Appendix D| Hydraulic Model

MIDDLE ENTIAT RIVER REACH ASSESSMENT UPDATE

February 2026

Table of Contents

1 Introduction

A hydraulic analysis of the Entiat River was conducted as part of the reach assessment. This analysis includes a preliminary-level 2-dimensional (2-D) hydraulic model of Reaches 1 to 12 of the Entiat River (RM 15.6 to 26.7). The hydraulic model is used to understand general hydraulic characteristics of the river at a range of high flows, including stream energy (e.g. velocity), floodplain inundation patterns, and the effects of human and natural features on streamflow patterns. Model results were used to support the geomorphological interpretations that are included in the main document and were also used to inform the sediment transport analysis that is presented in the main document.

2 Hydraulic Model Methodology

The hydraulic model was developed in the U.S. Army Corps of Engineers HEC-RAS 6.6 software (USACE, 2024), which can compute hydraulic properties related to the physical processes governing water flow through natural rivers and other channels. Characteristics of the Entiat River, such as regions of high sinuosity, multiple regions of split flow, and a wide and complex floodplain, make it a good candidate for a 2-D model, as such features are difficult to accurately model using a 1-dimensional model. The model was developed for existing conditions to assess the current channel and floodplain dynamics, as well as to assess the impacts of a range of flows on the landscape. This model only accounts for surface water flows and does not include groundwater fed features. This document describes parameterization, assumptions, and set up of the hydraulic model. Results are depicted and described in Section 3.

2.1 MODEL SETUP

2.1.1 Model Terrain

A digital terrain model (DTM) was created using publicly available LiDAR data. The LiDAR dataset (NV5 Geospatial, 2022) includes topographic and bathymetric data from 2022, and was deemed to be a sufficient representation of the Entiat River's channel and surrounding terrain for this analysis. The bathymetric LiDAR captures below water terrain. However, factors such as thick aquatic vegetation, algal growth, high turbidity, or deep water can affect the accuracy of the data. For many areas, more detailed bathymetric and topographic surveys would be needed to support detailed restoration project design.

2.1.2 Model Domain and Geometry

The model's domain extends from downstream the Potato Creek confluence (near RM 14.3) to downstream of the Burns Creek confluence (near RM 27.7) (Figure 1). The computational mesh consists of grid cells ranging from 15-50 feet, with the smallest grid cells providing higher resolution results closer to the channel and terrain features of interest (Figure 2). To improve model runtime, channel cell size ranged between 15x15 and 30x30 ft, while much of the floodplain is made up of 50x50 ft cells. Larger cells on the floodplain can result in overestimation of flow inundation if cells span across high ground areas that would be a flow barrier. Breaklines were added along topographic high points to align cell faces along high ground to improve the representation of the underlying terrain and limit this "leaking" effect, but there may still be some overestimation of floodplain inundation. Breaklines are also added along the channel to force cell alignment perpendicular to flow, improving efficiency and accuracy.

