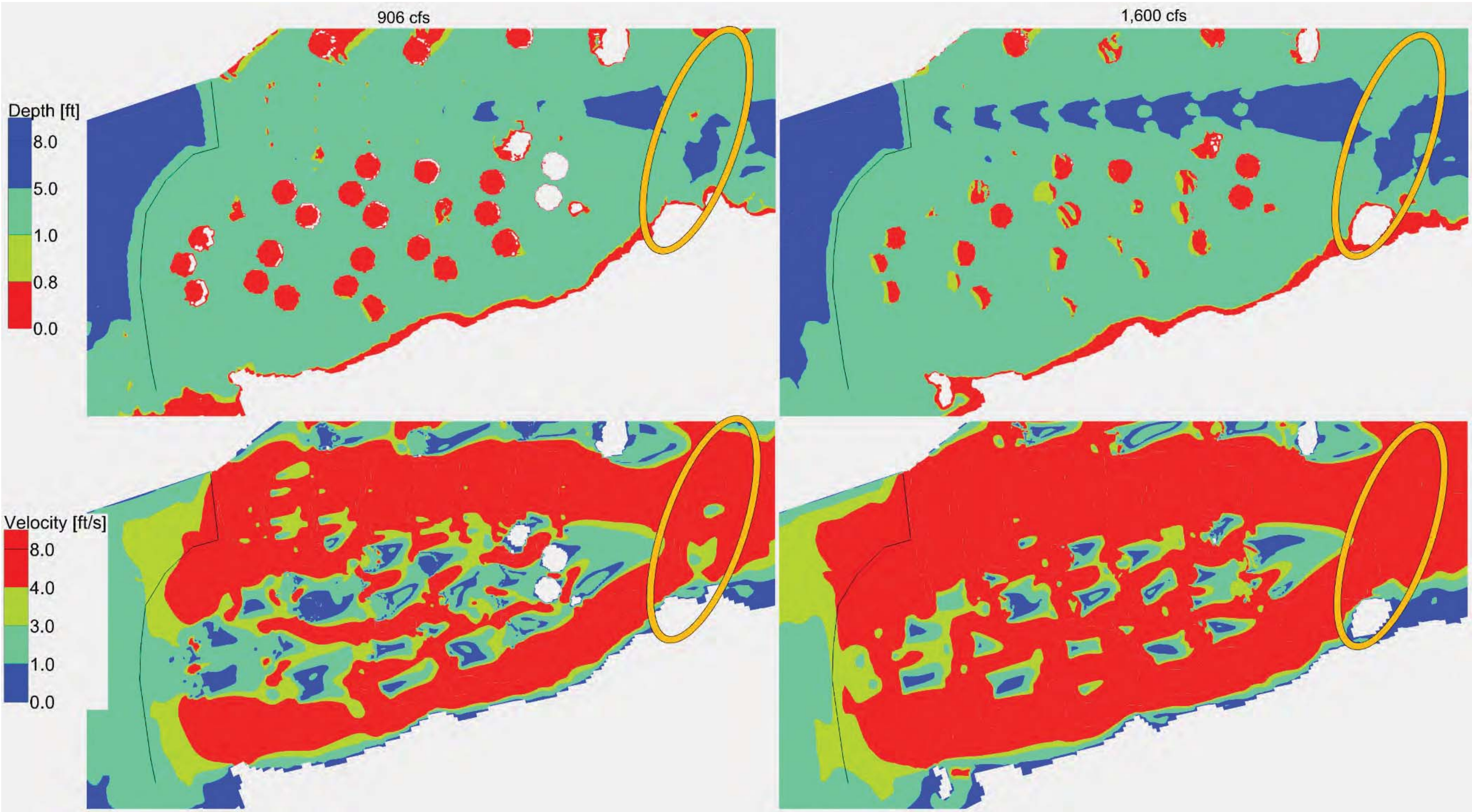


Figure 25. Contours showing the modeled depth (left) and velocity (right) for discharges 906 and 1,600 cfs based on criteria. The natural boulder drop directly downstream of the proposed roughened channel is circled (yellow) for reference to natural conditions in Icicle Creek.

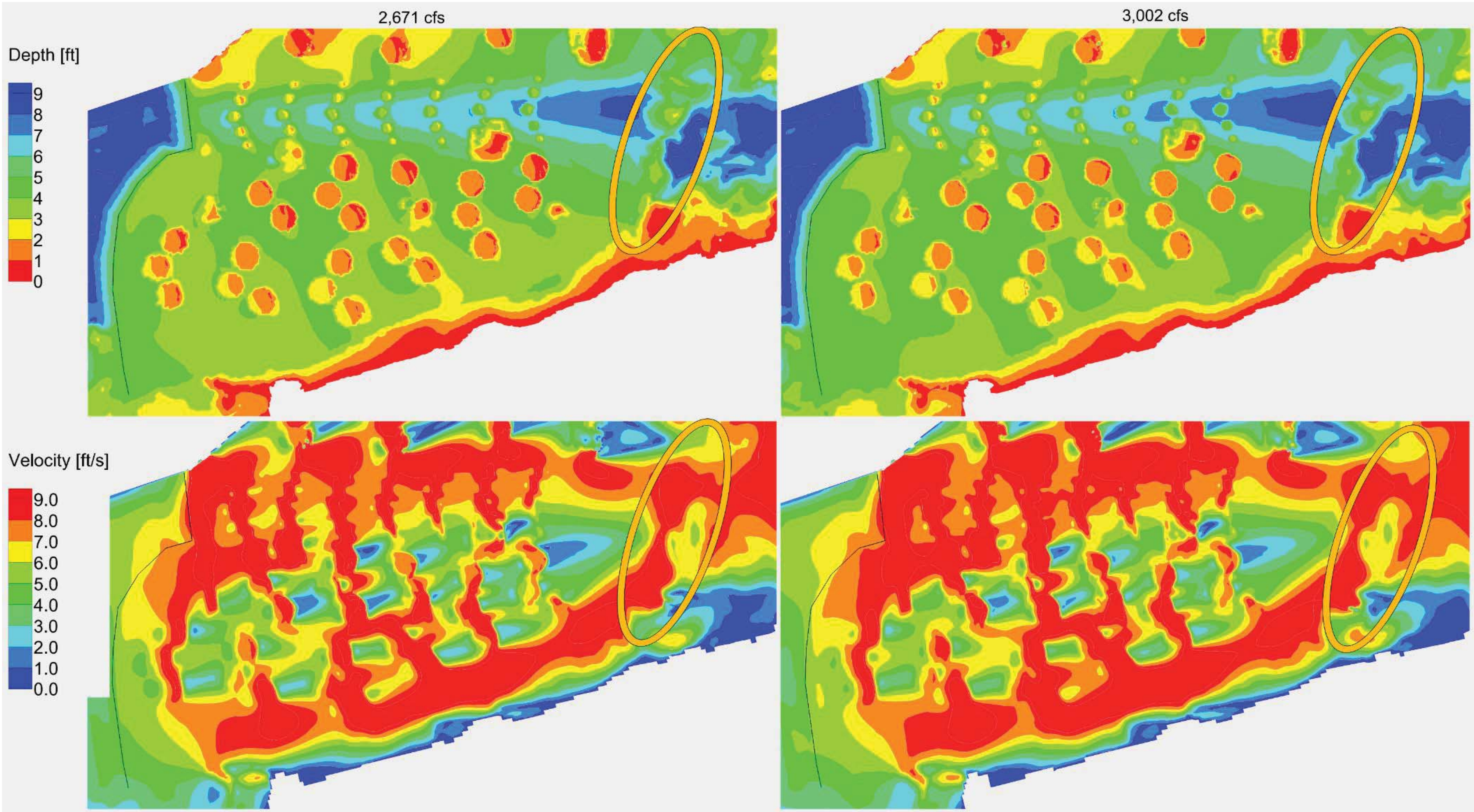


Figure 26. Modeled depth (left) and velocity (right) contours 2,671 and 3,002 cfs shown with 1 ft and 1 ft/s intervals, respectively. The natural boulder drop directly downstream of the proposed roughened channel is circled (yellow) for reference to natural conditions in Icicle Creek.

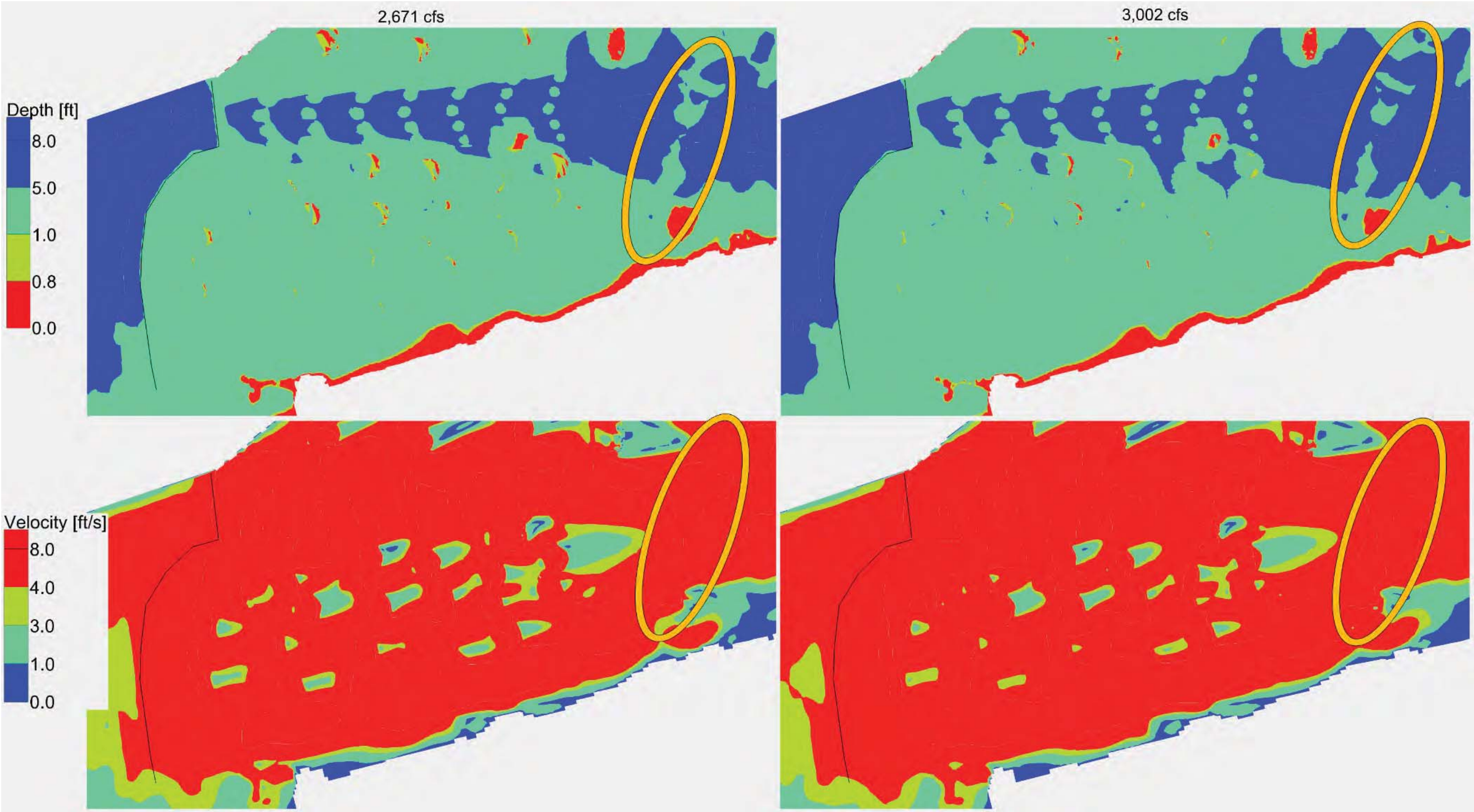


Figure 27. Contours showing the modeled depth (left) and velocity (right) for discharges 2,671 and 3,002 cfs based on criteria. The natural boulder drop directly downstream of the proposed roughened channel is circled (yellow) for reference to natural conditions in Icicle Creek.

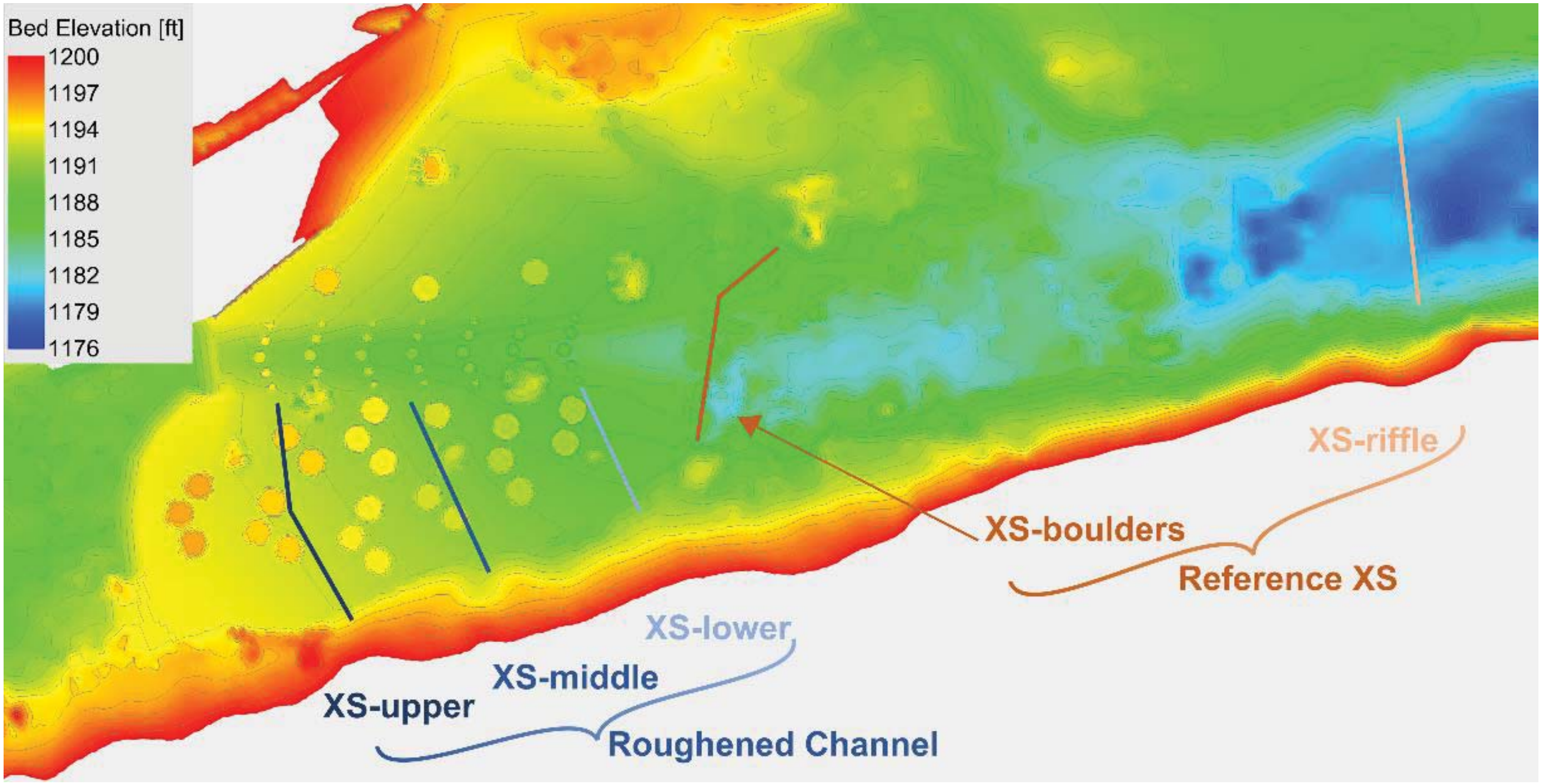


Figure 28. Modeled velocities were sampled along the cross-section locations shown. Three roughened channel cross-sections (XS-upper, XS-middle, and XS-lower) and two reference (XS-boulders and XS-riffle).

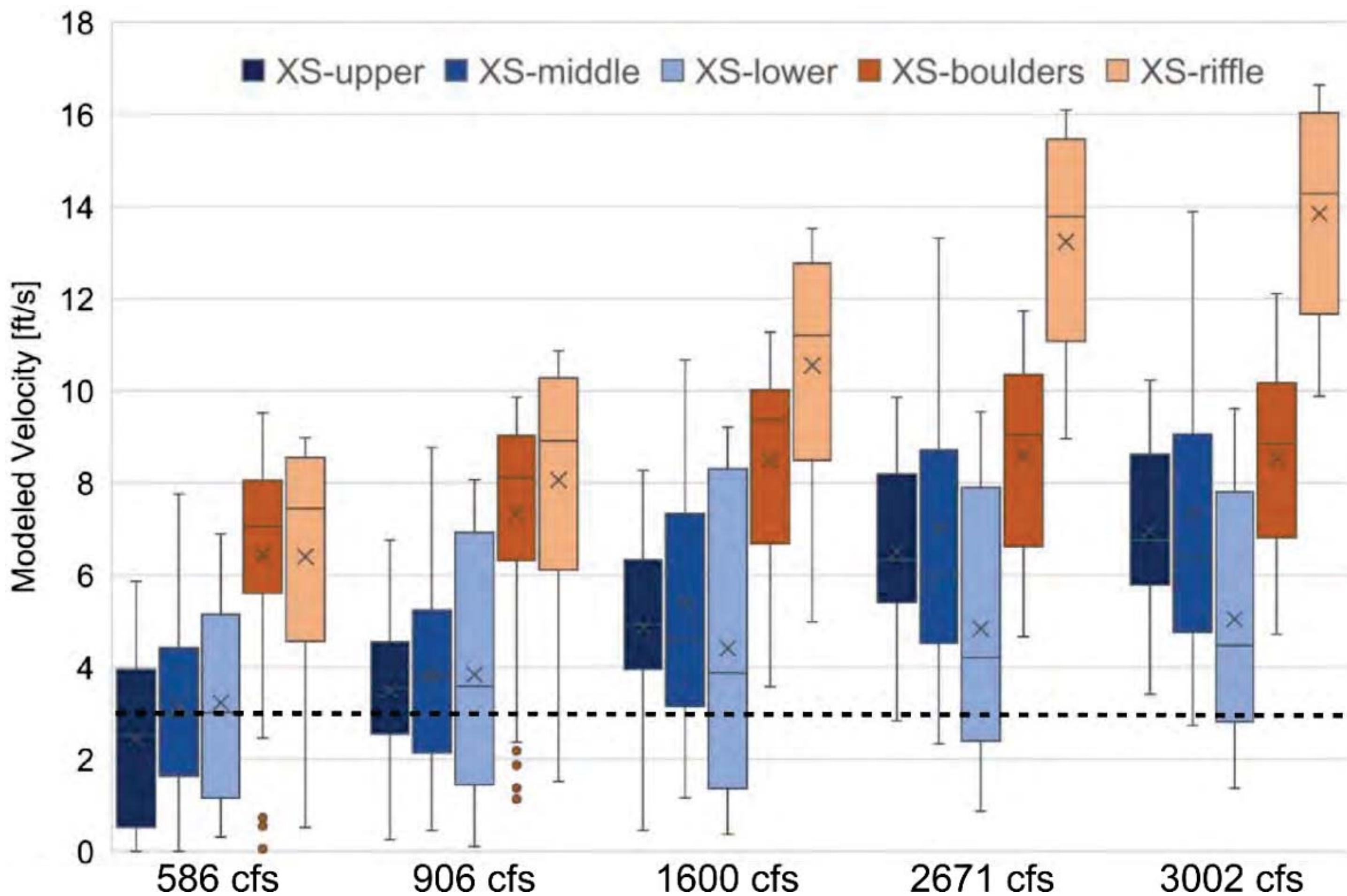


Figure 29. Comparison of modeled velocity between proposed design and natural channel sampled along five cross-sections. The XS-upper, XS-middle, and XS-lower are located within the proposed designed roughened channel at the upstream end, the middle, and downstream end, respectively. These are compared to two natural reference cross-sections: XS-boulders and XS-riffle. The line represents the median velocity, the X is the mean velocity, the box represents the upper and lower quartile range, the whiskers show the upper and lower extremes, and outliers are shown in as circles. The black dashed line shows the velocity criteria of 3 ft/s.

