

# Icicle Creek Reach Assessment

## Appendix D | Hydraulic Model

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Icicle Creek RM 0 – 22

*February 2026*

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## 1 Introduction

A hydraulic analysis of the lower 22 river miles (RMs) of Icicle Creek was conducted as part of the Icicle Creek Reach Assessment and Restoration Strategy. This analysis includes a preliminary-level 2-dimensional (2-D) hydraulic model of Reaches 1-20 of Icicle Creek. The hydraulic model is used to understand general hydraulic characteristics of the stream 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 various components of the reach assessment, including geomorphological characterization, sediment transport analysis, assignment of Reach-Based Ecosystem Indicator (REI) ratings, and project identification.

## 2 Hydraulic Model Methodology

The hydraulic model was developed in the U.S. Army Corps of Engineers HEC-RAS 6.5 software (USACE, 2024b), which can compute hydraulic properties related to the physical processes governing water flow through natural rivers and other channels. Characteristics of Icicle Creek, such as the regions of high sinuosity and a wide and complex floodplain in the lower 4 miles of the creek, 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 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

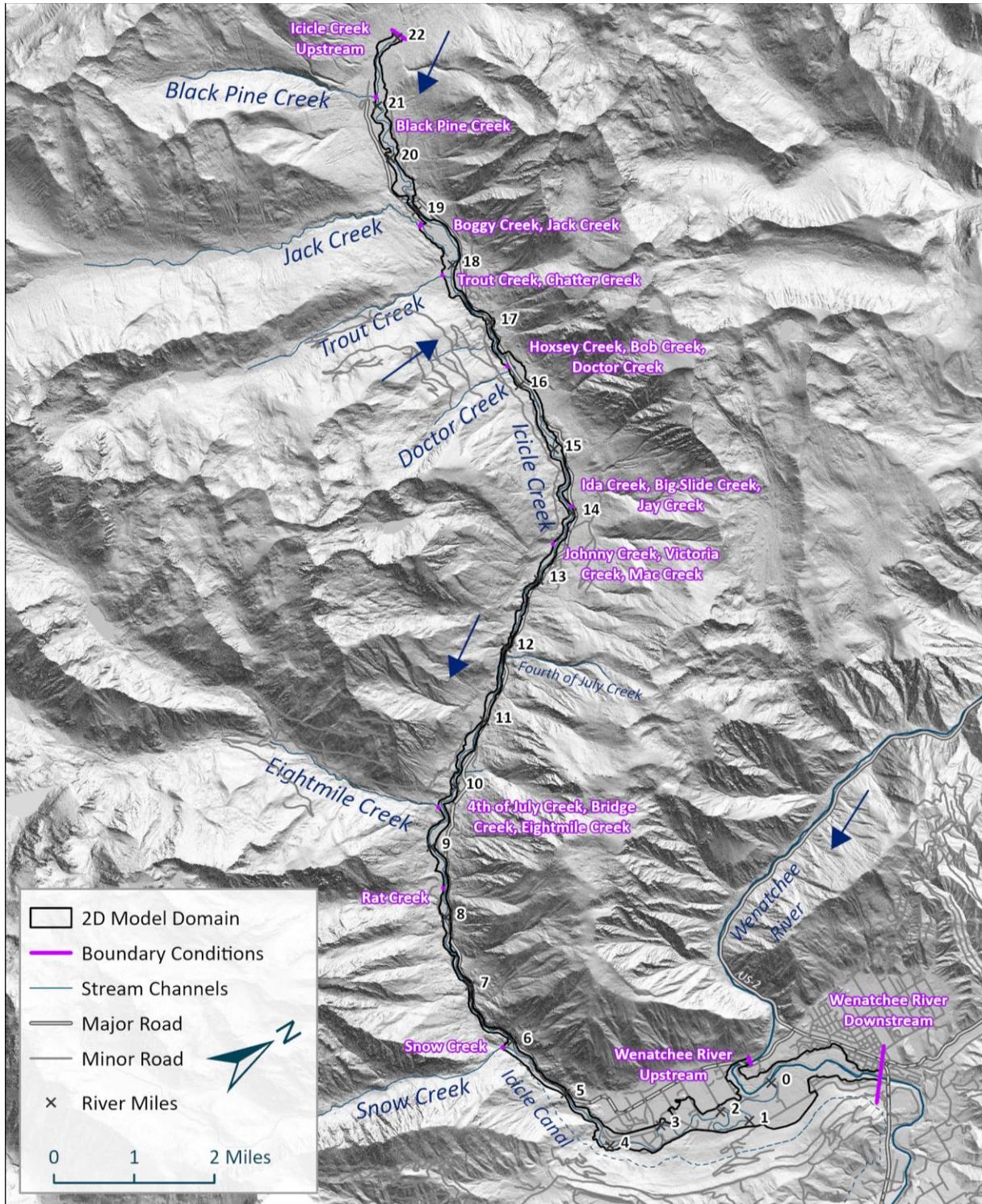
A digital terrain model (DTM) was created using publicly available LiDAR data of the project area. Available LiDAR datasets were available from 2015, 2018, and 2020 (NV5 Geospatial, 2022; Quantum Spatial, 2016, 2019). We utilized the most recent and high-resolution data where available for the model terrain except for a vegetated island near RM 19.25, where upon review our geomorphology team observed that the 2020 LiDAR appeared to be artificially elevated due to dense vegetation; to address this, the 2018 LiDAR was used in this location as it was believed to better represent the bare ground elevation. None of the LiDAR datasets captured ground elevations below water, leaving considerable data gaps of the bathymetry of the river channels, or any areas that were wetted during the LiDAR flights. The effect of these data gaps on the modeling would be greatest in the lower reaches of Icicle Creek where the channel is deeper, with many large pools. As a result, the model is likely to underestimate the depth and conveyance of Icicle Creek; although at large flood events, the effects of these data gaps may be relatively minor. Overall, the model results were generally consistent with indicators of inundation observed by geomorphologists during site surveys and the model is believed to adequately represent flooding conditions at a resolution and scale sufficient to support the purposes of the reach assessment. Future project design-level modeling will require more detailed survey data, including bathymetry of the channel.