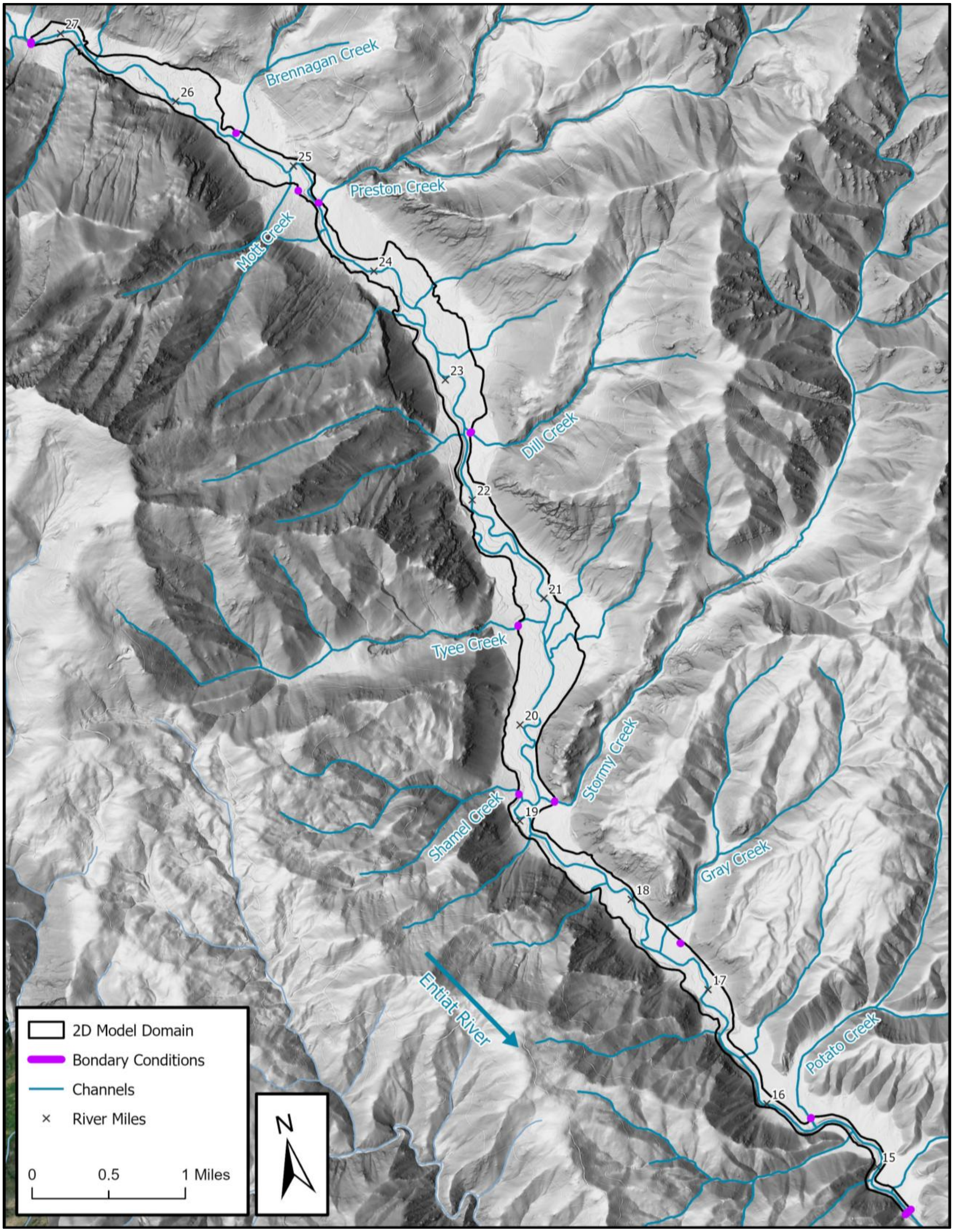


Figure 1. 2D model domain for the Entiat River with all National Hydrology Dataset tributary flowlines for the region and tributaries included in the model labeled with their model external boundary locations highlighted.

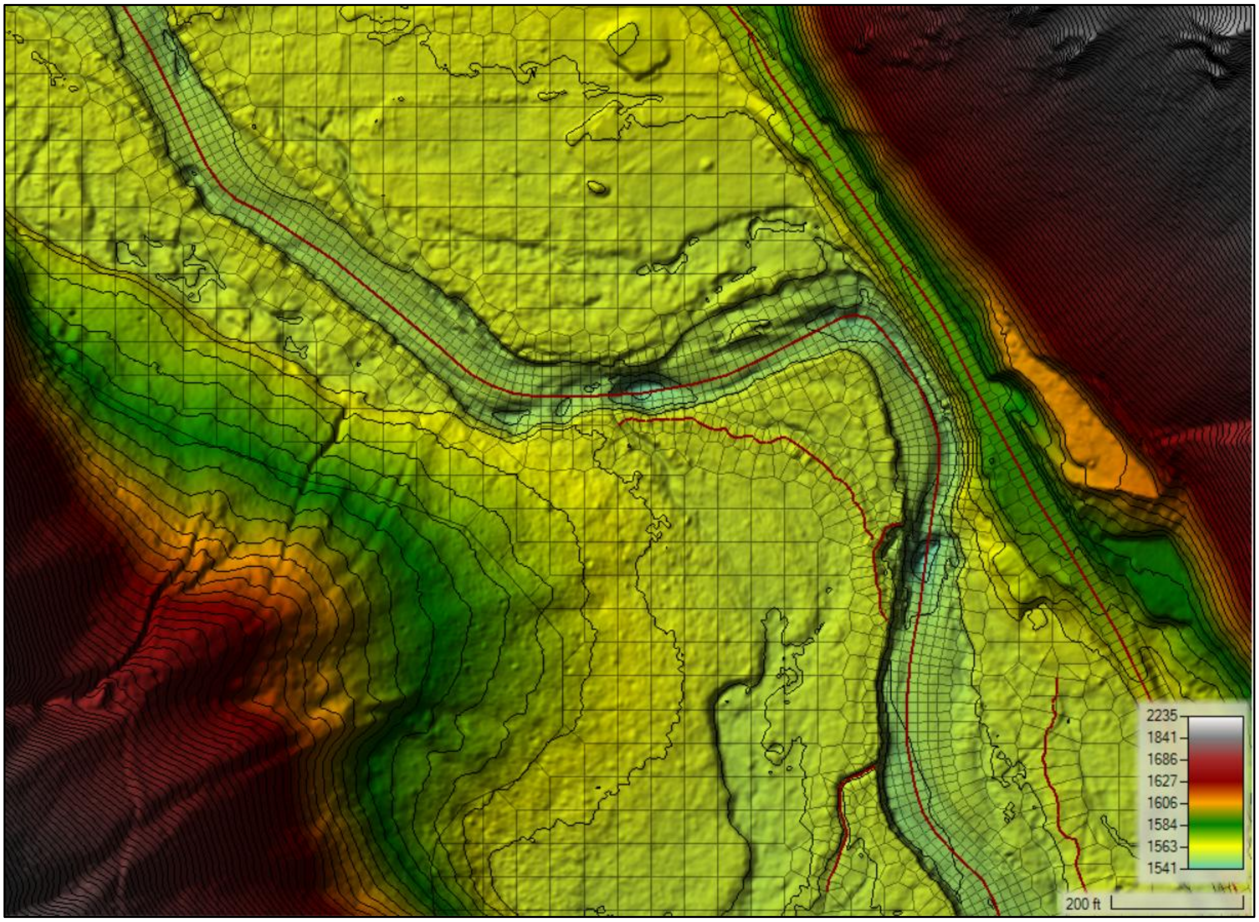


Figure 2. Representative computational mesh in the model domain (with 5 ft contours shown). Grid cells within the channel have a nominal size of 13-30 ft, while the outer floodplain cells are 50 ft. Breaklines (seen in red) are enforced along the channels and high ground features to align cell faces perpendicular to the prominent flow direction.