## 5.3 Fish Screen Operations

Hydraulic conditions at the intake structure entrance are of concern for fish screen operations and impingement risk (submergence, sweeping velocity, and exposure time along the screen) and design considerations for freeboard during the 100-yr flood. To analyze fish screen hydraulic criteria for submergence, sweeping velocity, and exposure time, the full range of mean daily flows within a typical hydrologic year are considered.

The required submergence of 5 ft is calculated from the concrete pad elevation of 1,188 ft over which the screens will be constructed. The top of the screen is at 1,191.75 ft. Modeled WSE at lowest modeled discharge, 75 cfs, at the intake structure is approximately 1,193.6 ft. The total submergence at this discharge is 5.6 ft and depth to the top of the screen is 1.85 ft.

Sweeping velocity is required to be greater than 0.8 ft/s, or two times the fish screen approach velocity of 0.4 ft/s. The roughened channel creates deep, slow moving flow near the intake structure. At the lowest modeled discharge (75 cfs), the modeled sweeping velocity at the intake structure is approximately 0.6 ft/s and increases with discharge (Table 8). Several additional discharges are shown to highlight when sweeping velocity is achieved. At approximately 100 cfs, , the sweeping velocity meets the required 0.8 ft/s. It should be noted that velocity reported is depth-averaged velocity and does not reflect actual 3-dimensional velocities at the fish screens. Exposure time across the 22.6 ft length of the screens is calculated based on the depth-averaged sweeping velocity in the dominant main channel flow path leading toward the low-flow notch in the fishway. At the lowest design discharge and corresponding lowest average sweeping velocity, the exposure time is greatest at 35 seconds, but well under the 60 second exposure time recommended criteria (Table 8). Exposure time decreases as discharge and average sweeping velocity increase.

Because the screen criteria require sweeping velocity be met for the entire hydrologic year, it is noted that a flow of 100 cfs or greater currently occurs 326 days of the year, or 89% of the time. Therefore, based on historical conditions, sweeping velocity would typically be met 89% of the year and require an exception for the remaining 11% of the year.  Recall that these data are “adjusted” and represent flows incoming to the diversion pool after accounting for diversions and inflows of water between the USGS gage and the project site (Clarkin, 2019). Based on historical data, accounting for adjustments documented in Clarkin (2019) mean-daily flow ranges from 16 cfs (September 3, 2003) to 14,540 cfs (November 30, 1995). Therefore, 89% is conservative as it is unlikely that LNFH would divert 42 cfs and leave the river dry when flows less than 42 cfs. The Icicle Creek Working Group has a goal of setting the minimum flow coming into the diversion pool in the future to be at least 100 cfs in drought years (allowing for 42 cfs to be diverted and ~60cfs routed into fishway and downstream to hatchery).  If this goal can be achieved, it is likely sweeping velocity will be met 100% of the year.

Table 8. Summary of hydraulic conditions for juvenile downstream Bull Trout and Steelhead passage based on MPOR. Sweeping velocity and exposure time are averaged over the total length in front of the intake fish screens

| | May | | June | | September | | October | |
|---|---|---|---|---|---|---|---|---|
| **Juvenile Downstream Passage Discharges (cfs)** | 572 (95%) | 3,494 (5%) | 599 (95%) | 3,478 (5%) | 54* (95%) | 295 (5%) | 70* (95%) | 651 (5%) |
| **Model Discharge Across Intake Screen** (cfs)** | 586 to 544 | 3,483 to 3,441 | 586 to 544 | 3,483 to 3,441 | 75 to 33 | 298 to 258 | 75 to 33 | 586 to 544 |
| **Average Sweeping Velocity*** (ft/s)** | 2.4 | 5.9 | 2.4 | 5.9 | 0.7 | 1.5 | 0.7 | 2.4 |
| **Exposure Time Across Total Screen Length (sec)** | 9 | 4 | 9 | 4 | 35 | 16 | 35 | 9 |
| **Total screen exposure time less than 60 seconds** | Criteria met | | Criteria met | | Criteria met | | Criteria met | |
| **Sweeping velocity criteria met (0.8 ft/s)** | 30 days (100% month) | | 31 days (100% month) | | 17 days (57% month) | | 25 days (80% month) | |

*Minimum incoming design flow for fisheries analysis is 75 cfs based on design assumption from Icicle Working Group that future incoming discharge past diversion weir will not be less than ~100 cfs.
** Model discharge at upstream end based on incoming flow and downstream end of screens after 42 cfs diversion.

***Approach velocity is 0.4 ft/s; sweeping velocity goal is 2 times approach or 0.8 ft/s

Table 9. Summary of hydraulic conditions for juvenile downstream Bull Trout and Steelhead passage based on MPOR. Sweeping velocity and exposure time are averaged over the total length of the intake fish screens (~21.4 ft)

| | May and June | September and October | Annual (January to December) |
|---|---|---|---|
| **Period Mean Daily Discharges (cfs)** | 581 (95%) and 3,483 (5%) | 64* (95%) and 523 (5%) | 75 (95%) and 2,219 (5%)<br>16* (min) and 14,540 (max) |
| **Model Discharge Across Intake Screen** (cfs)** | 586 to 544 (95%)<br>3,483 to 3,441 (5%) | 75 to 33 (95%)<br>523 to 481 (5%) | 75 to 33 (95%)<br>2,219 to 2,177 (5%) |
| **Average Sweeping Velocity for 95% and 5% Flow (ft/s)** | 2.4 to 5.8 | 0.6 and 2.2 | 0.6 and 4.7 |
| **Exposure Time Across Total Screen Length (sec)** | 4 to 10 seconds | 10 to 35 seconds | 5 to 35 seconds |
| **Total screen exposure time less than 60 seconds** | Criteria met | Criteria met | Criteria met |
| **Sweeping velocity criteria met (0.8 ft/s)** | 61 days (100% of time period) | 41 days (68% of time period) | 326 days (89% of time period) |

*Minimum incoming design flow for analysis is 75 cfs (95% annual flow exceedance) based on design assumption from Icicle Working Group that future incoming discharge past diversion weir will not be less than an incoming 102 cfs (60 cfs in fishway after 42 cfs diversion).
** Model discharge at upstream end of screens based on incoming flow and downstream end of screens after 42 cfs diversion.

## 5.4 Flood Protection

The top of the intake structure is set at an elevation of 1,207 ft. The modeled WSE at the 100-yr flood is between 1,205 and 1,206 ft at the upstream side of the intake structure (Figure 30). The WSE along drops to 1,204 ft near the intake fish screens. Modeled WSE for the 100-yr flood (13,300 cfs) for existing conditions ranges between 1,201 to 1,202, ft, which indicates this project will likely increase the pool elevation by 4 to 5 ft during the 100-yr flood. However, change in the extent of inundation is small due to the steep slope of the upstream rapid. Additionally, the largest peak flood of record (19,800 cfs) was also modeled. The modeled WSE at the flood of record is approximately 1 to 2 feet higher (1,208 to 1,209 ft) than the elevation of the intake structure.

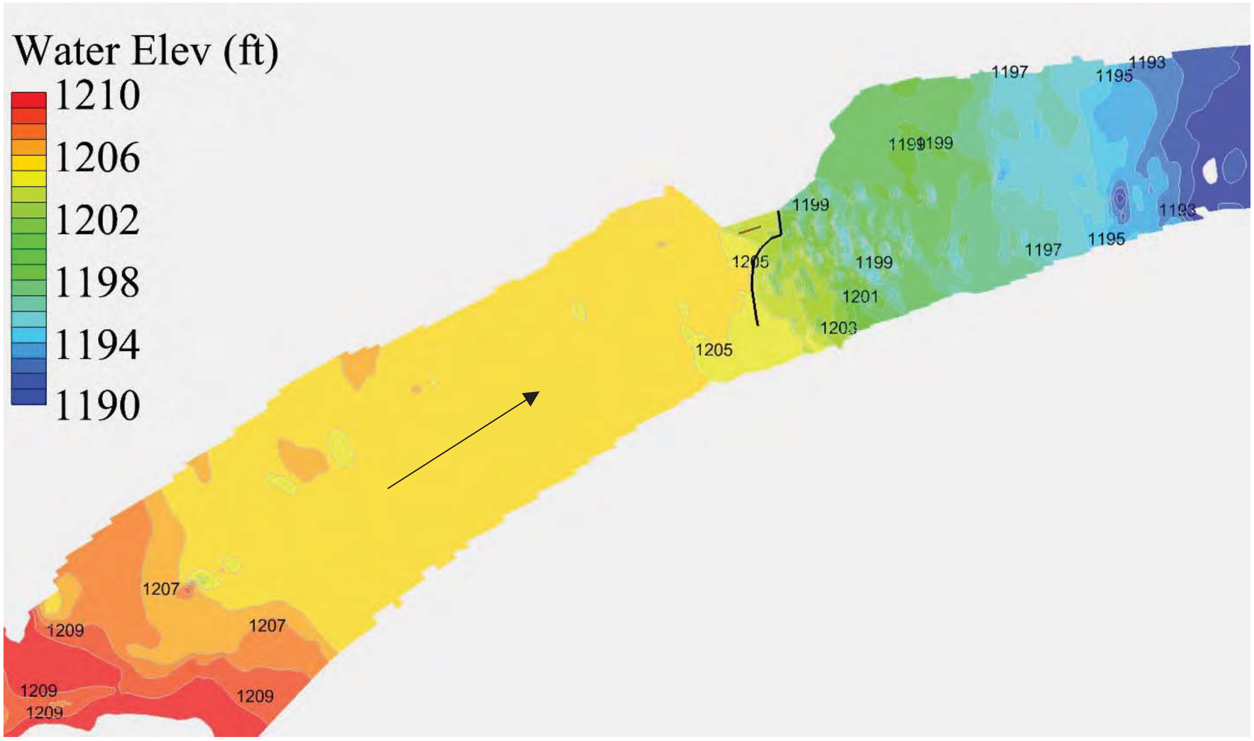


Figure 30. Contours showing the modeled WSE at 1 ft increments for the 100-yr flood (13,300 cfs). The WSE is highest at the upstream side of the intake structure (1,205 to 1,206 ft) and drops about 1 ft in front of the fish screens (1,204 ft). Weir crest location is shown with black line. Inundation beyond the black line on river right is along the steep hillslope.

At the 100-yr discharge (13,300 cfs), modeled velocities in the channel average approximately 17 ft/s, with local maximum values around 24 ft/s. The model output shows hydraulic jumps on the roughened channel at high discharges. Larger rock diameters should be keyed into the riffle material mix at these locations. Due to the high velocities, grout is necessary in the low-flow fishway and recommended along the crest of the roughened channel. The design engineers used the computed 2D hydraulics at the 100-yr flood to select a gradation with a $D_{50}$ of 3 ft to minimize risk of mobilization of the roughened channel material. The design specifications state that the scattered large boulders on the roughened channel are 5 to 8 ft in diameter. Since the roughened channel is not grouted, local elevation adjustments around the scattered boulders will likely develop flow paths that better mimic a natural channel. Annual monitoring should be done to determine if rock mobilization has occurred and the roughened ramp material needs to be replenished.

## 5.5 Sediment Deposition at Intake

The concrete pad under which the fish screens will sit is at an elevation of 1,188 ft, approximately 1ft lower than the existing bed. The bottom of the fish screens is at 1,189.25 ft, or 1.25 ft above the concrete pad. Because of slower velocities in the pool upstream of the structure, sediment deposition is expected. Larger amounts of sedimentation can be expected after large flooding events and alterations in the contributing watershed, especially wildfires. However, current intake configurations combined with the fish screens will prevent sediment from entering the water deliver pipeline.

To analyze potential grain size of expected deposition, sediment mobility was computed based on calculating a critical diameter. Critical diameter is based on shear stress and compares a computed dimensionless shear stress value, Shield's parameter, to a standard mobilization value from literature (0.042; Pemberton & Lara, 1984). Estimates of sediment mobility for 4,100 cfs (2-yr flood, Figure 31) and 7,500 cfs (10-yr flood, Figure 32) show gravel and larger sized sediment (≥ 2 mm) will be transported during typical floods. Areas of deposition of sand and fines (silt and clay) will be primarily located along the channel margins and in recirculation zones. The sediment mobility plots indicate that sands and gravels will be transported through the diversion pool during floods larger than the 2-yr recurrence interval. On the roughened ramp some large boulders have the potential to be mobilized (1,024 mm is equivalent to 3.4 ft). The $D_{50}$ of the roughened channel rock mix is about 3 ft, so the larger gradation sizes up to 5 ft will help in these locations. The natural bed is armored with bedrock and natural large boulders which will help limit additional scour even if some of the roughened ramp material is mobilized as the design surface adjusts during floods post-construction. During the falling limb of the hydrograph, some sands and gravels are expected to deposit near the intake as transport capacity reduces. Based on current deposition at the diversion structure and other locations with check structures on Icicle Creek, the thickness of deposition may range between 1 and 1.5 ft. In years with fires or landslides combined with heavy rains and stream flow, higher than average sediment loads would be expected and sediment deposition at the intake screens may exceed this prediction and require mitigation to remove.

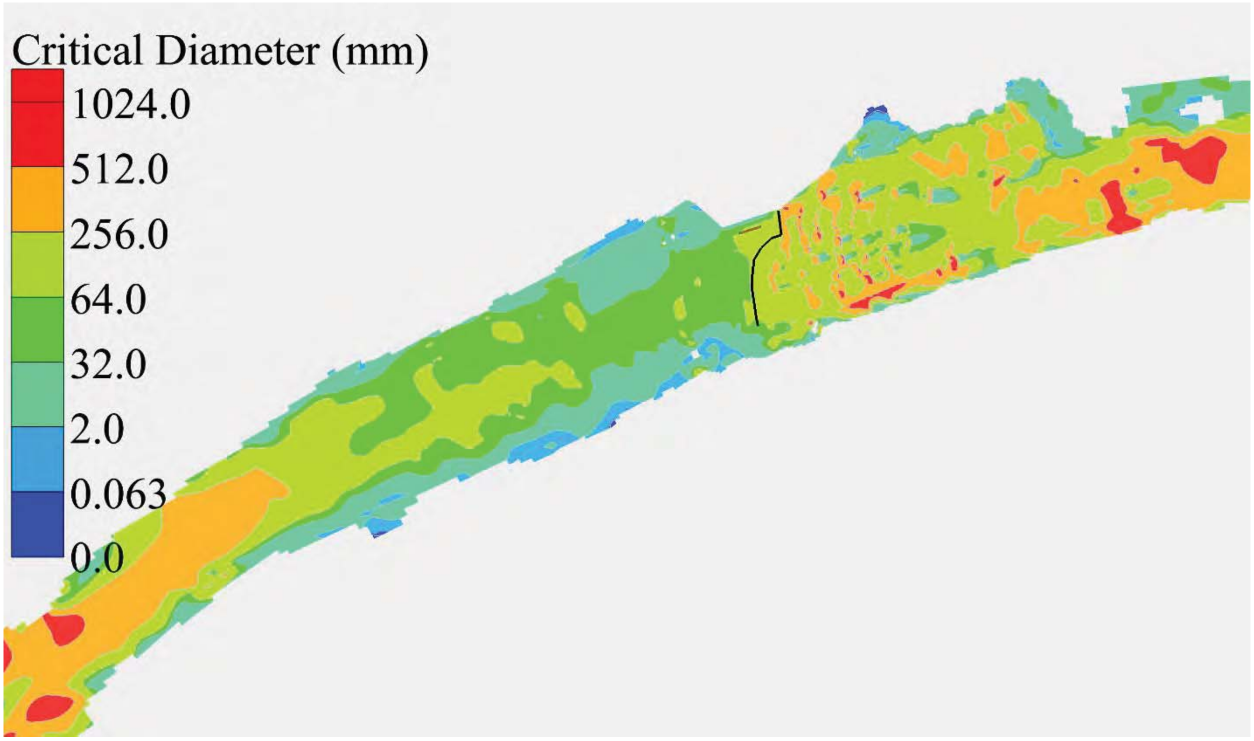


Figure 31. Potential sediment mobility based on dimensionless shear stress for 4,100 cfs (2-yr flood). Contours show areas of mobility for fines (dark blue), sand (light blue, 0.063 to 2 mm), very-fine to coarse gravel (teal, 2 to 32 mm), coarse-gravel to very-coarse gravel (green, 32 to 64 mm), cobbles (light green, 64 to 256 mm), small boulders (orange, 256 to 512 mm), and large boulders (512 mm and up). New weir location shown with black line.