### **2.1.2 Model Domain and Geometry**

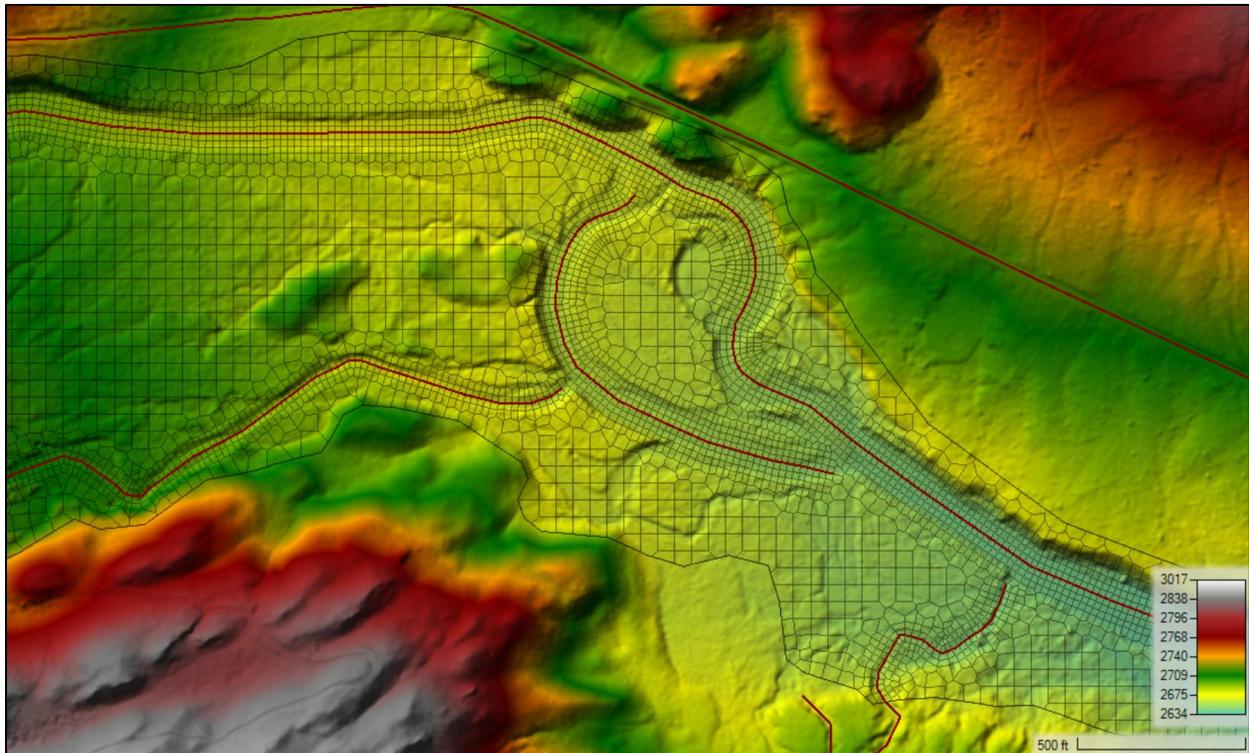
The model domain extends from approximately RM 22 just upstream of the end of Forest Road NF-7609 (and the Icicle Creek Trailhead) to downstream of the confluence with the Wenatchee River near the city of Leavenworth (Figure 1). The computational mesh consists of grid cells ranging from 10-100 feet, with the smallest grid cells utilized to provide higher resolution results closer to the channel and terrain features of interest (Figure 2). To save hours to days of run time, channel cell size ranged between 12x12 and 25x25 ft, while much of the floodplain is made up of 50x50 ft cells. Larger cells on the floodplain can sometimes result in overestimation of flow inundation if cells span across high ground areas that would in reality 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 to limit this “leaking” effect, but there can still be some overestimation of floodplain inundation in some areas. The Leavenworth National Fish Hatchery is located near RM 3 and the hatchery diversion canal is located between RM 3 and 4; the canal diverts much of the Icicle Creek flow from the natural channel at this location (USFWS, 2024). This man-made channel was represented in the model by adding breaklines and computation points into the computational mesh in order to capture flow perpendicular and parallel to the channel, prevent leakage out of the channel walls, and to mitigate water surface elevation errors along the steep spillway dam. Breaklines are also added along the channel to force cell alignment perpendicular to flow, improving efficiency and accuracy.