2.1.3 Bridges and Water Control Structures

Although there are several bridges that cross the Entiat River within the assessment area, bridge surveys were not performed and therefore no bridges were included in the model. Most bridges in this region are high and likely have relatively minor or insignificant effects at the reach-scale at the flows used in the model. In addition, water control structures in the project area were deemed to be adequately represented by the LiDAR-based model terrain for this preliminary analysis. Future design-level modeling will likely require survey of bridges and water control structures.

2.2 MODEL INPUTS

2.2.1 Model Roughness

A spatially varying Manning’s n layer was developed using ArcGIS tools to represent hydraulic roughness throughout the model domain. The roughness layer was developed using a vegetation height layer created by subtracting the LiDAR bare ground layer (DTM) from the LiDAR first return layer (Digital Surface Model) and reclassifying these data to approximate vegetation communities by canopy height that would be represented by different Manning’s n values. These data were supplemented with hand-digitized polygons, representing more discrete features such as creek and river channels. A table of Manning’s n coefficients and their associated classifications is provided in Table 1. Assumed channel roughness coefficients range from 0.03 across most of the reach to 0.05 in turbulent sections where the channel is steeper and the river bed is made up of gravel. Floodplain roughness coefficients range from 0.02 to 0.65.

Table 1. Roughness coefficients (Manning's n values) utilized in the preliminary existing conditions modeling.

Area Description	Roughness Coefficient (Manning’s n Value)
Entiat River Channel	0.03
Entiat River Channel (Turbulent Areas)	0.05
Side Channels	0.035
Tributary Channels	0.04
Pond	0.025
Woody Pond	0.04
Road	0.02
Bare Ground (vegetation height <0.5 ft)	0.03
Sparse Grasses (0.5-4 ft)	0.04
Small Tree Forest (4-30 ft)	0.055
Tall Tree Forest (>30 ft)	0.065

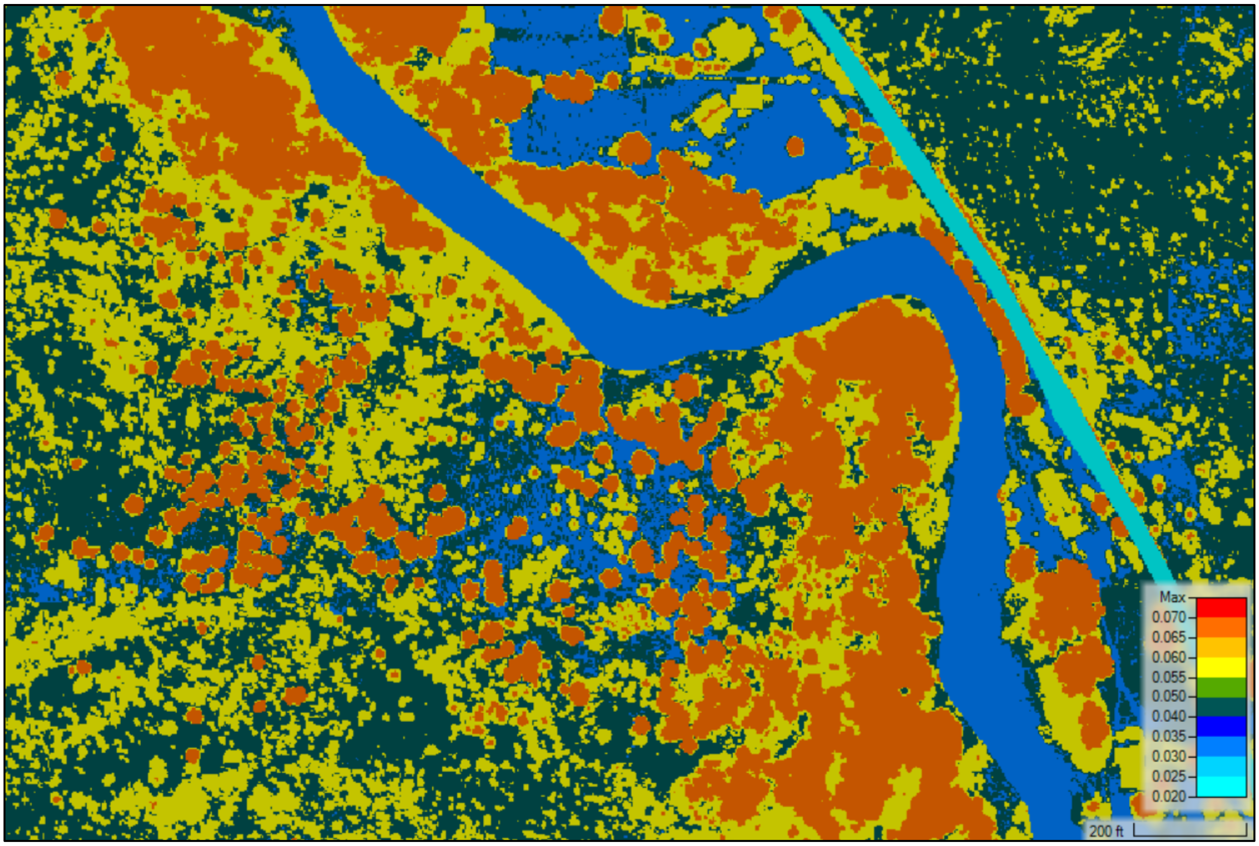


Figure 3. Representative depiction of roughness regions assigned to the existing conditions Entiat River model.