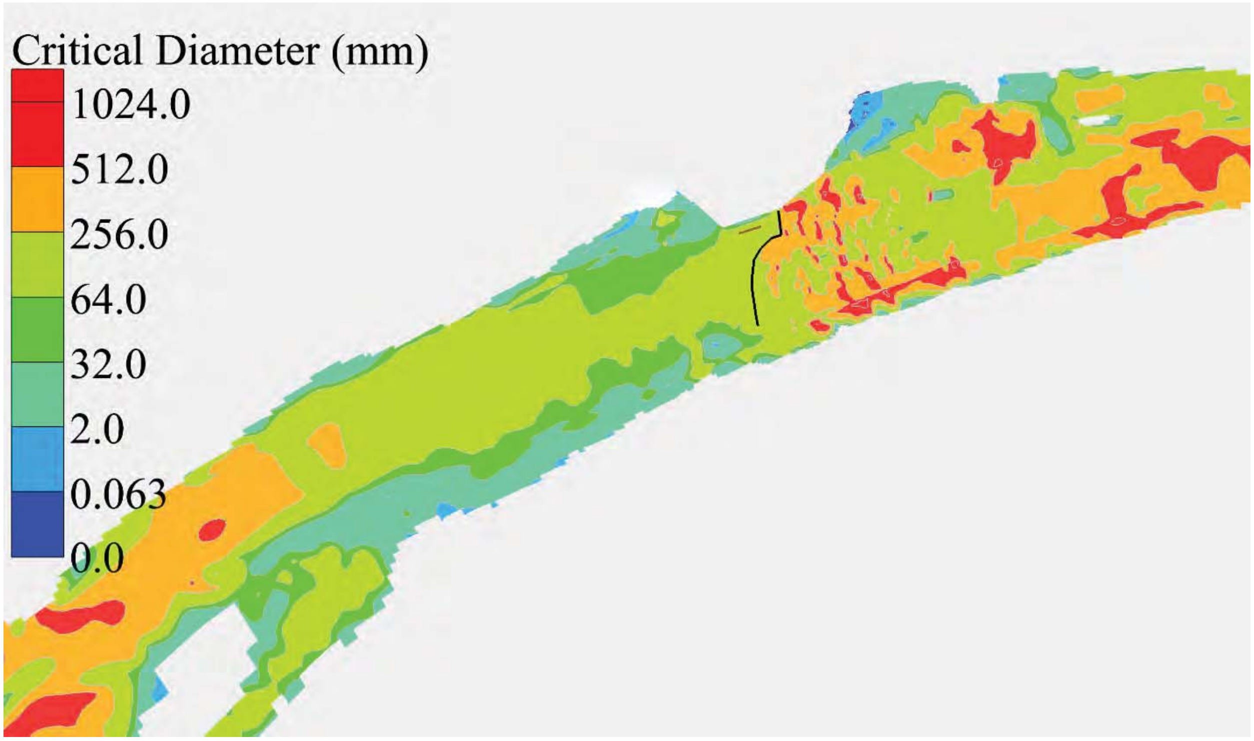


Figure 32. Potential sediment mobility based on dimensionless shear stress for 7,500 cfs (10-yr flood). Contours show areas of mobility for fines (dark blue), sand (light blue, 0.063 to 2 mm), very-fine to coarse gravel (teal, 2 to 32 mm), coarse-gravel to very-coarse gravel (green, 32 to 64 mm), cobbles (light green, 64 to 256 mm), small boulders (orange, 256 to 512 mm), and large boulders (512 mm and up). New weir location shown with black line.

## 5.6 Construction Cofferdam

The design team requested hydraulic modeling of the government proposed cofferdam phases to inform estimation of material quantities needed for the cofferdam, height requirements to prevent overtopping, and high velocity areas that may require aditional stabilization to prevent breaching failure from lateral erosion. Model results for the three cofferdam scenarios are presented in Appendix D. The actual cofferdam placement and timing implemented by the contractor may differ than the government proposed plan.

# 6.0 Discussion

The current design will require site specific exceptions to meeting fish passage and screening criteria as outlined below. The following site-specific constraints are important when considering the hydraulic conditions of the proposed design:

- The project site is in a confined canyon and channel width is limited.
- The slope of the natural channel is approximately 0.025 ft/ft with sections of steeper riffles (0.030 ft/ft).
- Large natural boulders create hydraulic controls and very complex hydraulic conditions throughout the reach.
- There is uncertainty in the hydrologic input, in part because of several diversions upstream of the site. Furthermore, water use and management may change in the future, particularly during low flows.
- Large variability in the hydrology requires designing for very low discharges (tens of cfs) as well as large flows (thousands of cfs).
- Winter conditions can develop frazil ice in the channel.

## 6.1 Sediment Management to Maintain Fish Screen Submergence Criteria

The current design successfully meets screen fish screen submergence criteria for the design low flow (75 cfs). Because Icicle Creek is naturally steep and shallow at low flows, the channel bed beneath the screens will be excavated approximately 1 ft below the current average stream bed in this location. Sediment deposition on the new concrete pad below the fish screens is expected, especially during years with large floods and following fire events in the upper watershed. The design has mitigated this potential by placing a channel at the downstream end to encourage sediment transport up and over the roughened channel rather than depositing near the screens. Additionally, the screens have been placed in the river thalweg and near the low-flow notch in the roughened channel to reduce potential for deposition. The smooth concrete pad and turbulence created in the constricted flow between the screens and concrete pad will help encourage sediment transport. However, the roughened channel will still create a backwater condition with the potential for deposition. Based on site specific topography and deposition observed in other locations, the thickness of deposition may range between 1 and 1.5 ft and be dominantly sand, with 5 to 10% gravels and small cobbles. If this prediction is correct, the current 1.25 ft of clearance will minimize the frequency of required sediment removal. Because of uncertainty in sediment deposition, an adaptive management plan could be developed to identify sediment removal methods that is fish-friendly and performed during safe, low-flow conditions.

## 6.2 Fish Screen Criteria

The recommended sweeping velocity of 0.8 ft/s for the selected cylindrical screens (approach velocity of 0.4 ft/s) is achieved for an estimated 89% of annual flow conditions, or all flows greater than or equal to 100 cfs. It is not achieved for low flows (< 100 cfs) for on average 11% of the year. A site-specific exemption is requested for periods of downstream fish migration less than 100 cfs. The roughened channel creates an artificially slow backwater pool, but the depth created by the roughened channel is necessary to meet fish screen submergence criteria and generate enough head to conduct gravity fed diversion to LNFH.

If downstream migration occurs during flows less than 100 cfs, the fishway has been designed such that if the fish stays within the main current, it is expected to be transported directly toward the low-flow fishway, away from the fish screens. Further, the computed exposure time along the screens at the critical design low flow is less than 60 seconds for all months evaluated. As mentioned previously, if the Icicle Creek Work Group is successful in achieving a 100 cfs minimum in-stream flow into the intake diversion pool, the sweeping velocity will be meet 100% of the year.

## 6.3 Upstream Adult Fish Passage Criteria

Upstream migration is evaluated for adult fish passage based on hydraulic results that are greater than 1 ft and less than 3 ft/s along a continuous path. If the NFMS depth criteria of 1 ft is met, then the WDFW criteria of 0.8 ft is automatically met. In the low-flow fishway, the fish are expected to burst through the boulder weirs (2 to 3 ft distance), and then swim through the seven pools (each 15 ft length). On the roughened channel, fish are expected to burst between low velocity areas behind large boulders located throughout.

The fishway provides adequate upstream passage between flows of approximately 75 to 401 cfs, meeting both depth and velocity criteria. At the fishway exit into the upstream pool, depth over the roughened channel crest is 0.4 ft at 75 cfs. The hydraulic drops between all pools in the low-flow fishway meet criteria and do not exceed 1 ft. Velocities within the fishway pools meet velocity criteria of 3 ft/s. The average velocity through the fishway at 75 cfs is 2.5 ft/s, with zones of recirculation behind the boulder weirs. There would be minimal flow residence time (approximately 1 minute) and therefore minimal impact on warming water temperature as flow passes through the steep 5.5% roughened channel.

Although velocity criteria are not met for flows over 401 cfs during migration season, hydraulic conditions in the proposed roughened channel would likely be similar to the natural channel.

Even at 1,600 cfs, a considerable portion of the roughened channel (~16% of XS sampled) were below the 3 ft/s criteria. However, at these discharges it is likely that the fish will be using low-velocity routes along the margins, as they are required to in portions of the natural channel. Comparison to modeled reference regions downstream of the project area suggest that at most discharges, velocity values less than 3 ft/s in the natural reach are not attainable (Figure 29). Further, there are slower velocities throughout the channel created in areas where large 5 to 8 ft rocks will create hydraulic roughness. The hydraulic model surface was represented as a uniform, static surface. The as-built surface will be very rough with a D50 of 3 ft. Local hydraulics around individual rocks in the roughened channel will likely result in local scour with deeper depths and lower velocities. The un-grouted portions of the roughened channel are expected to adjust over time and develop more variability likely to support improved fish passage conditions. Twenty-five boulders were placed on the channel to break up the hydraulics. The boulders should be ‘field fit’ during construction under supervision of hydraulic design engineers to ensure optimum placement.

Anglin (2013) notes that the existing fish ladder is partially washed out at flows of approximately 1,200 cfs or greater and "Steelhead, spring Chinook, fluvial bull trout, and Pacific lamprey could be moving upstream during the time period that the fishway is washed out, but passage directly over the dam is possible at these higher flows [up to 2,600 cfs], with the exception of Pacific lamprey." With the improved design of a roughened channel, fish passage at higher flows should be improved over existing conditions. While the roughened channel does not meet 3 ft/s criteria for the entire length at flows greater than 906 cfs, there are multiple slower velocity zones created by the placed boulders that create velocities equivalent or slower than adjacent reference areas in Icicle Creek.

## 6.4 Roughened Channel Rocks and Grouting Needs

Based on the hydraulic modeling of the 100-yr discharge, rock sizing and grouting locations are very important factors to consider. The stability of the crest of the roughened channel is crucial to ensure adequate submergence of the fish screens. Therefore, the crest will be grouted to ensure stability. Similarly, the low-flow fishway design uses boulders of 3.5 ft and less need to be grouted to maintain the configuration for optimal hydraulics in the low-flow fishway. When grouting the surface of the roughened channel or the low-flow fishway, a portion of the top layer of roughened channel fill should be exposed to create additional roughness. Also, rounded rocks should be used in grouted portions to improve potential fish passage for Pacific Lamprey.

The uncertainty in model roughness and discharge for the 100-yr flood indicates higher velocities could occur on the channel, which further reinforces the need to grout the roughened channel crest and low-flow boulder weir fishway. The higher velocities also suggest that rather than 5 to 8 ft diameter placed boulders in the roughened channel, rocks closer to the 8 ft range would be more stable and less likely to erode away if a large flood similar to the flood-of-record (19,800 cfs; 6,500 cfs greater than 100-yr flood) were to occur again. The existing large boulders should be used in-place to add stability to the design and hydraulic complexity for fish passage. The only exception is that the large boulder in the center of the designed low-flow fishway will have to be removed and should be repurposed as large boulders in the roughened channel. The scattered large boulders in the hydraulic model were placed based on previous model results to optimize their efficacy in providing resting areas for upstream fish passage. Placement of the large boulders can be adjusted, and additional boulders can be used in the final design or during construction. Post-construction, local adjustments to the un-grouted areas of the roughened channel is expected and could be beneficial to best mimic the flow paths of a natural channel for upstream fish passage. However, monitoring the roughened channel for large areas of scour, especially after large discharge events, should be monitored and potential mitigation measures be included in the monitoring and maintenance plan.

## 6.5 Large Wood and Debris

During large discharge events, there is the potential for large floating debris. Therefore, a log boom to protect the intake screen could be used to provide protection as recommended in NMFS (2011). Floating debris may periodically become lodged in the low-flow fishway and removal may be necessary. Similarly, sediment deposition downstream of the roughened channel, upstream of the natural boulder drop, may occur. This will likely adjust with natural flows. This could be added into an annual monitoring and maintenance plan.

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# Appendix A – 2010 Sediment Analysis at Hatchery Channel

This section on sediment is reproduced for reference from Bountry, 2010, 2D Hydraulic Modeling for the Leavenworth National Fish Hatchery, Icicle Creek Restoration, Project Technical Report No. SRH-2010-5.

Two-dimensional hydraulic modeling was performed in 2010 to evaluate a pumping plant option for water diversion at the hatchery site (Figure 33). While sediment transport was not numerically evaluated, potential sediment deposition at the proposed intake location was qualitatively assessed from field observations, local accounts, and a limited number of particle gradation analyses of river bed-material samples (Figure 34). The bed-material samples were taken upstream of the hatchery channel that has a spillway that backs up sediment, and upstream of two structures operated in the historical channel to control water flow and fish passage (structures 2 and 5 in Figure 33). The spillway structure is 21 ft high (as measured along the invert), has a crest elevation of 1132.9 ft, and has a footprint of 209 ft by 80 to 90 ft wide. It has a fish ladder at its tailwater that allows fish to swim up to the hatchery. The study concluded that incoming sediment load of Icicle Creek ranges in size from sand to cobbles, with sand and gravel being transported more frequently and in greater quantities.

The river upstream of the hatchery alternates between steep riffles and rapids with deep pools. Many of the riffles and rapids are composed of boulders (Figure 9). In some locations gravel bars and vegetated islands are present. Hatchery personnel noted that they must clean sediment out of the existing diversion dam at RM 4.6 after large floods (verbal communication with Steve Croci, August 20, 2009). The sediment removed upstream of the diversion dam was noted to range from sand to cobbles. Softball-sized cobbles have been observed moving over the top of the diversion dam during higher flows, but hatchery personnel note that the percentage within the total volume removed is small, possibly 5 to 10% (Steve Croci, personal communication August 20, 2009). The $D_{50}$ of a sediment sample taken in the diversion channel originating at the surface water diversion was 9 mm (gravel), but there is a screen at the entrance that limits large cobbles (sediment > 64 mm). The sediment trap at the hatchery contains sand and gravel because of a second set of grates that are 1 ½” (38 mm) in diameter that prevent larger material from entering the intake pipe. Personnel also noted that sediment filling at the diversion dam appears to have been greater in recent years, locally thought to be occurring from upstream fires and related debris flows into the channel. Eight hatchery channel test pits were inspected in August 2009 that showed, on average, 1 to 1.5 ft of river sediment deposition since the hatchery channel was excavated in the 1930s. Based on visual observations in the test pits, the sediment deposited in the hatchery channel is generally composed of sand with increasing volume of gravel in the upstream direction (Appendix A; Bountry et al, 2009). At three of the test pits in the hatchery channel the D50 of the sediment historically deposited by the river was 2 mm, which is the break point between sand and gravel classifications. One test pit near the upper end of the hatchery channel had a larger D50 of 20 mm (coarse gravel).

A D50 of 26 mm was measured from the subsurface of a gravel bar about 0.6 miles below the spillway on river left. The bed in this area was generally armored by cobbles. Landowners downstream of the hatchery in lower Icicle Creek have observed “fishing holes” fill and scour with sand (Steve Croci, personal communication August 20, 2009).

Despite evidence that cobble sized sediment are mobilized above and below the hatchery channel, there was no evidence that cobbles are currently being transported through the hatchery channel during floods. Up until a few years ago the gates to the historical channel were closed during floods indicating cobbles could not be transported through this reach either. One cobble was visible on structure #2 and one on #5 during the August field trip indicating a limited volume of cobbles may be getting through to the historical channel in the last few years when the gates are opened during floods.

It is estimated that cobbles drop out upstream of the hatchery channel in the transition area between Icicle Creek and the start of the backwater from the spillway where sediment transport capacity likely decreases. During floods the backwater starts in a cobble riffle, located just upstream of the proposed intake area. Because there is not a large volume of cobbles in this transition area or in the samples collected, it is estimated that the volume of cobbles transported is relatively small compared to sand and gravel. Additionally, it is estimated that cobbles are transported less frequently and over much shorter distances relative to sands and gravels based on local accounts. Often, cobbles and larger-sized sediment are estimated to armor the bed. Bedload sampling and sediment transport modeling would be needed to validate and refine these hypotheses.

Hatchery personnel have also observed large wood loads during floods and development of ice during winter (verbal communication with Steve Croci, August 20, 2009). Wood was noted to accumulate to the right of the spillway bottom where the historical channel reconnects with hatchery channel flows at Structure #5.

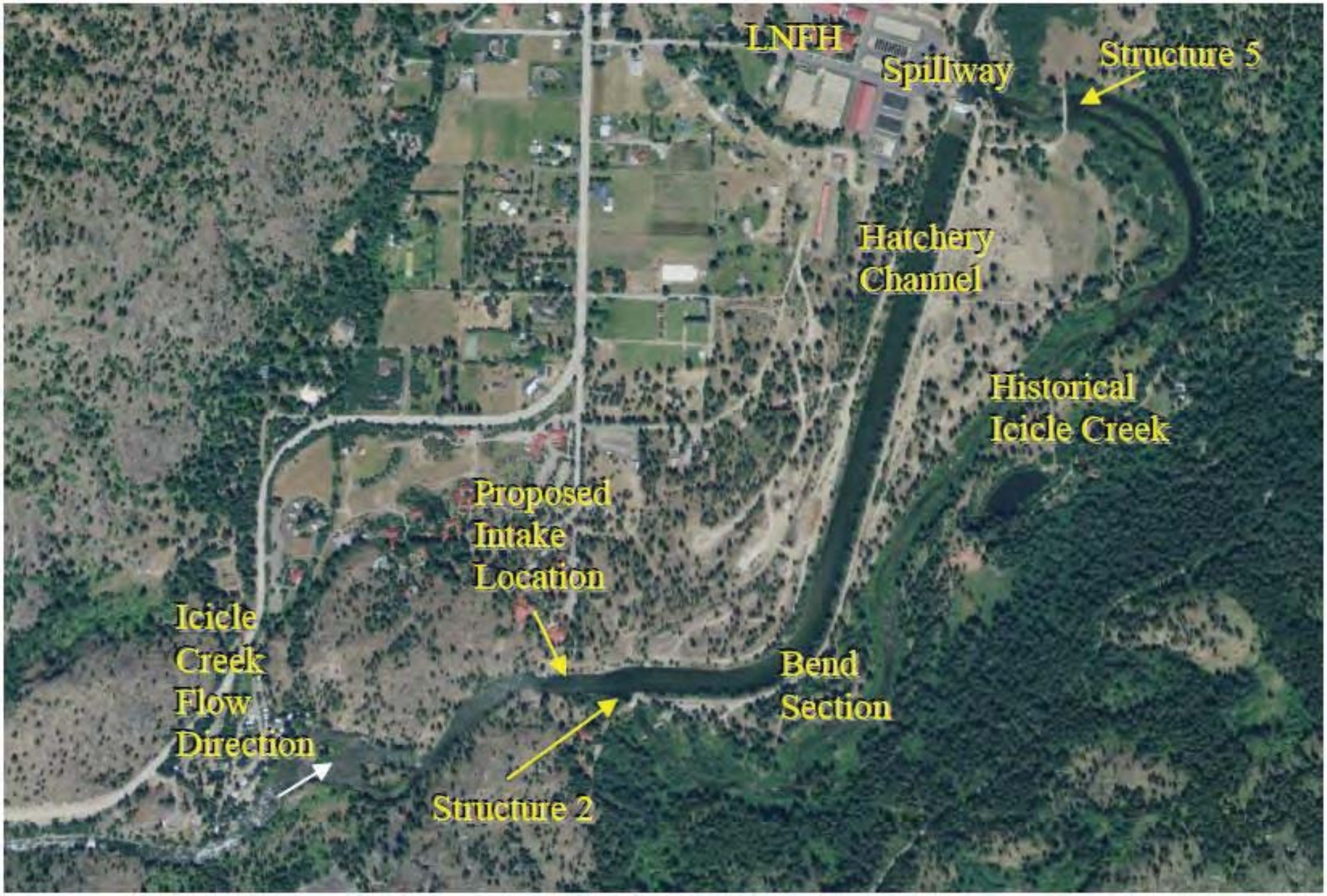



Figure 33. Location map of Icicle Creek and Leavenworth National Fish Hatchery (LNFH) on 2009.