2.2.2 Model Hydrology

The hydrologic inputs for the Entiat River model were calculated by performing a variety of hydrologic analyses using data from various sources. For the mainstem Entiat River, a flood frequency analysis was performed using data from the Entiat River Near Ardenvoir, WA gage (USGS gage 12452800), which is situated in the middle of the project area near RM 18. The USGS gage has a period of record from September 1958 to present (USGS, 2025). Peak flows from water years 1958 to 2023 were used to complete a bulletin 17C peak flow analysis with the HEC-SSP software (USACE, 2023). The 17C analysis was conducted using a weighted skew, with a regional skew of -0.07 and a regional skew MSE of 0.18, as outlined by Mastin et al. (2017). The peak flows from this analysis were scaled using the weighting equations for Region 2 in Mastin et al (2017) to obtain the flow input at the upstream and downstream boundary of the model. Nine tributaries to the Entiat River were identified as additional flow inputs to the hydraulic model: Brennegan Creek, Mott Creek, Preston Creek, Dill Creek, Tyee Creek, Stormy Creek, Shamel Creek, Gray Creek, and Potato Creek. The drainage areas for each of these tributaries were used to scale the results of the Entiat River flood frequency analysis, such that hydrologic inputs could be apportioned among the tributaries. The drainage area for each tributary was estimated by delineating the Entiat River's drainage area just above and just below a tributary's confluence in the USGS StreamStats program (USGS, 2022), and then calculating the difference in these drainage areas. The difference in peak flows between the top and bottom of the project area (described previously) was then distributed among the tributaries based on the size of each tributary's drainage area (Table 2).

Table 2. Modeled flow events (in cfs) for the Entiat River and tributaries used in hydraulic modeling.

Flow Event	Entiat River Upstream Discharge	Brennegan Creek	Mott Creek	Preston Creek	Dill Creek	Tyee Creek	Stormy Creek	Shamel Creek	Gray Creek	Potato Creek
2 - year	2,260	80	30	90	80	50	130	20	50	150
5 - year	3,040	100	30	120	110	70	170	30	60	200
10 - year	3,540	110	40	130	120	70	190	30	70	220
20 - year	4,160	130	40	150	140	90	220	40	80	260
50 - year	4,610	140	50	160	150	90	240	40	90	280
100 - year	5,050	150	50	180	170	100	260	50	100	300

The hydraulic model was used to evaluate existing conditions at flow events ranging from the 2-year to the 100-year flow event for the Entiat River (Table 2). A synthetic hydrograph containing inflows of interest was used as the model input hydrograph to simulate steady-state flow conditions for the peak flows, where the discharge of interest remains constant long enough to allow the model to reach a state of equilibrium (Figure 4). Allowing the model to reach a steady state during large flood events may overestimate flooding results, as floodplain storage areas throughout the model domain must reach capacity for the outflow of the model to reach steady-state conditions. In reality, this may not occur during short-duration events. However, it is a safe assumption for longer-duration events and is a more conservative (i.e., more likely to predict larger flooding extents) approach than was deemed appropriate for this preliminary-level model.

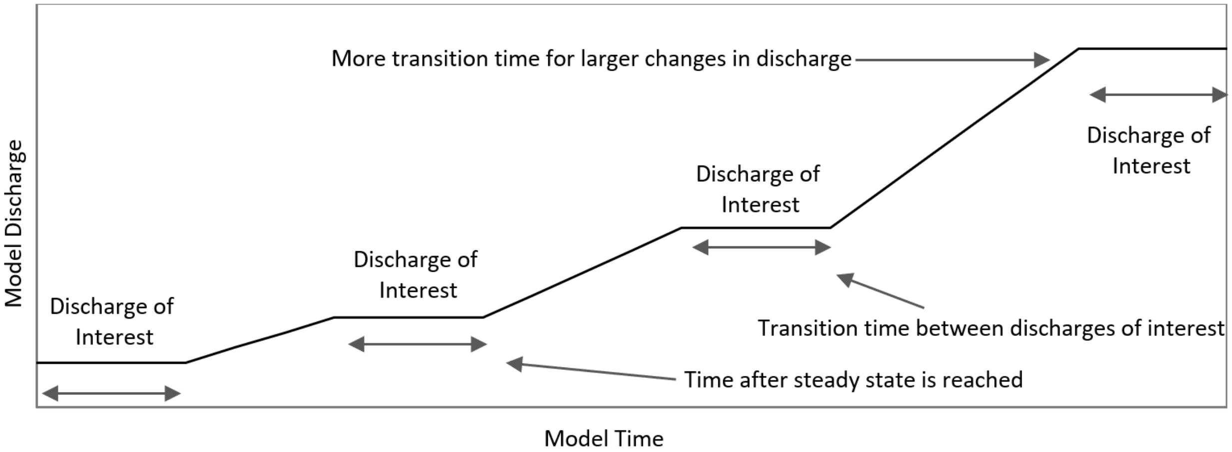


Figure 4. Demonstrative "stepped" flow input hydrograph.

2.2.3 Model Boundary Conditions

The upstream boundary condition was set to the "Entiat River Upstream Discharge" in Table 2, with an assumed Energy Grade Line slope of 0.002 based on the terrain at the location of the upstream boundary, which estimates the energy loss across the boundary condition. Each of the nine tributaries, Brennegan Creek, Mott Creek, Preston Creek, Dill Creek, Tyee Creek, Stormy Creek, Shamel Creek, Gray Creek, and Potato Creek, were added to the model as external boundary conditions with their own hydrograph and energy slopes estimated based on the channel bed slope from the LiDAR-based terrain, and with peak flow timings corresponding to the mainstem Entiat River peak flows. The downstream boundary of the model is a normal depth boundary condition with an assumed Energy Grade Line slope of 0.013 based on the terrain at the location of the boundary.

2.3 MODEL CALIBRATION AND VERIFICATION

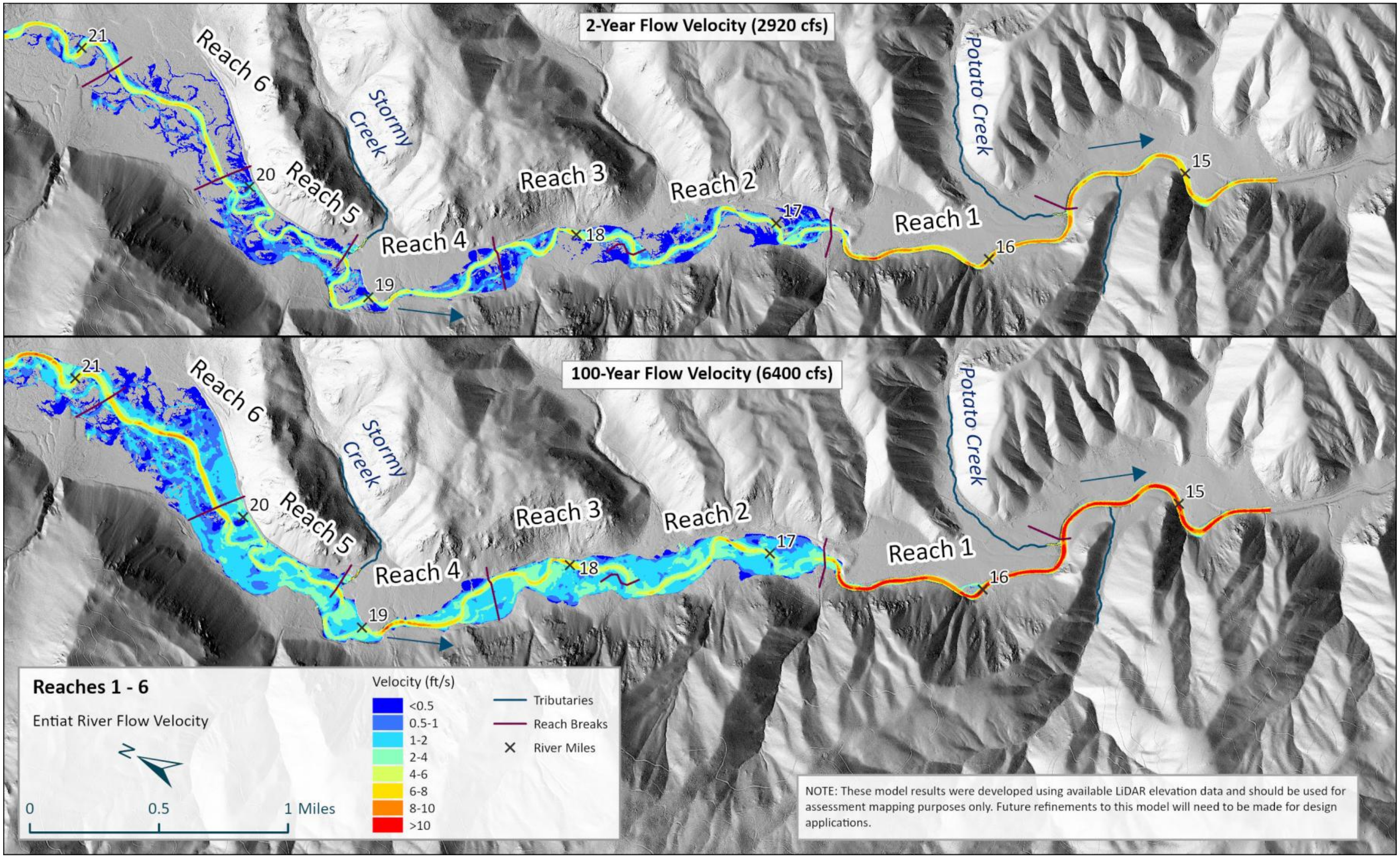
This model was not calibrated quantitatively, as it is a preliminary model that covers a large region with several ungaged tributaries. The available bathymetric LiDAR was deemed to be a sufficient representation of the Entiat River channel and floodplain for this analysis, and roughness values were informed by previous work done in the area that were calibrated based on previous field observations.