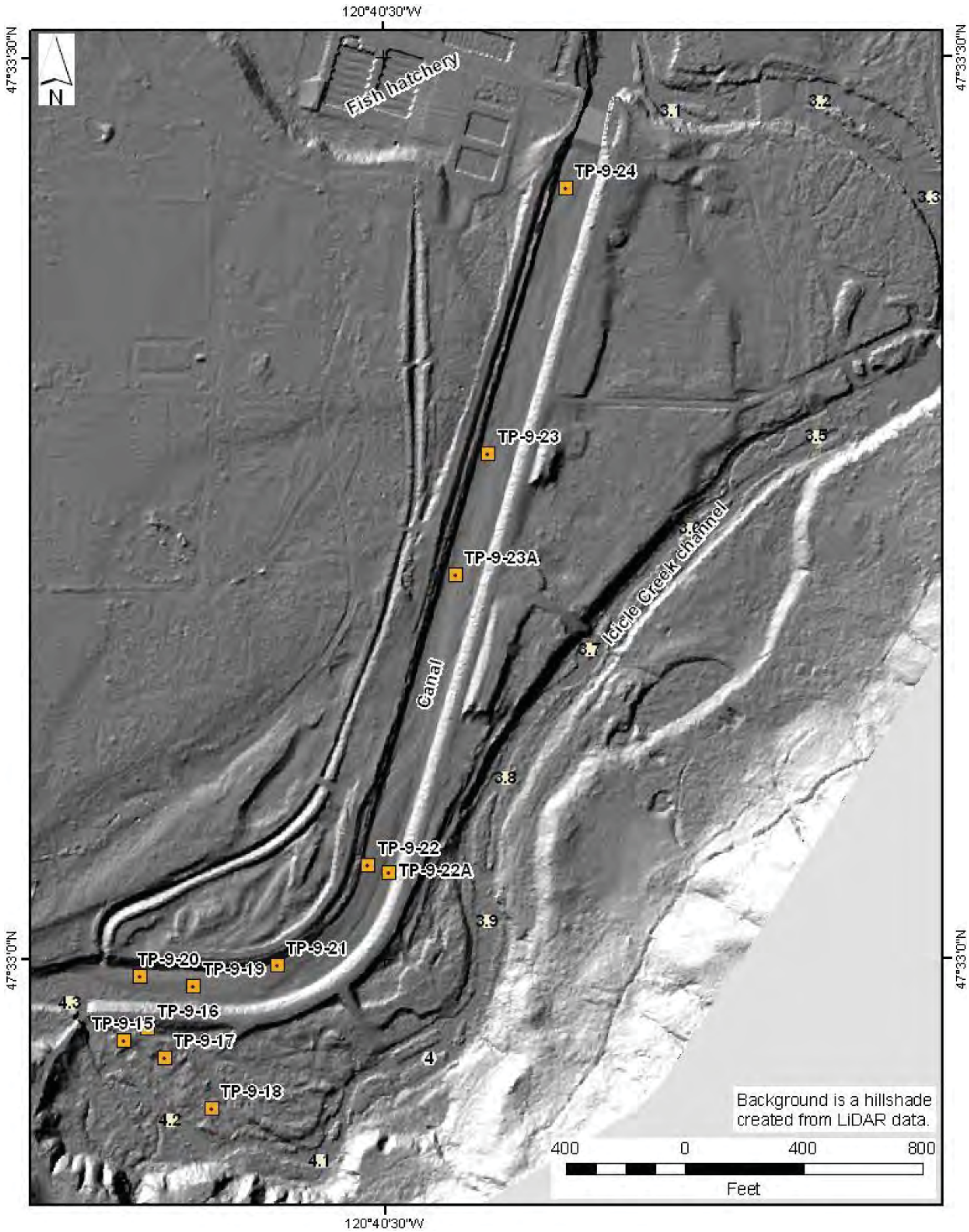



Figure 34. Approximate locations of test pits excavated upstream of fish hatchery in August 2009. Locations are from waypoints taken with a hand-held GPS unit.

# Appendix B – Sediment sample results from laboratory analysis (Hardee and Bountry, 2019)

*Copy of laboratory reports for two samples located just upstream of existing diversion weir and collected from excavated sediment from sand settling basin.*

# Appendix C - Hydraulic Model Development

The 2D numerical modeling was conducted using Sedimentation and River Hydraulics – Two-Dimension (SRH-2D) (v 3.0), which is a 2D, depth-averaged hydraulic model developed and maintained by Reclamation's SRH group (Lai 2008). Major capabilities of the SRH-2D fixed-bed model include:

- 2D depth-averaged dynamic wave equations (the standard St. Venant equations) are solved with the finite-volume numerical method;
- Steady state (with constant discharge) or unsteady flows (with flow hydrograph) may be simulated;
- An implicit scheme is used for time integration to achieve solution robustness and efficiency;
- An unstructured polyhedron mesh is used, which includes the structured quadrilateral mesh, the purely triangular mesh, or a combination of the two. Cartesian or raster mesh may also be used. In most applications, a combination of quadrilateral and triangular meshes is the best in terms of efficiency and accuracy;
- All flow regimes, i.e., subcritical, transcritical, and supercritical flows, may be simulated simultaneously without the need for special user intervention;
- Modules to simulate in-stream structures such as weir, gate, culvert, bridge, obstruction, internal boundary, and 2D pressurized zones;
- Robust and seamless wetting-drying algorithm; and
- Solved variables include water surface elevation, water depth, and depth averaged velocity. Output variables include the above, plus Froude number and bed shear stress.

## Topographic Data

Data is presented in Washington State Plane North American Datum (NAD) 1983 ft and North American Vertical Datum 1988 ft (NAVD88 ft). The channel bottom in the pool upstream of the existing weir, the weir itself, and the channel immediately downstream of the weir was represented by topographic and bathymetric data collected by Reclamation in August 2019 (Hardee and Bountry, 2019). Supplemental data available from 2002, 2003 and 2008 were added where needed after adjusting the vertical datum to match NAVD88 ft. Light detection and ranging (Lidar) data collected on August 4, 2015 was used for the remaining areas outside the project area and for hillslopes and floodplains (Quantum Spatial, 2016). The estimated discharge incoming to the diversion site is 54 cfs, and 12 cfs downstream of the weir. Observations by hatchery personnel concur that summer of 2015 was very low water year and water depths in Icicle Creek between the diversion weir and the hatchery were very shallow. Further, an aerial photograph from this time period shows the shallow flow depths in this same area with much of the bed material exposed.

Although the flow downstream of the weir was very low, the Lidar does not represent the portion of the channel below the water surface elevation. To estimate the channel bottom, the Lidar was lowered 0.7 ft upstream of the project area and 0.3 ft downstream of the project area. The amount of lowering was based on when the modeled water surface elevation matched the in-channel Lidar elevation. The incoming flow and estimated diversion discharge are 70 cfs incoming to the project area, and 13 cfs downstream accounting with an estimated diversion of 57 cfs on August 4, 2015 (Clarkin, 2019).

The top of the existing weir with the wood stop logs in placed measured 1194 ft during the 2019 topographic survey. Large boulders are present in the channel and one is located within the weir (weir built on either side). Boulders larger than 5 ft in diameter downstream of the existing weir were represented in the topographic surface using either data collected in August 2019, 2015 Lidar, or a combination of both.

Proposed conditions were created using a combination of existing topographic/bathymetric data and proposed design drawings. The design drawings were imported as triangular irregular networks (TIN) files and converted into representative, high density (~0.5 ft spacing) point files. The existing terrain data were clipped in areas with proposed design updates and replaced with the design point files. The large scattered boulders along the roughened channel were also added as point files and merged with the proposed design point files. Figure 35 shows the proposed locations of the roughened channel boulders and their relative height above the existing bed elevation. Design specifications of the roughened channel large boulders are shown in Table 10.

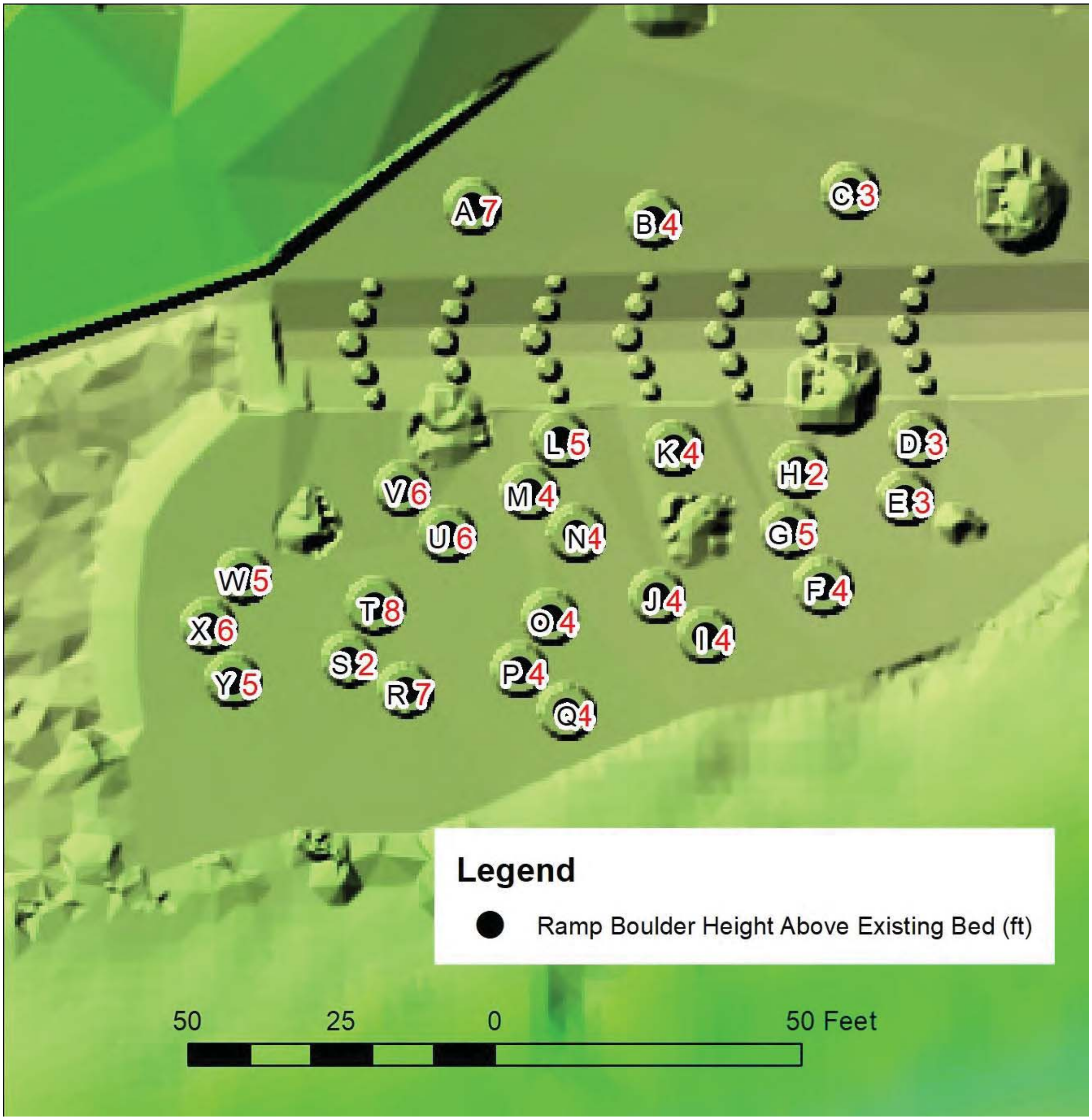



Figure 35. Location and rock height above existing bed (ft) for placed boulders on ramp. Letters designate label that corresponds to Table 10 and numbers represent rock height.

Table 10. Locations and elevations of the large, roughened channel boulders

| Label | Easting (ft) | Northing (ft) | Existing Elevation (ft) | Ramp Elevation (ft) | Top Rock Elevation (ft) | Height Above Bed (ft) | Exposed Height Above Ramp (ft) |
|---|---|---|---|---|---|---|---|
| **A** | 1674919 | 199676 | 1188.1 | 1192.9 | 1195.0 | 7 | 2 |
| **B** | 1674948 | 199674 | 1189.8 | 1191.0 | 1193.5 | 4 | 3 |
| **C** | 1674980 | 199678 | 1188.9 | 1189.4 | 1192.0 | 3 | 3 |
| **D** | 1674991 | 199638 | 1188.6 | 1188.0 | 1191.5 | 3 | 4 |
| **E** | 1674989 | 199628 | 1188.8 | 1188.6 | 1191.5 | 3 | 3 |
| **F** | 1674976 | 199614 | 1188.0 | 1189.9 | 1192.0 | 4 | 2 |
| **G** | 1674970 | 199623 | 1186.6 | 1189.6 | 1192.0 | 5 | 2 |
| **H** | 1674972 | 199633 | 1189.8 | 1189.1 | 1192.0 | 2 | 3 |
| **I** | 1674957 | 199606 | 1189.0 | 1191.0 | 1193.0 | 4 | 2 |
| **J** | 1674949 | 199612 | 1189.0 | 1191.1 | 1193.0 | 4 | 2 |
| **K** | 1674952 | 199636 | 1189.1 | 1190.1 | 1193.0 | 4 | 3 |
| **L** | 1674933 | 199638 | 1189.2 | 1191.0 | 1194.0 | 5 | 3 |
| **M** | 1674928 | 199629 | 1190.1 | 1191.3 | 1194.0 | 4 | 3 |
| **N** | 1674936 | 199622 | 1190.0 | 1191.3 | 1194.0 | 4 | 3 |
| **O** | 1674931 | 199609 | 1189.9 | 1191.8 | 1194.0 | 4 | 2 |
| **P** | 1674926 | 199600 | 1190.1 | 1192.2 | 1194.0 | 4 | 2 |
| **Q** | 1674934 | 199593 | 1189.5 | 1192.2 | 1194.0 | 4 | 2 |
| **R** | 1674908 | 199597 | 1187.9 | 1193.0 | 1195.0 | 7 | 2 |
| **S** | 1674899 | 199602 | 1192.9 | 1193.2 | 1195.0 | 2 | 2 |
| **T** | 1674903 | 199611 | 1186.7 | 1192.8 | 1195.0 | 8 | 2 |
| **U** | 1674915 | 199622 | 1188.9 | 1192.1 | 1195.0 | 6 | 3 |
| **V** | 1674907 | 199630 | 1188.5 | 1192.3 | 1195.0 | 6 | 3 |
| **W** | 1674881 | 199615 | 1190.7 | 1193.4 | 1196.0 | 5 | 3 |
| **X** | 1674876 | 199607 | 1190.3 | 1193.7 | 1196.0 | 6 | 2 |
| **Y** | 1674880 | 199598 | 1190.6 | 1193.7 | 1196.0 | 5 | 2 |

## Mesh Generation

Mesh development was accomplished within Aquaveo's Surface-water Modeling System (SMS, V 13.0.12) software. The final computational mesh comprised both triangular and quadrilateral elements of varying density (Figure 36). Generally, quadrilateral elements were used throughout except in areas near the intake area where triangular elements better matched the complex topography. Mesh density is approximately 6.5 ft near the boundaries and as small as 0.5 ft in near the proposed roughened channel. The final mesh consists of approximately 126,000 computational elements.

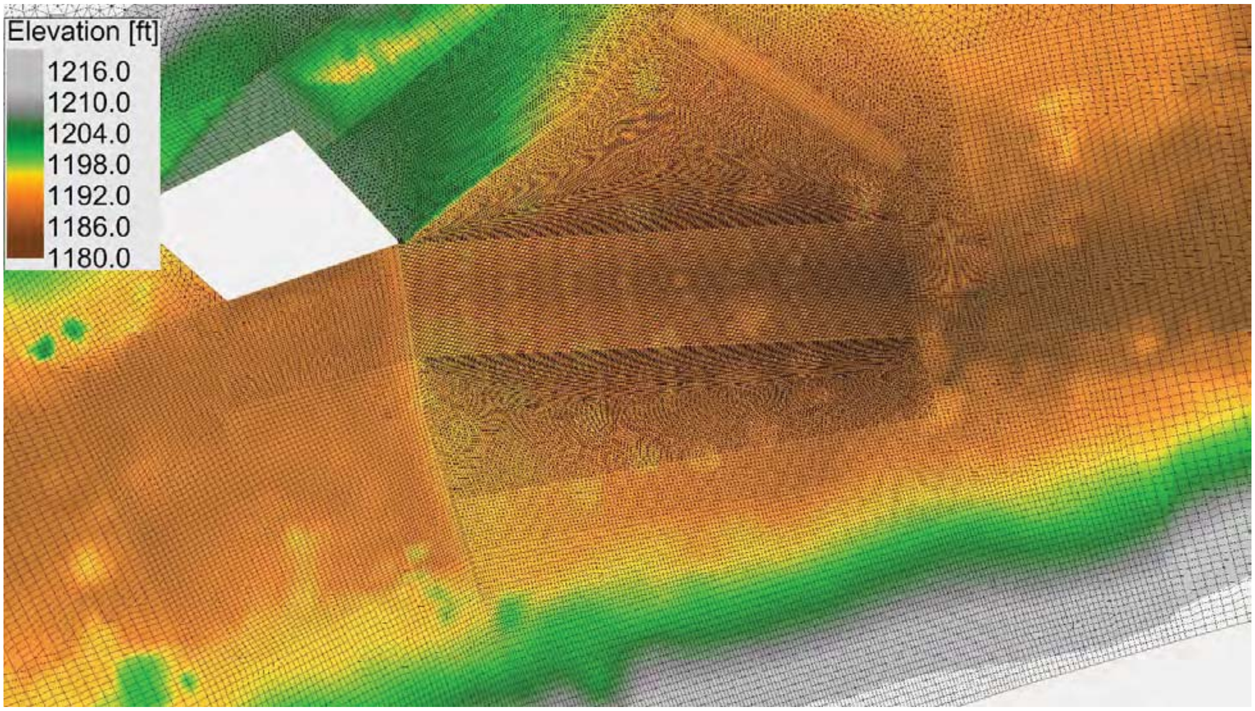



Figure 36. Computational mesh developed in SMS on proposed modeled bed elevation at the project site.

## Hydraulic Roughness

The only calibration data available for the site was water surface elevations collected during an August 2019 topographic survey. However, the area surveyed is largely controlled by the existing weir crest elevation, making it difficult to calibrate Manning's n values for modeling. Literature was used to estimate the hydraulic roughness values (Chow, 1959) based on mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stages. Chow (1959) recommends for gravel/cobble channel bottom with a few boulders Manning's n values can range from 0.030 to 0.050; if the channel bottom contains mostly cobbles with large boulders the bed can range from 0.040 to 0.070. Icicle Creek has elements of both categories depending on the location. Roughness values for the active, unvegetated channel in Icicle Creek were set at 0.045; 0.07 for the vegetated areas, and 0.15 for the crest to simulate additional energy loss not accounted for in a 2D model (Figure 37). The weir crest n value was selected by iterating until the modeled water surface elevation in the backwater pool matched measured water surface elevation during the August 2019 survey. Minor flow leakage was visible in the weir during the survey along with uncertainty in the incoming and diverted flow estimates as reported in Clarkin (2019).

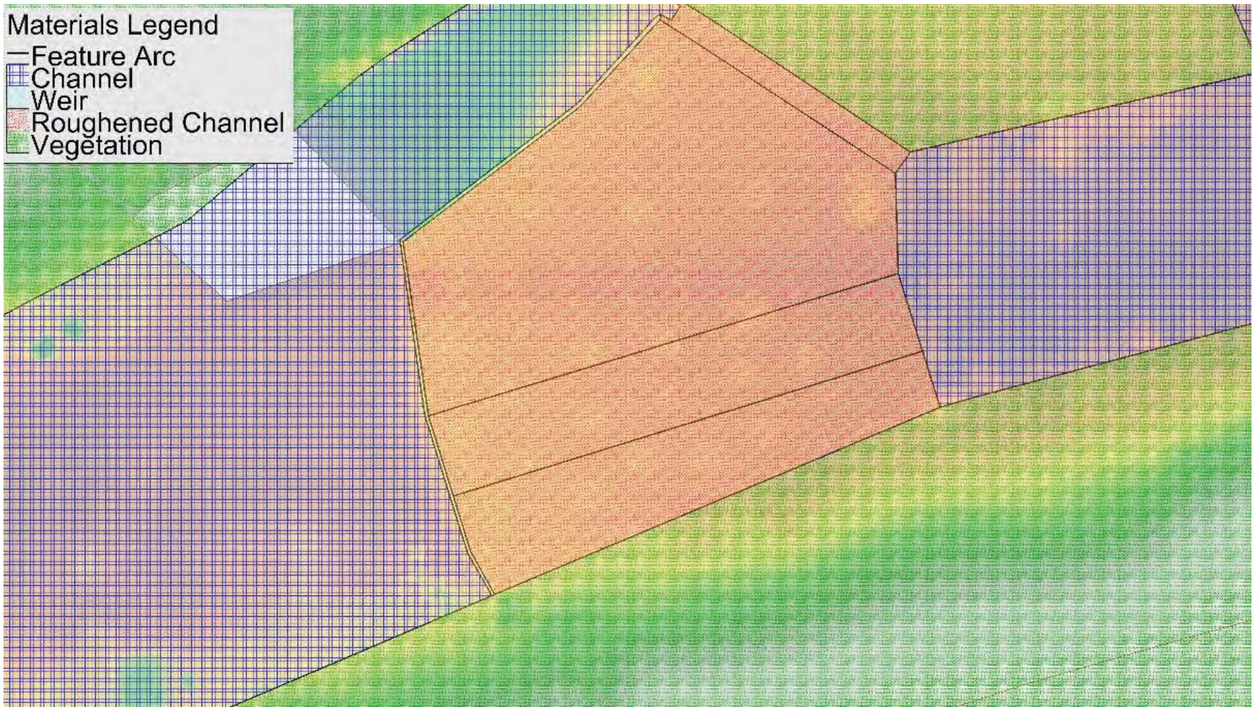



Figure 37. Model roughness values at the project site.

## Boundary Conditions

The upstream and downstream boundary conditions were chosen well above and below the project site. The upstream boundary was the provided discharge values. For most discharge values, the downstream boundary was calculated as a cross-sectional normal flow calculation based on average channel slope of 0.024, measured using the last 500 ft of the modeled terrain. At approximately 4,000 cfs, the downstream boundary water surface elevation was computed using supercritical flow conditions based on a 1D model output that extended farther downstream showing when Froude number exceeded 1.0, thus indicating supercritical flow. A sensitivity analysis was conducted for the 100-yr flood (13,300 cfs) by varying the downstream WSE. Due to the steep slope of the channel, boundary conditions were not found to affect hydraulic conditions at the project site.

## Calibration/Sensitivity

The selected weir height and roughness values matched well with measured low flow water stage data on Icicle Creek from August 2019. No other calibration data was available. Sensitivity testing was done with the roughness values adjusted by 10% and using the Strickler equation to address uncertainty in flood stage at the 100-yr flood (U.S. Army Corps of Engineers, 1994). The flood of record was also run at 19,800 cfs for the infrastructure design sensitivity, which is larger than the 100-year flood but within the hydrologic range of uncertainty for the estimate. The increased discharge of using the flood of record results in an increased water stage of approximately 2 ft along the fish screens and approximately 3 ft on the upstream side of the intake structure. The depth-averaged velocity on the roughened channel for the flood of record (19,800 cfs) increases by 2 to 4 ft/s relative to the 100-yr flood (13,300 cfs). The 10% increase in roughness results in less change than using the flood of record, so the flood of record is used for uncertainty discussion and design.

Sensitivity with 10% change in roughness was also done at the 95% low flow for design to look at variability in the water stage and uncertainty with submergence criteria at the fish screen location. The change in water stage and velocity were minimal and did not impact any design assumptions or conclusions of successfully meeting low-flow upstream passage or challenges with meeting fish screen criteria. These results are expected because at the low flow, the flow over the weir crest is very shallow and, therefore, the weir crest elevation dominates the backwater stage computation at the fish screens rather than roughness.

A 10% increase and decrease in roughness was modeled for 2,671 cfs model runs to check sensitivity on the impact on meeting fish passage criteria of velocity on the roughened channel. Average velocity across three XSs (Figure 28) varied by up to 0.2 ft/s, with some individual local maximum differences of approximately 0.8 ft/s. The roughness values were determined to have a negligent effect on modeled velocity with respect to the fish migration criteria.

## Model Limitations

Calibration data for the model was limited to measured water surface elevations during low-flow conditions and anecdotal accounts of flood extent. If additional measured hydraulic data becomes available it could be used to further refine, if necessary, the 2D model. However, we do not feel this step is critical for the present study objectives.

Flow withdrawal into the intake was approximated for the purposes of evaluating sweeping velocity across the screens. Hydraulic values represent depth-averaged values at each 2D element, but do not represent vertical variations. Exact hydraulics at the intake screen would require a three-dimensional numerical model, possibly a physical model.

The model utilized in this study imposed a static topography and did not incorporate the predictive sediment transport and erosion module. Actual topography in the intake pool area may fluctuate as a result of the intake construction, sediment loads, and flood magnitude and frequency.

While the model extends well beyond the proposed intake area, the upper portions of the model are based largely on LiDAR data. If hydraulic results are needed in these areas, additional topographic data should be collected to define riffle crests and pools and incorporated into the model. For the current project, detailed topography in these areas is not necessary.

# Appendix D – Construction Cofferdam Results

The cofferdam design is estimated to be approximatley 12-foot wide at the base with a tapered (narrower) width as it rises up to the approximately 9-foot design height. Each cofferdam was inserted to the 2D model mesh with the 12-ft wide footprint along the alignment shown in

Figure 14 in the main report. Depending on the phase of construction, either the existing conditions (Phase 1), combination of existing and proposed ocnditions (Phase 2), or proposed conditions (Phase 3) terrain were used to represent the model topography. The height of each cofferdam was set in the model to not overtop as a baseline assumption for each flow modeled. Because the contractor may develop unique cofferdam plans and timing, four flows were selected that provide a range of potential hydraulics within the July through October construction window that will be utilized:

- 298 cfs (50% exceedance mean annual mean daily flow),
- 906 cfs (20% exceedance mean annual mean daily flow),
- 1,600 cfs (1.05 annual peak flow), and
- 3,400 cfs (1.5 year annual peak flow).

For the cofferdam runs, the year-round diversion for the hatchery was not removed from the model discharge to provide conservative results. In reality, 20 to 40 cfs will be diverted during all three construction windows using a bypass pipe or the new intake, slightly decreasing flow depths and velocity magnitudes.

The July through October window was selected because of in-water work periods designated for Icicle Creek, because high flows generally occur in May and June, and because winter months may have high flows or extensive snow and ice conditions. Occasionally peak annual floods have occurred in July and October which may require adjustement to the start and completion date for a given construction year.

| | Phase 1/Cofferdam 1 | Phase 2/Cofferdam 2 | Phase 3/Cofferdam 3 |
|---|---|---|---|
| Dates | July – September | September | October |
| 95% Exceedance Prob. | 100 cfs | 54 cfs | 70 cfs |
| 5% Exceedance Prob. | 2,000 cfs | 295 | 651 |
| **Model Flows Likely to Occur in Construction** | **298, 906, 1,600 cfs** | **298 cfs*** | **298 and 906 cfs*** |
| **Terrain** | **Existing Conditions** | **Proposed Conditions for Phase 1 Construction Area & Existing Conditions in Reamining Areas** | **Proposed Conditions** |

*Model runs also available for 906, 1,600, and 3,400 cfs due to uncertainty in final construction timing.

## Cofferdam 1 for Phase 1

Cofferdam 1 modeling used the existing conditions topography and was represented by an approximate 12-foot wide structure at an artifically high elevation to prevent overtopping during model runs (Figure 38). Cofferdam 1 is estimated to be in place between July through September during the first year of construction. Water depth and velocity results are presented for 298 cfs, 906 cfs, and 1,600 cfs in Figure 39, Figure 40, and Figure 41, respectively. Water depths do not exceed
9 ft at 298 and 906 cfs. At 1,600 cfs water depths reach 9 to 10 ft in Location B; at 3,400 cfs water depths reach 10 to 12 ft in Location B-C. The highest velocity occurs where water is routed over the existing weir adjacent to Location C. At 1,600 cfs, Section A-B-C predicted water surface elevations are 1,198 to 1,197 ft (NAVD88); along Section C-D predicted water surface elevations are from 1197 (Location C) to 1,188 ft (Location D), and along Section D-E predicted water surface elevations are 1,188 to 1,187 ft. At 3,400 cfs, Section A-B-C predicted water surface elevations are 1201 to 1200 ft (NAVD88); along Section C-D predicted water surface elevations are from ,1200 (Location C) to 1,190 ft (Location D), and along Section D-E predicted water surface elevations are 1,190 to 1,189 ft.

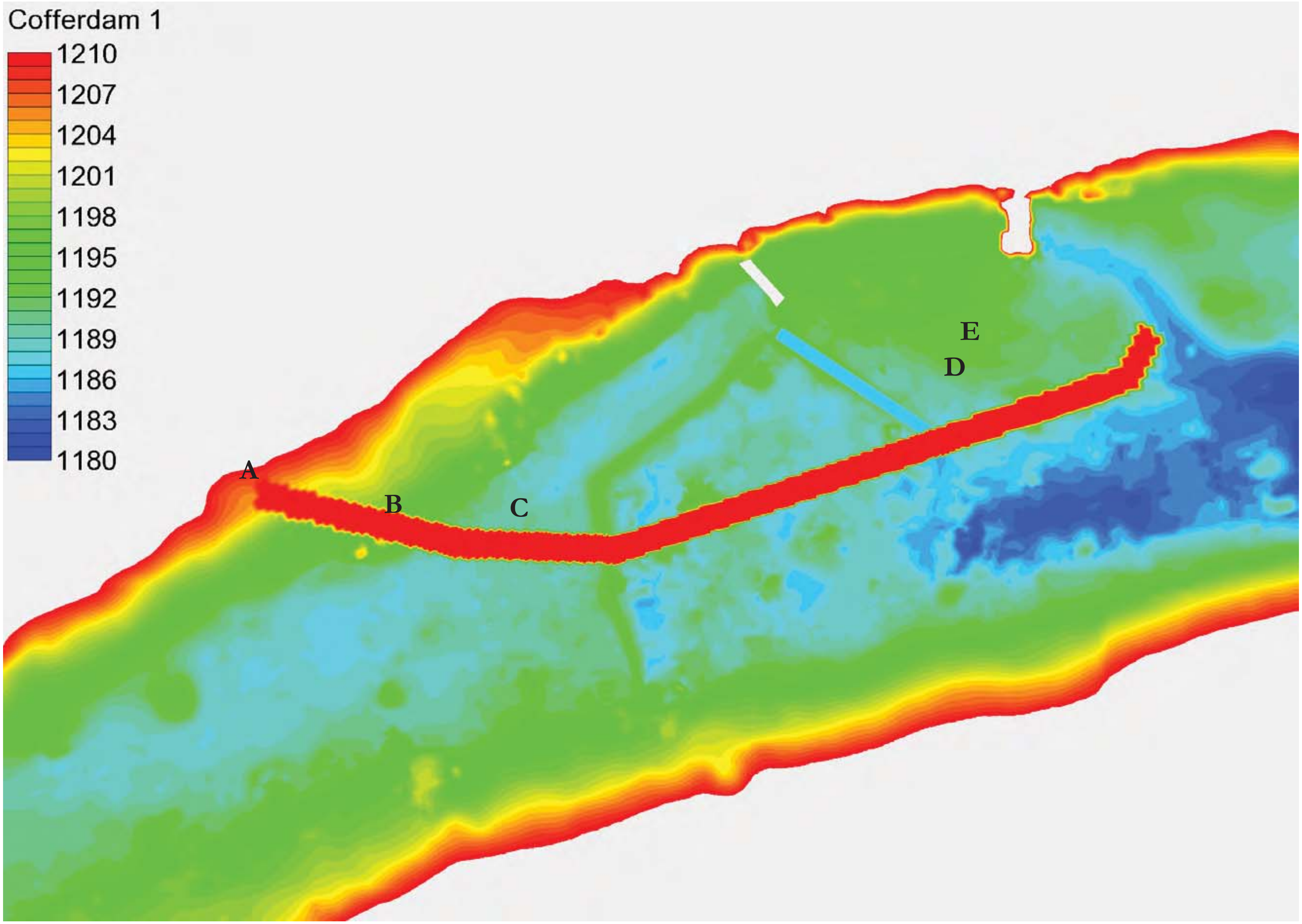



Figure 38. Representation of existing conditions terrain and Cofferdam 1 during phase 1 of construction. Letters A to E are provided for reference locations in the discussion. Flow moves from left to right across the image.

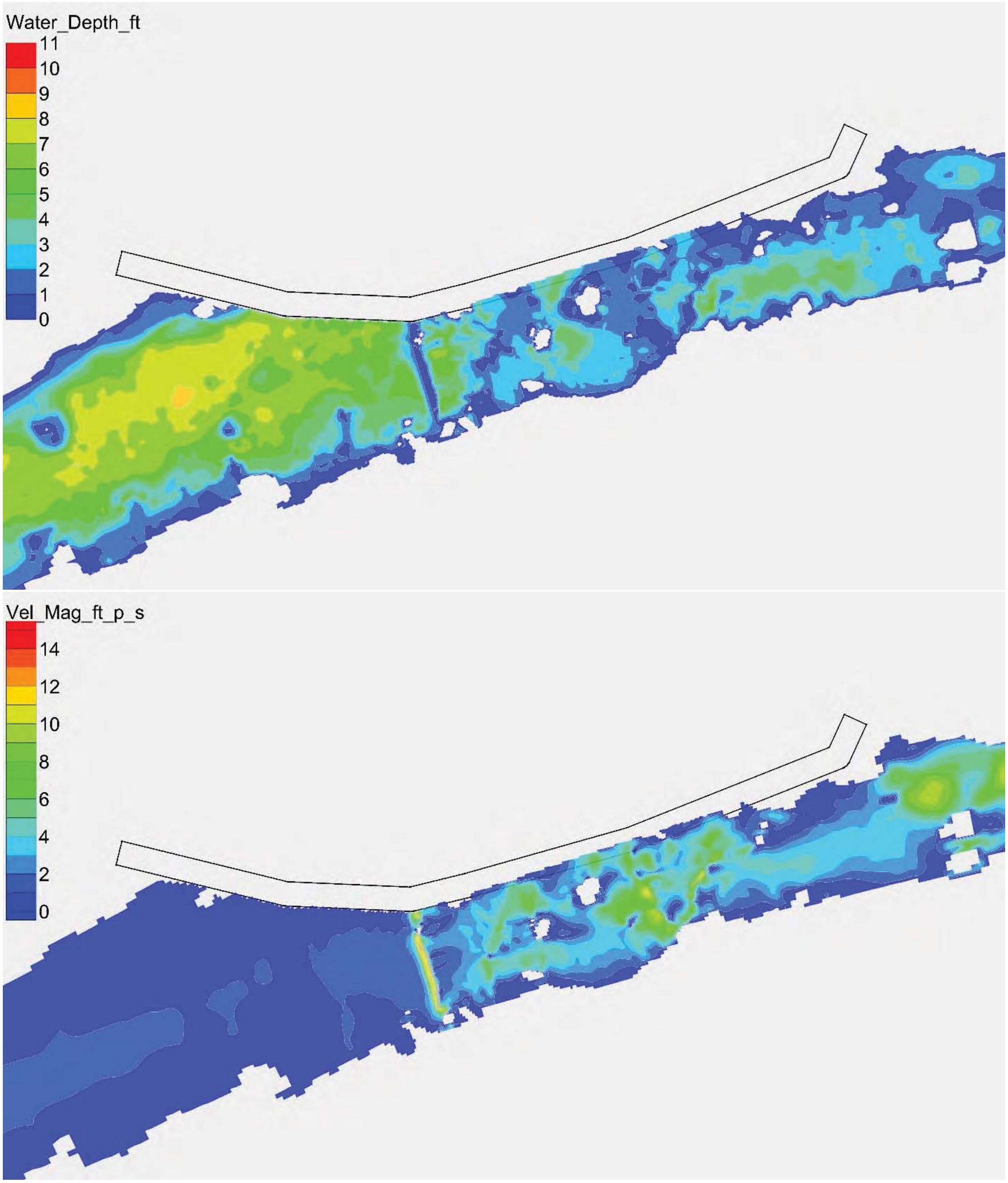



Figure 39. 2D results at 298 cfs with Cofferdam 1 for water depth (ft) and velocity (ft/s) in top and bottom images, respectively. Contour interval is in 1-ft (ft/s) increments for this figure and all following figures. Flow is from left to right in this figure and all subsequent figures.