3 Summary of Hydraulic Model Results

The results of the Entiat River model were used to assess existing condition channel hydraulics and floodplain dynamics. A wide range of flows were run in the model (2, 5, 10, 20, 50, and 100-year flood events); however, for simplicity, the 2-year and 100-year floods are presented below as the 2-year flood is a high flow event expected to be experienced fairly regularly at the site, and the 100-year flood is a key regulatory flood when considering future project work.

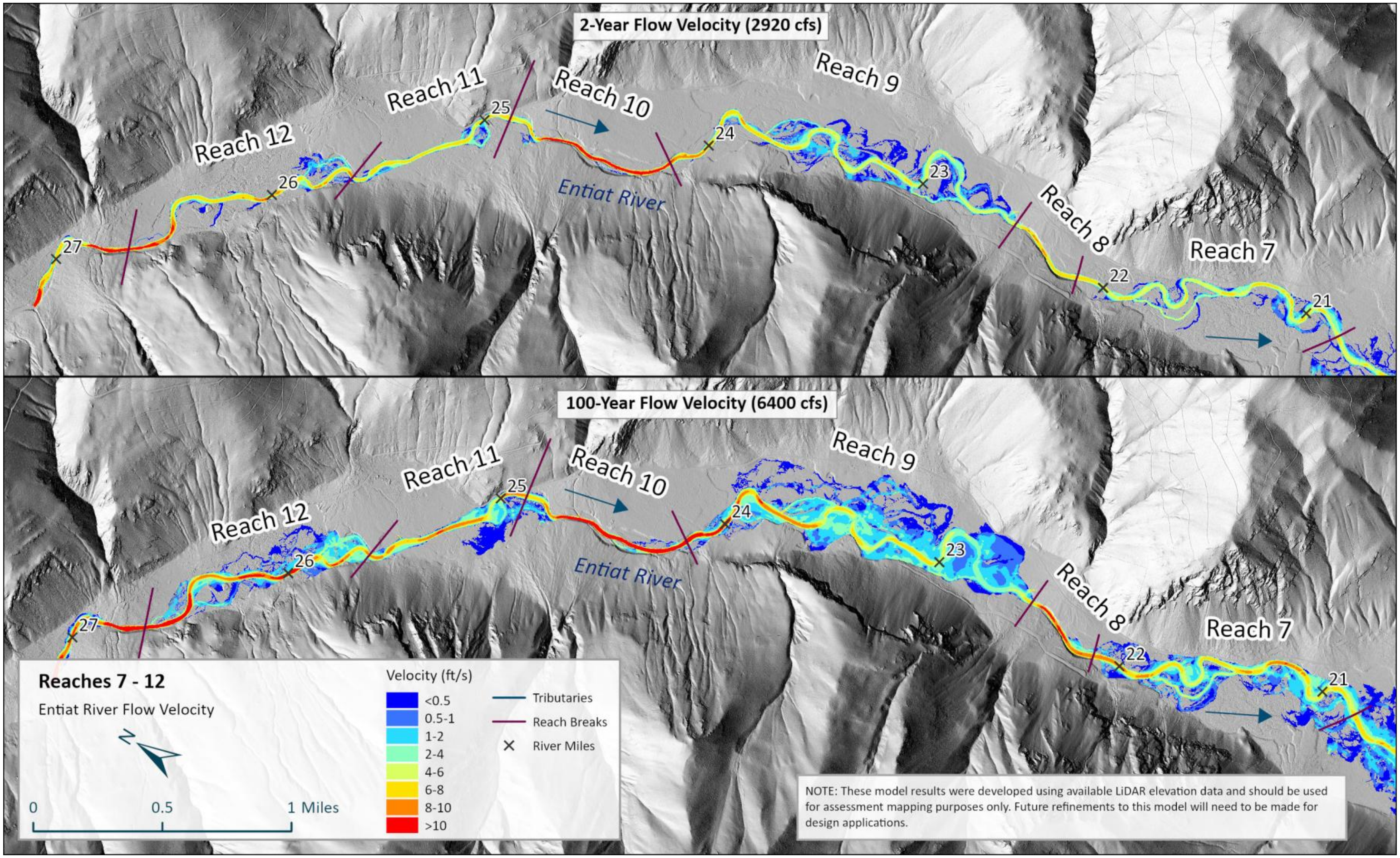
3.1 MODELED VELOCITY AND DEPTH RESULTS

Modeled velocity results for the 2-year and 100-year floods can be seen below in Figure 5 and 6. Modeled depth results for the 2-year and 100-year floods are shown in Figure 7 and 8.