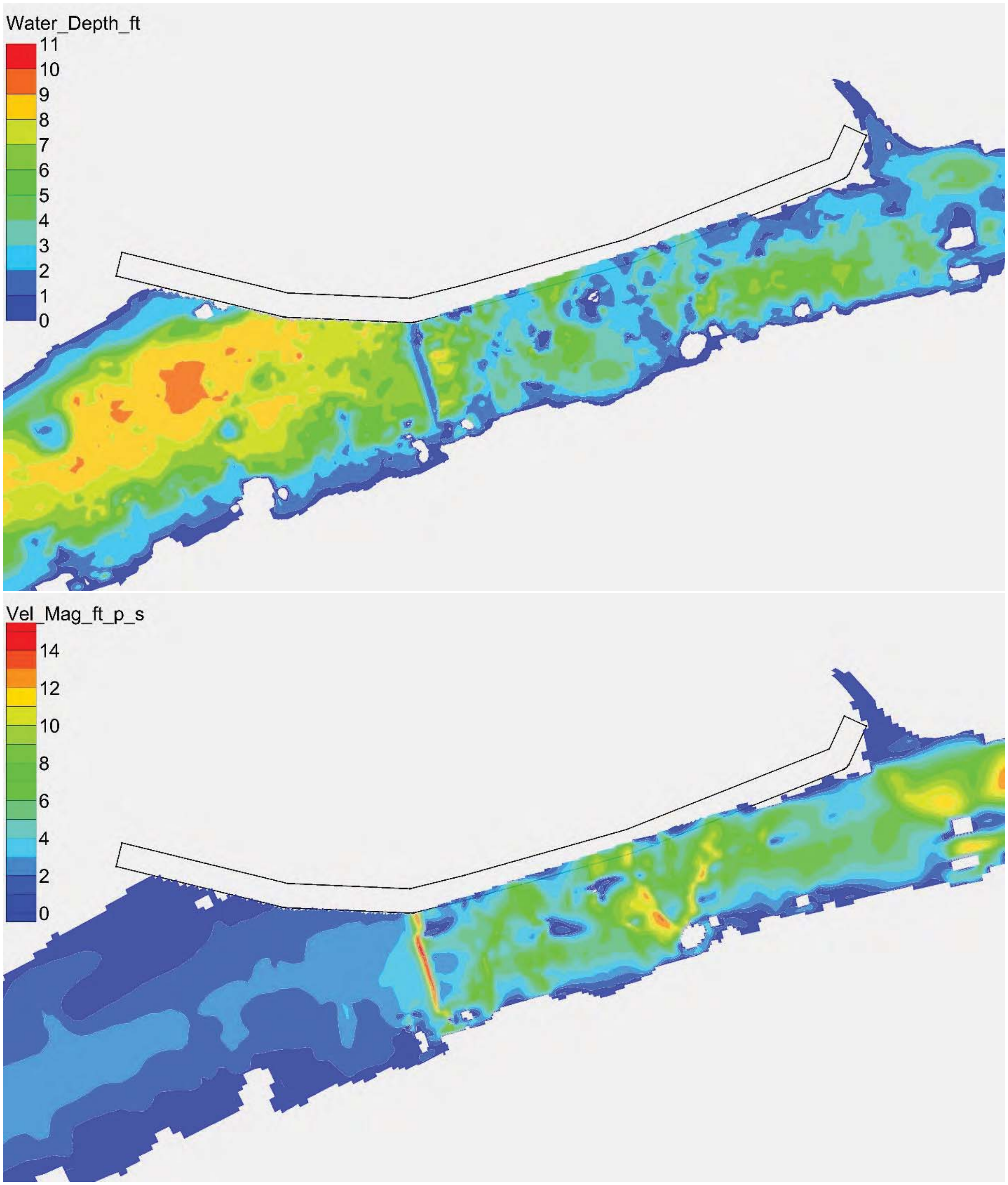



Figure 40. 2D results at 906 cfs with Cofferdam 1 for water depth (ft) and velocity (ft/s) in top and bottom images, respectively.

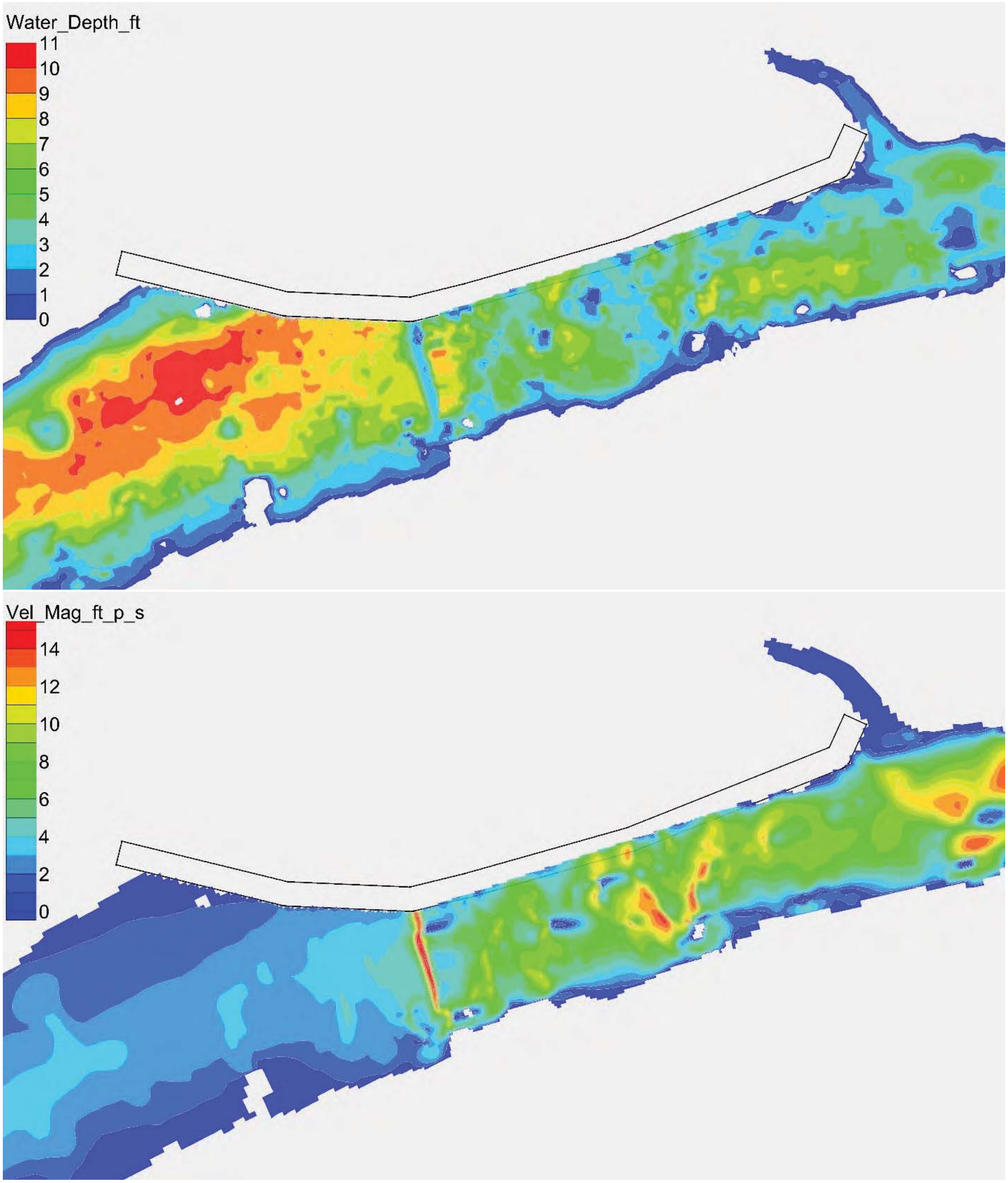



Figure 41. 2D results at 1,600 cfs with Cofferdam 1 for water depth (ft) and velocity (ft/s) in top and bottom images, respectively.

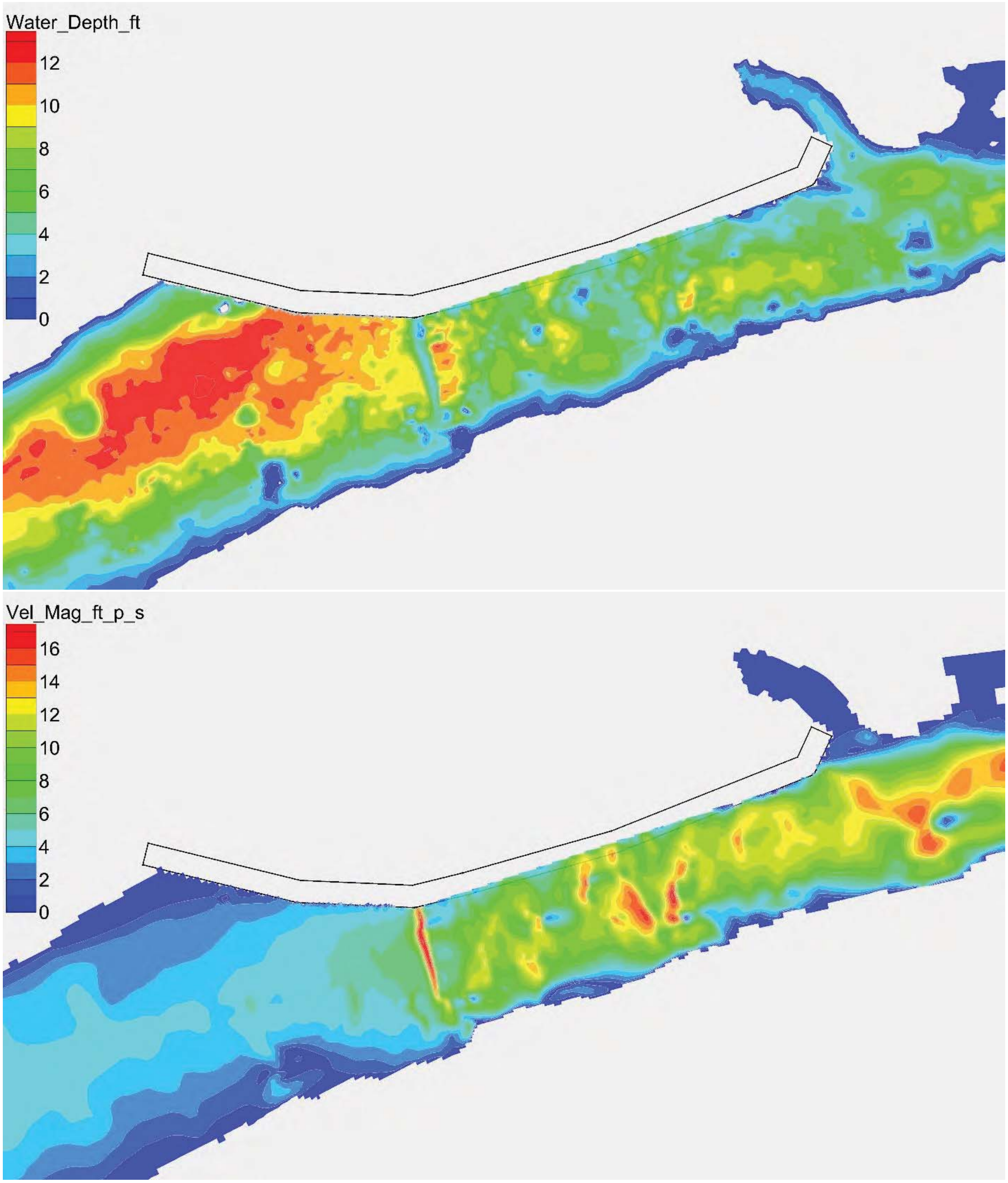



Figure 42 2D results at 3,400 cfs with Cofferdam 1 for water depth (ft) and velocity (ft/s) in top and bottom images, respectively.

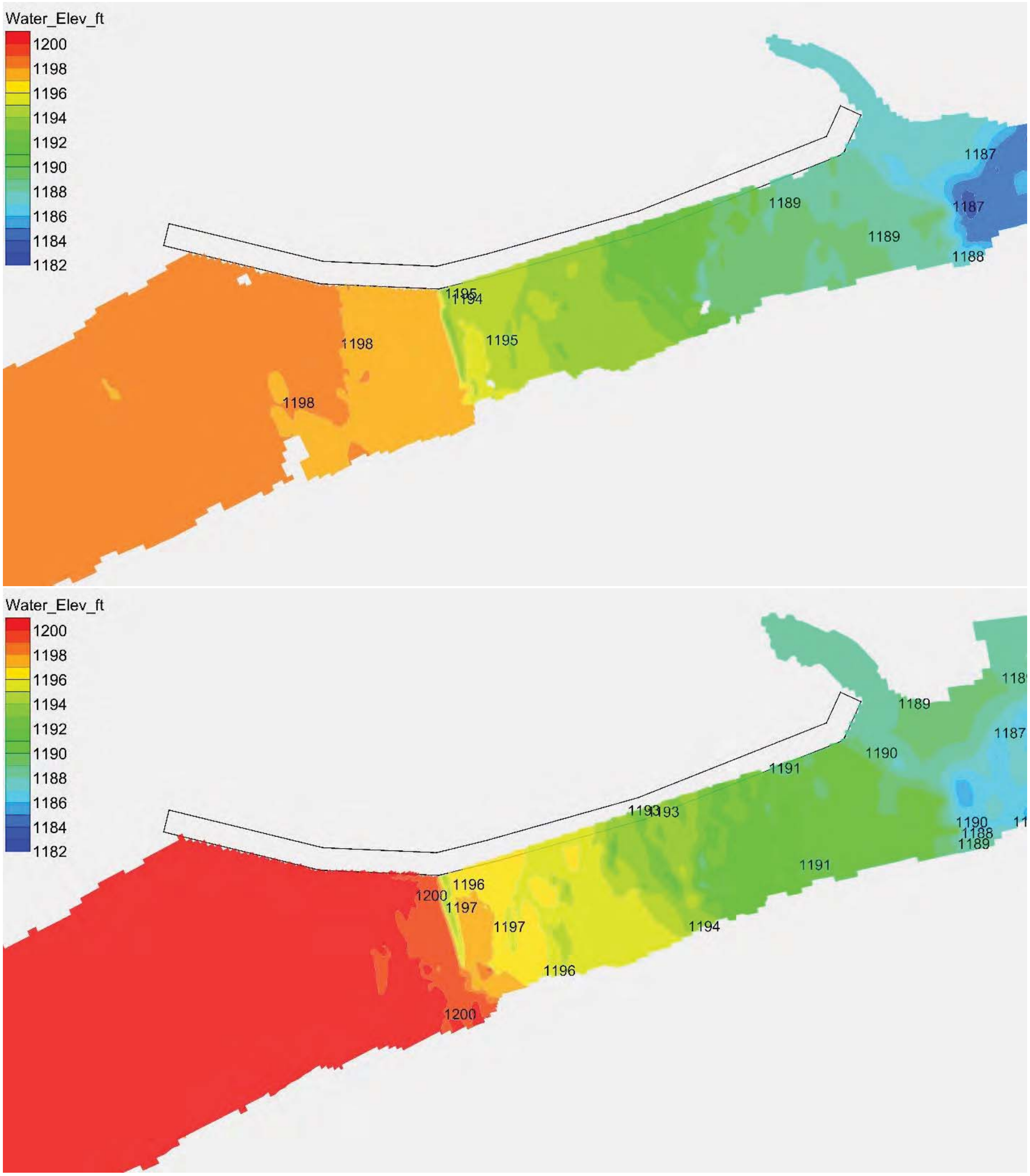



Figure 43. 2D water surface elevation (NAVD88 ft) results for Cofferdam 1 at 1,600 (top) and 3,400 cfs (bottom). Contour interval is in 1-ft increments.

## Cofferdam 2 for Phase 2

Cofferdam 2 modeling used the proposed conditions topography in the area that was behind cofferdam 1 from the Phase 1 construction (intake structure), and existing conditions topography in the remaining portions of the mesh including the main channel (Figure 44). Cofferdam 2 was represented by an approximate 12-foot wide structure at an artifically high elevation to prevent overtopping during model runs. Cofferdam 2 is estimated to be in place in September during the first year of construction. Water depth and velocity results are presented for 298 cfs, 906 cfs, and 1,600 cfs in Figure 45, Figure 46, and Figure 47, respectively. Water depths will not exceed 9 ft at 298 or 906 cfs. At 1,600 cfs, water depth would be between 9 and 10 ft at location C, but the remainder of the cofferdam would be exposed to less than 9 ft of water depth. At location C, velocities will be high even at low flows (298 cfs) and may require more protection to prevent erosion. At 1,600 cfs, Section A-B predicted water surface elevations are 1,198 ft (NAVD88); along Section B-C predicted water surface elevations are from 1198 (Location B) to 1,190 ft (Location C), and along Section C-D predicted water surface elevations are 1,190 to 1,189 ft. At 3,400 cfs, Section A-B predicted water surface elevations are 1,201 to 1,202 ft (NAVD88); along Section B-C predicted water surface elevations are from 1201 (Location B) to 1192 ft (Location C), and along Section C-D predicted water surface elevations are 1,192 to 1,190 ft.

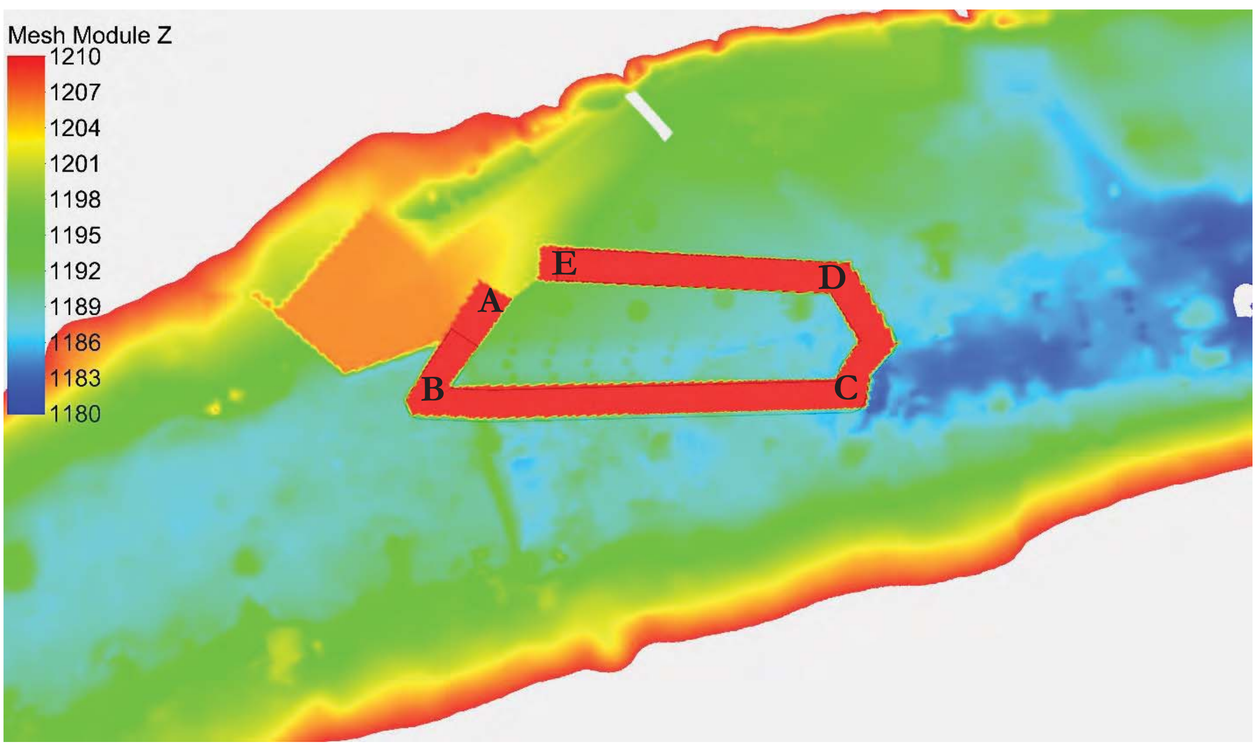



Figure 44. Representation of existing conditions terrain and Cofferdam 2 during phase 2 of construction. Letters A to E are provided for reference locations in the discussion.

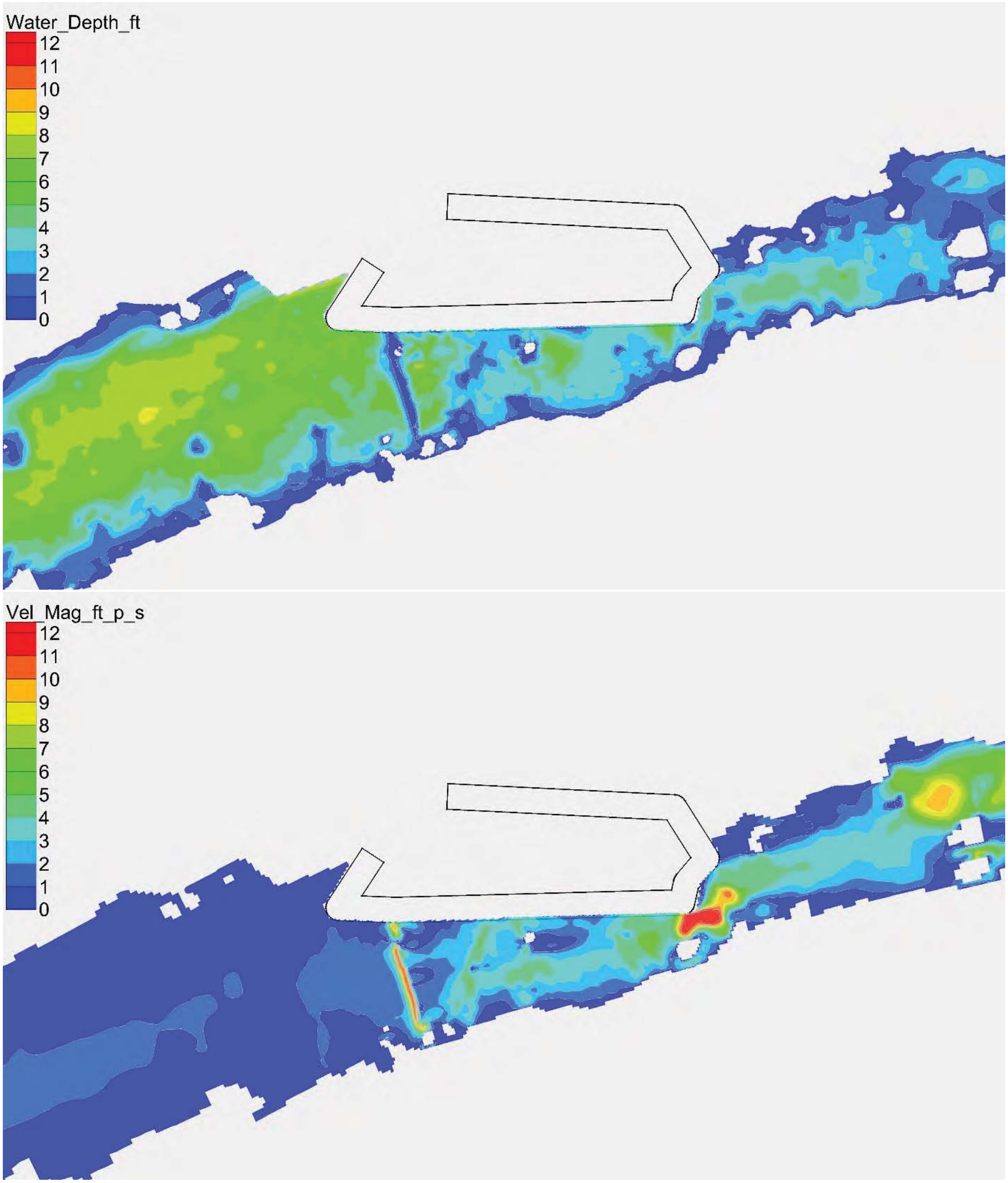



Figure 45. 2D results at 298 cfs with Cofferdam 2 for water depth (ft) and velocity (ft/s) in top and bottom images, respectively.

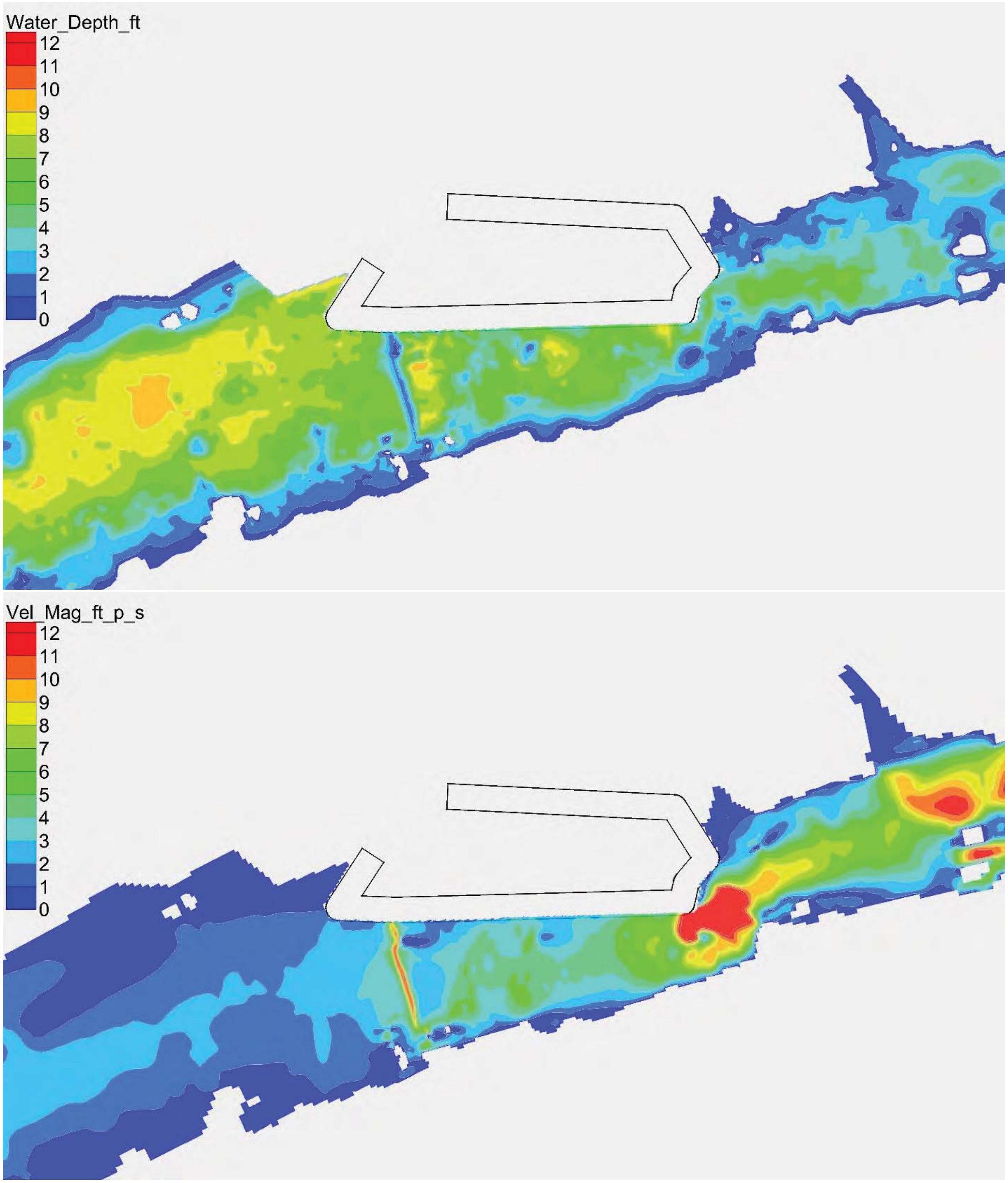



Figure 46. 2D results at 906 cfs with Cofferdam 2 for water depth (ft) and velocity (ft/s) in top and bottom images, respectively.

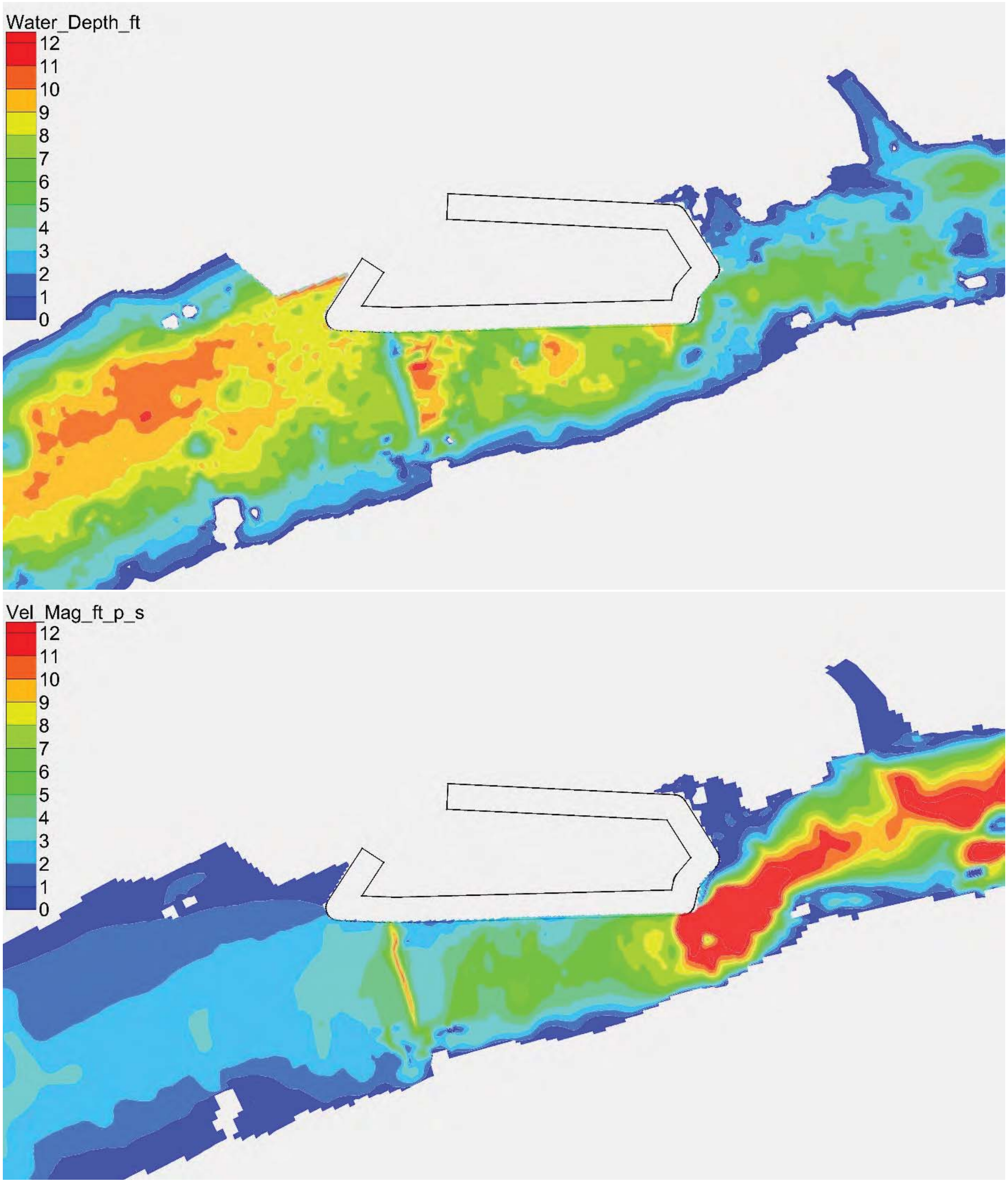



Figure 47. 2D results at 1,600 cfs with Cofferdam 2 for water depth (ft) and velocity (ft/s) in top and bottom images, respectively.

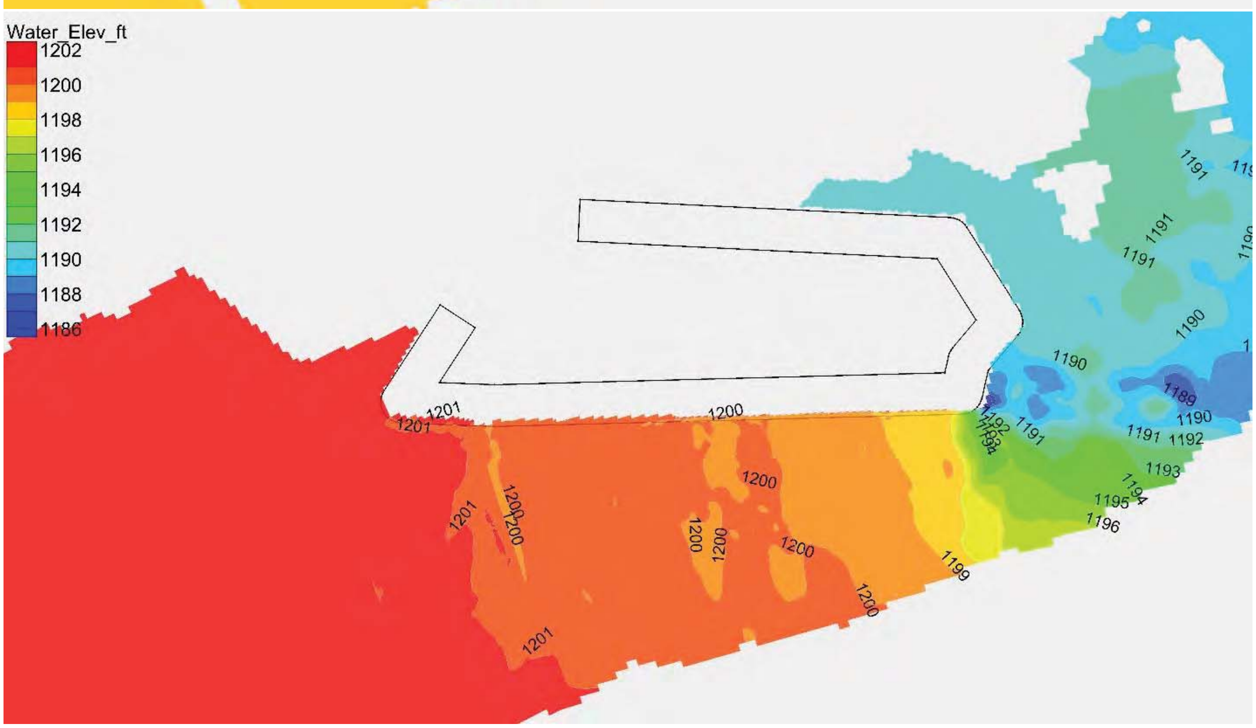




Figure 48. 2D water surface elevation (NAVD88 ft) results for Cofferdam 2 at 1,600 (top) and 3,400 cfs (bottom).

## Cofferdam 3 for Phase 3

Cofferdam 3 modeling used the proposed conditions topography and was represented by an approximate 12-foot wide structure at an artifically high elevation to prevent overtopping during model runs (Figure 49). Cofferdam 3 is estimated to be in place in October during the first year of construction, but may be shifted to year 2 of construction depending on the pace of construction. Water depth and velocity results are presented for 298 cfs, 906 cfs, and 1,600 cfs in Figure 50, Figure 51, and Figure 52, respectively. Water depths do not exceed 9 ft at 298 cfs. At 906 cfs and larger flows, water depths exceed 9 ft in Location B-C. Because the flow is constricted at Location C, velocities are high for 298, 906 and 1,600 cfs at Location C and along Location C-D. Additional protection to prevent erosion of the cofferdam would likely be required. At 906 cfs, Section A-B-C predicted water surface elevations are 1,199 to 1,200 ft (NAVD88); along Section C-D predicted water surface elevations are from 1,199 (Location C) to 1,190 ft (Location D), and along Section D-E predicted water surface elevations are 1,190 to 1,188 ft. At 1,600 cfs, Section A-B-C predicted water surface elevations are 1,202 to 1,203 ft (NAVD88); along Section C-D predicted water surface elevations are from 1,201 (Location C) to 1,191 ft (Location D), and along Section D-E predicted water surface elevations are 1,191 to 1,189 ft. At 3,400 cfs the newly constructed intake structure on river left would be overtopped requiring the cofferdam to be removed.