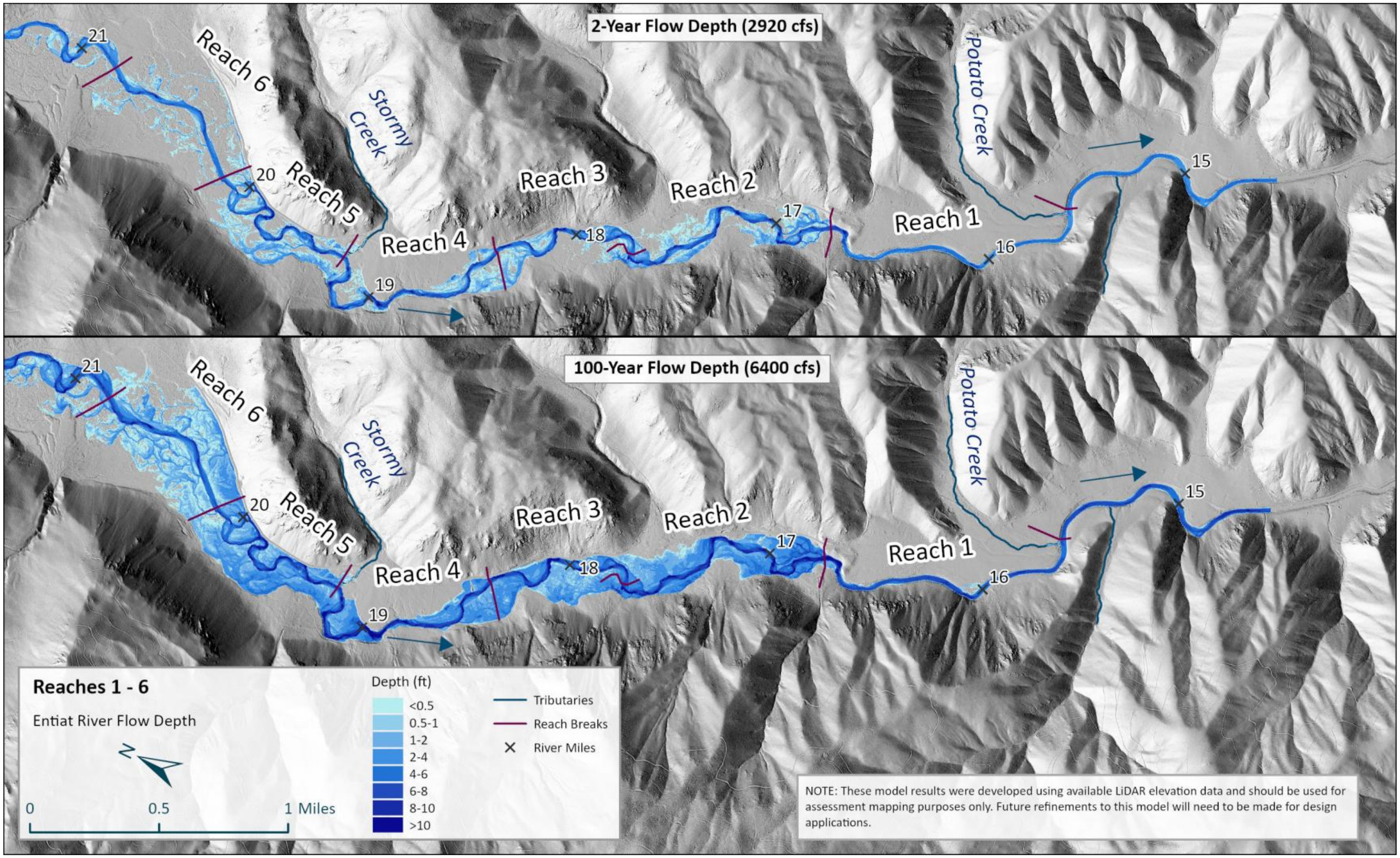
NOTE: These model results were developed using available LiDAR elevation data and should be used for assessment mapping purposes only. Future refinements to this model will need to be made for design applications.

Figure 5. Modeled 2-year flood and 100-year flood velocities for reaches 1 to 6.



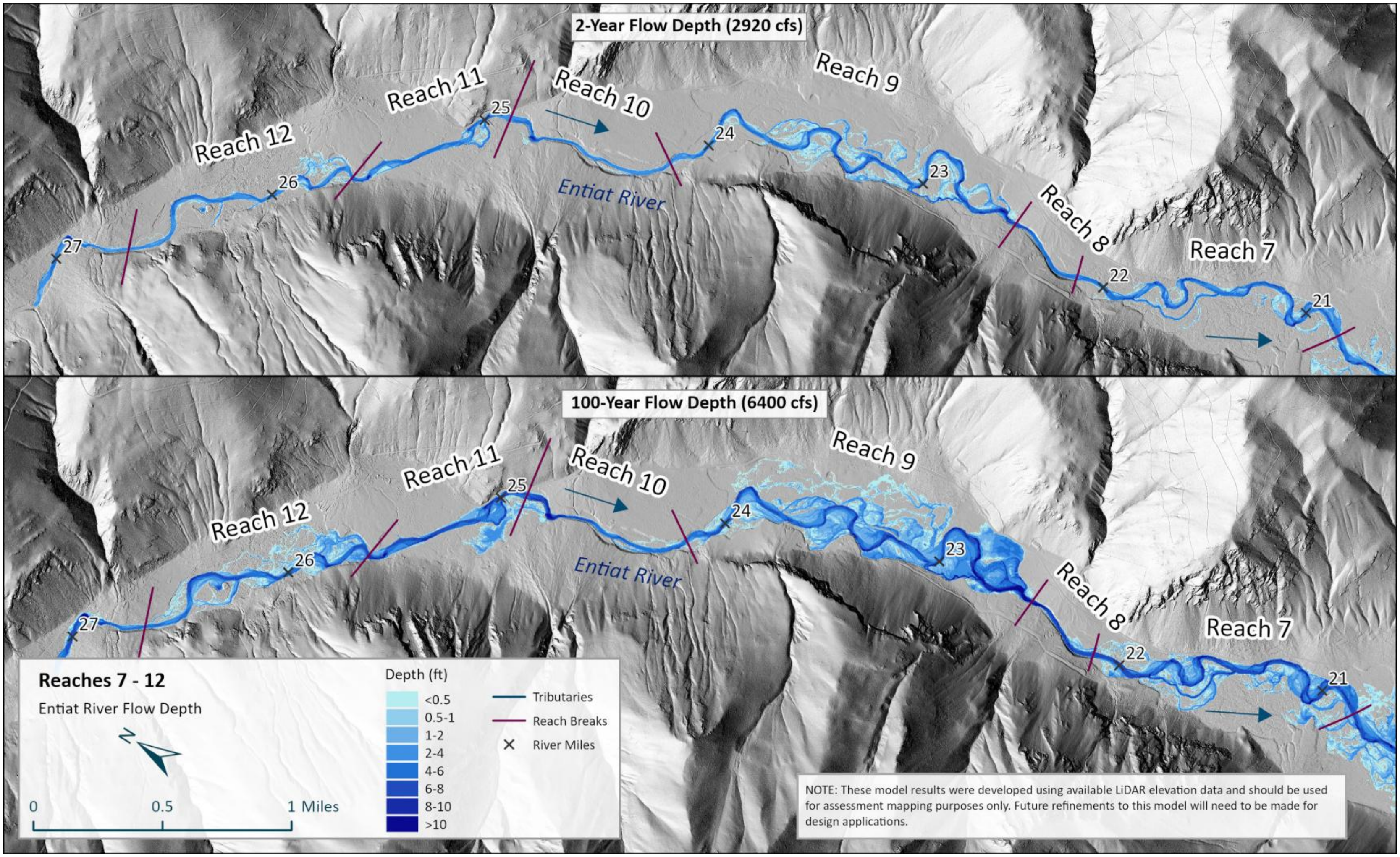
NOTE: These model results were developed using available LiDAR elevation data and should be used for assessment mapping purposes only. Future refinements to this model will need to be made for design applications.

Figure 6. Modeled 2-year flood and 100-year flood velocities for reaches 7 to 12.



NOTE: These model results were developed using available LiDAR elevation data and should be used for assessment mapping purposes only. Future refinements to this model will need to be made for design applications.

Figure 7. Modeled 2-year flood and 100-year flood depths for reaches 1 to 6.



NOTE: These model results were developed using available LiDAR elevation data and should be used for assessment mapping purposes only. Future refinements to this model will need to be made for design applications.

Figure 8. Modeled 2-year flood and 100-year flood depths for reaches 7 to 12.

3.2 MODEL RESULTS DISCUSSION

3.2.1 Model Results Overview

Floodplain inundation and connectivity vary throughout the study area. Flow starts to flow onto adjoining floodplains in reaches 2 to 6, 9, and 12 at the 2-year flood, whereas in the other reaches flow is mostly confined to the main channel, which experiences high velocities (6 to 10 feet per second in many locations). At the 100-year flood, floodplains in these same reaches (as well as Reach 7) become further inundated, and in Reaches 2 to 6, almost the entire valley bottom is covered with 0.5 to 4 ft of water. Velocities in the more confined Reaches 1, 8, and 10, as well as portions of Reach 12, exceed 10 feet per second at the 100-year flow.

The model results indicate that high flows impact some infrastructure within the study area. Based on aerial imagery, it appears that several small structures in the floodplain in Reaches 2, 4, and 9 are inundated at the 100-year flood. Most large roads in the region appear to be out of the 2-year and 100-year inundation zone in the study area. It appears that the Entiat River Road is overtopped with less than half a foot of water on river-left in Reach 3 at the 100-year flood, as is the road branching off from Entiat River Road on river-right at the bridge crossing in Reach 11. Many small rural and private roads appear to be impacted by the 100-year flood event.

3.2.2 Model Results Considerations

This preliminary model was built using readily available data for the key terrain and hydrology inputs for the study area. While these data are very informative, they lack the detail to be used to design restoration projects. Future restoration projects in this study area will need to include ground surveys and other analyses to provide more accurate and precise data to support restoration design. Bathymetric surveys should be conducted to confirm that the available bathymetric LiDAR is sufficiently representing the conveyance of the Entiat River. Topographic surveys should be conducted to capture important infrastructure that may be affected by a given project. For more accurate site-specific evaluations, bridge crossings should be surveyed and incorporated into models.

Although there are several long-term gages in the Entiat River watershed, there are still large data gaps for inflows into the study area. This model included nine tributaries to the Entiat River, all of which are ungaged. In addition to these tributaries, there are many smaller creeks (also ungagged) that flow into the Entiat throughout the study area as can be seen in Figure 1, and these were not explicitly included in the model. Future design efforts should investigate what additional flow inputs may be relevant to a given project, and how to best estimate the discharge of flow inputs with available data. In addition, this model does not include groundwater inflows, nor the infiltration of surface water into soil on the floodplain.

4 References

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