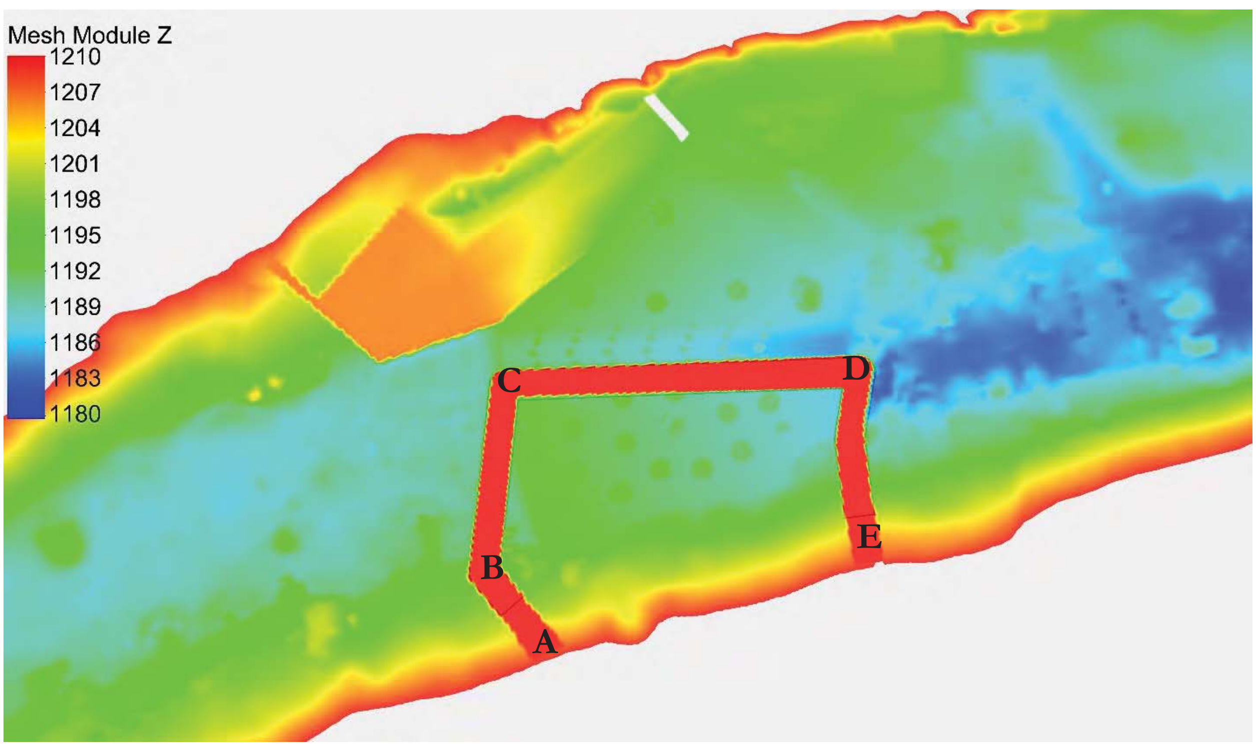
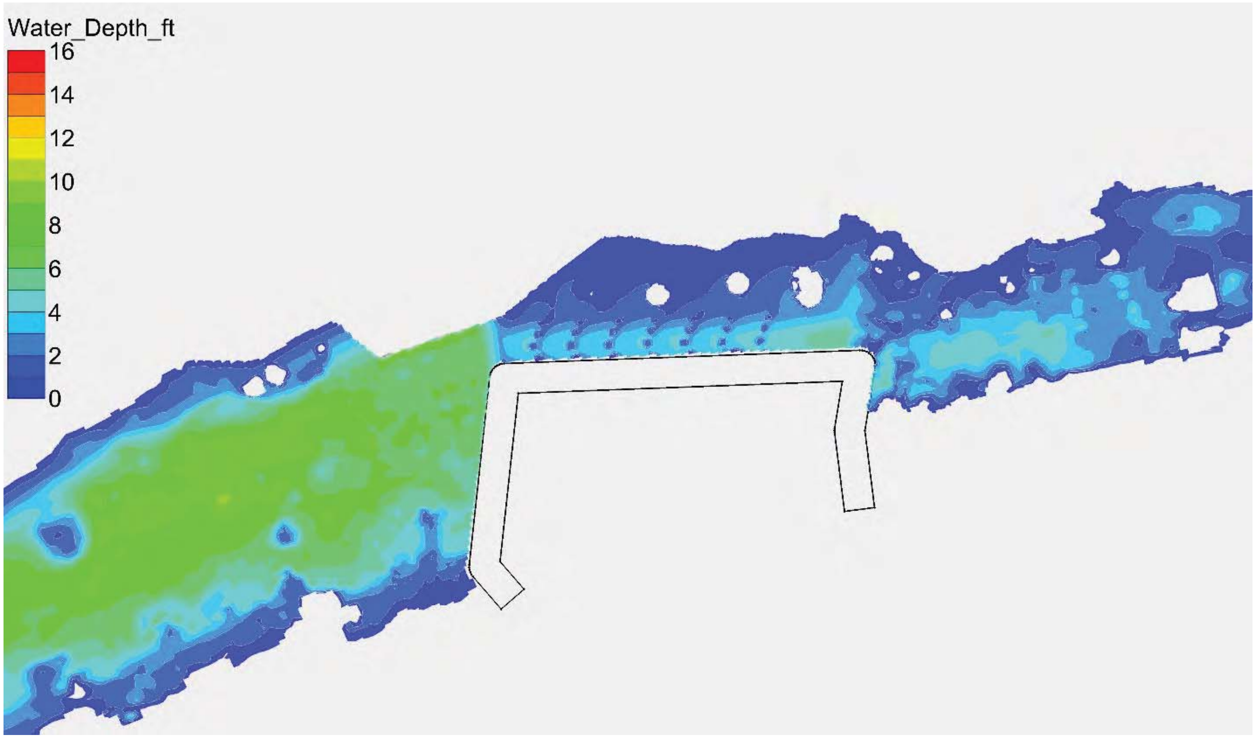



Figure 49. Representation of existing conditions terrain and Cofferdam 3 during phase 3 of construction. Letters A to E are provided for reference locations in the discussion.



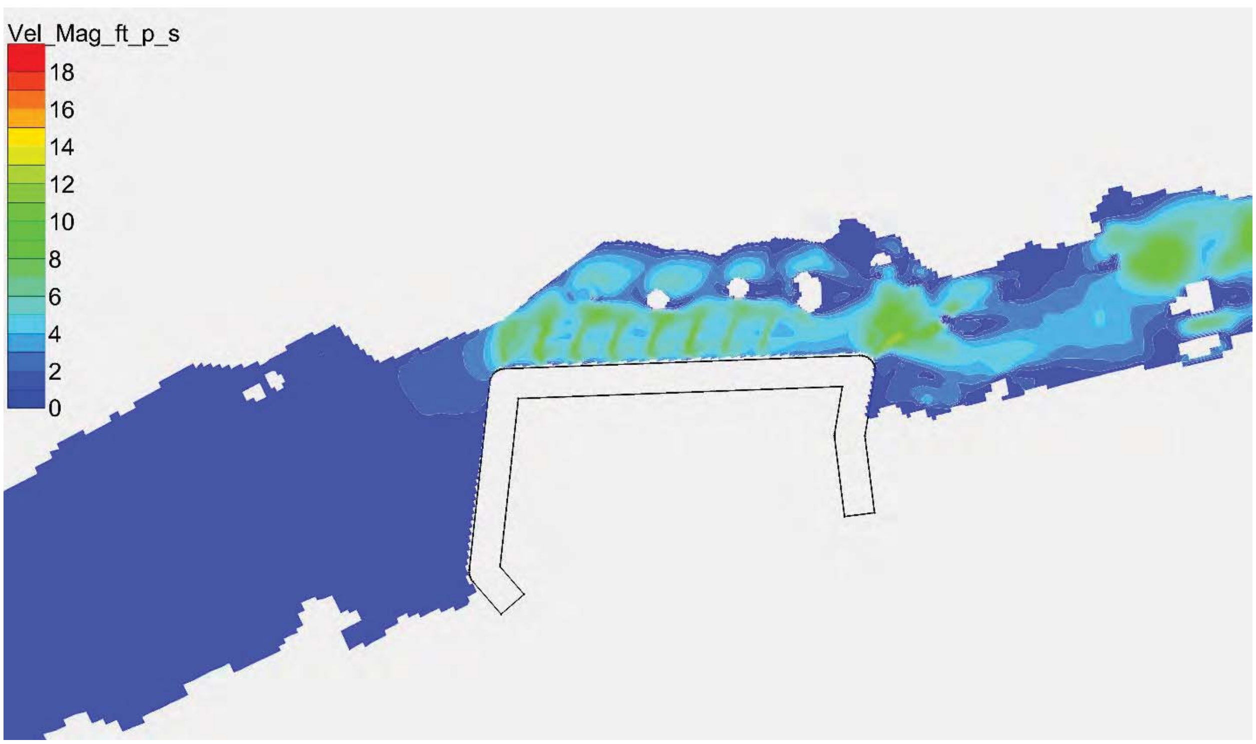




Figure 50. 2D results at 298 cfs with Cofferdam 3 for water depth (ft) and velocity (ft/s) in top and bottom images, respectively.

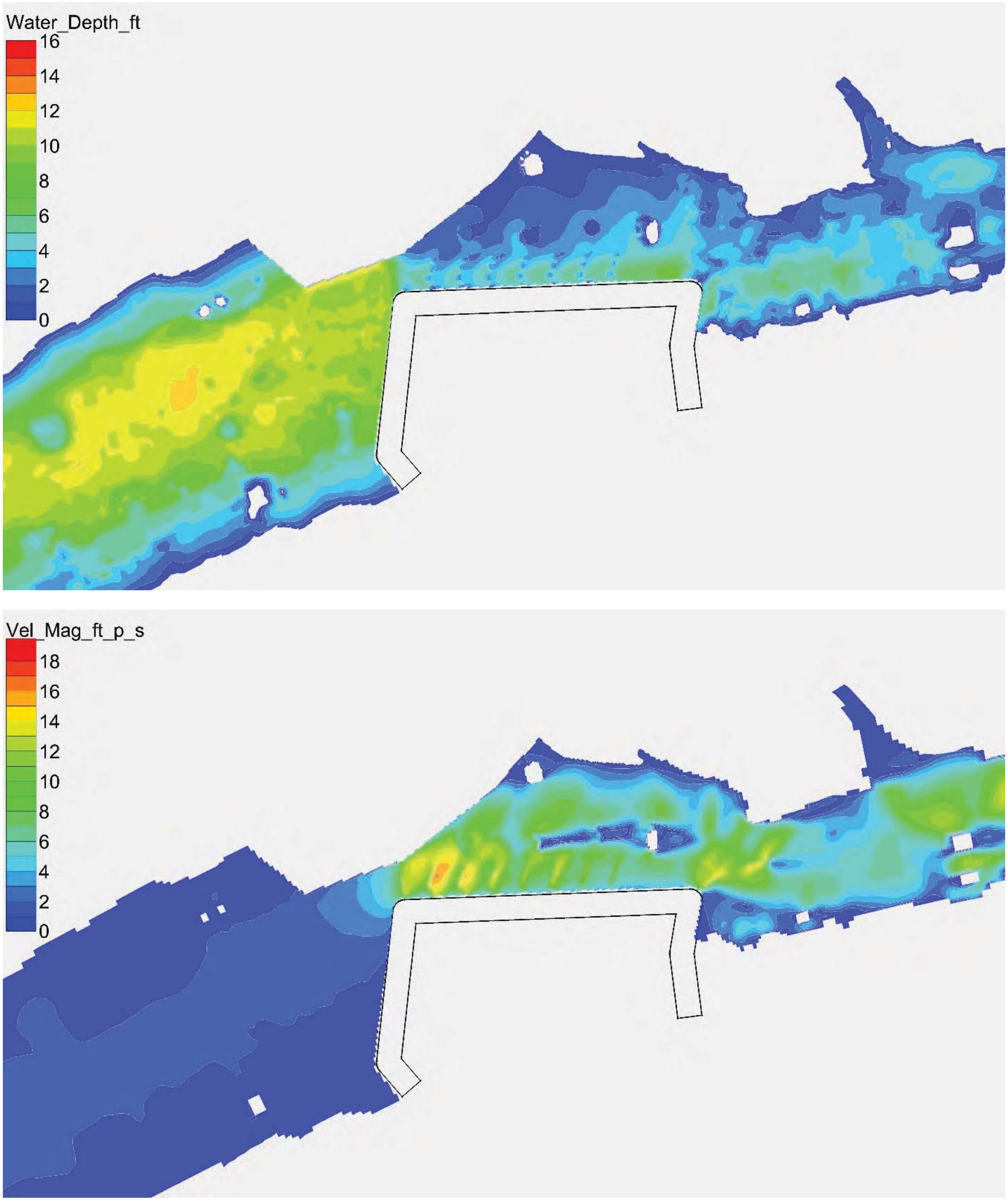



Figure 51. 2D results at 906 cfs with Cofferdam 3 for water depth (ft) and velocity (ft/s) in top and bottom images, respectively.

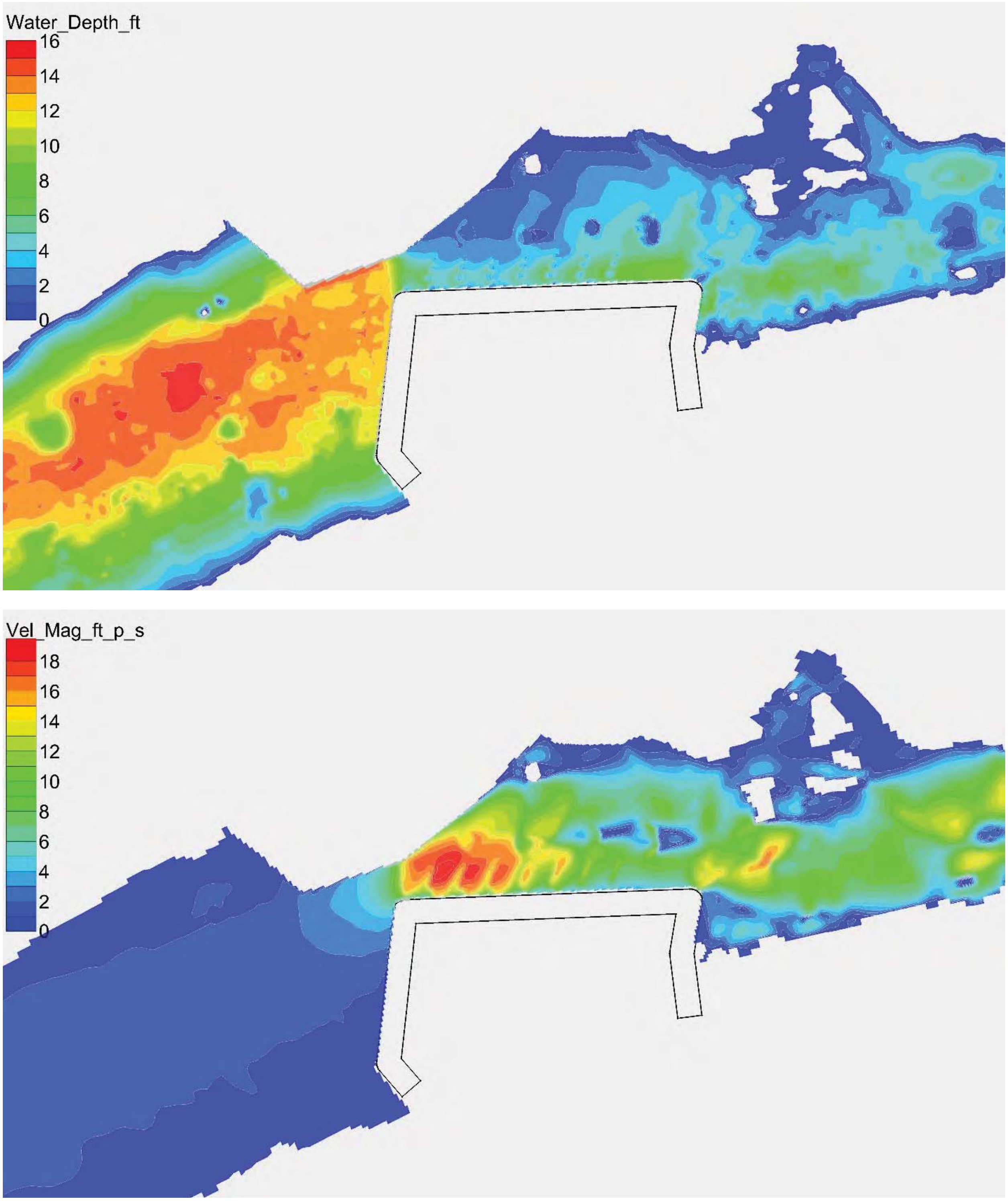



Figure 52. 2D results at 1,600 cfs with Cofferdam 3 for water depth (ft) and velocity (ft/s) in top and bottom images, respectively.

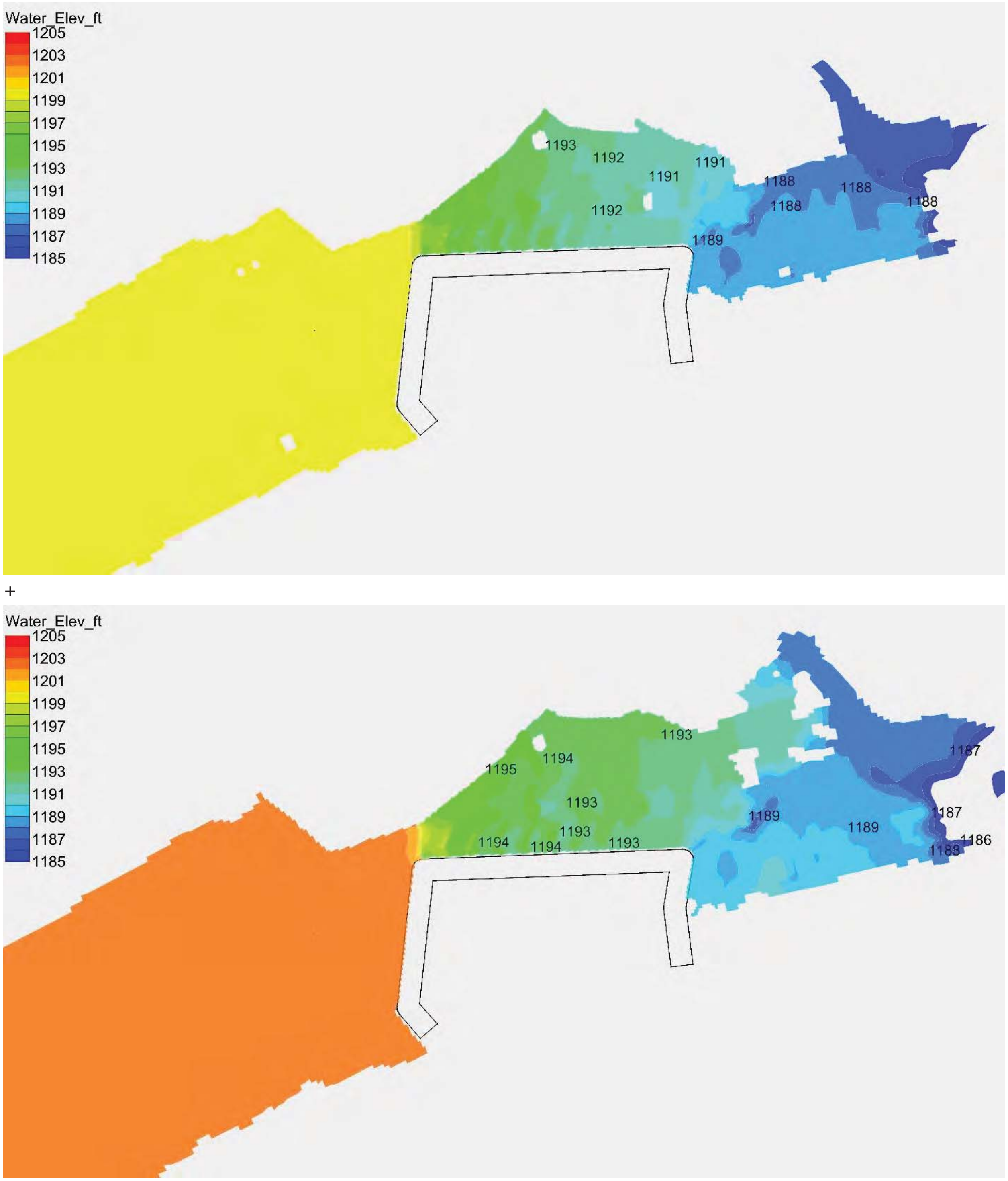



Figure 53. 2D water surface elevation (NAVD88 ft) results for Cofferdam 3 at 906 (top) and 1,600 cfs (bottom).