### **2.1.3 Bridges and Water Control Structures**

Although there are several bridges that cross Icicle Creek within the assessment area, bridge surveys were not performed and therefore no bridges were included in the model. Most of the bridges are high and likely have relatively minor or insignificant effects at the reach-scale at the flows used in the model. The LiDAR captures the lateral constriction at bridge locations. However, the deck and any pilings would not be represented in the model, which may underrepresent any local backwatering that occurs at these crossings. Also, the lack of channel bathymetry data in the model will underrepresent the conveyance of the channels through these crossings. Water control structures in the project area were deemed to be adequately represented by the LiDAR-based model terrain for this preliminary analysis. The complexity of how the Leavenworth National Fish Hatchery and its water control structures are managed (in Reach 3 of this assessment) is outside of the scope of this model. Therefore, the hydraulic characteristics around the hatchery will vary from the results reported here based on specific structure configurations and their management. Future design-level modeling should include surveys of bridges and water control structures, especially those associated with irrigation diversions and the Leavenworth National Fish Hatchery.



**Figure 1. Terrain map of Icicle Creek showing tributaries included in the model, flow input locations, and model external boundary conditions. Blue arrows indicate the general direction of flow inputs.**



**Figure 2.** Example cell size at the upstream end of the model. Cells near the channel are 12 to 25 ft in width. The outer floodplain cells are 50 ft. Breaklines (seen in red) are enforced along the channels and roads.

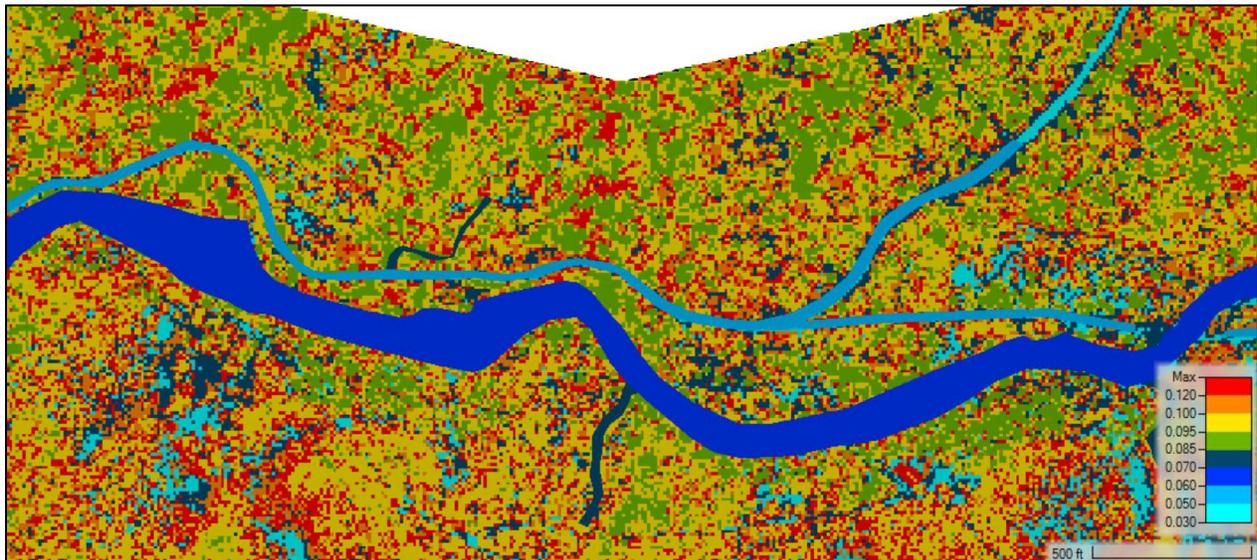
## 2.2 MODEL INPUTS

### 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 densities based on observations of vegetation communities surrounding Icicle Creek that would represent different Manning’s  $n$  values. These data were supplemented with hand-digitized polygons representing creek and river channels, prevalent roads, and developed areas around Leavenworth, WA near the downstream boundary of the model. Hydraulic roughness coefficients and their associated classifications are provided in Table 1. Channel roughness coefficients range from 0.06 where the channel is steep and dominated by boulders to 0.025 at the downstream end where the gradient is low and the bed is comprised of fine substrate. During field surveys, the hatchery diversion canal was observed to be comprised of gravel or partially paved and was assigned a roughness of 0.02. Floodplain roughness coefficients range from 0.03 to 0.12. Roughness values were determined through a combination of resources including the NLCD Land Cover types (USACE, 2024a), USGS and HEC-RAS roughness value recommendations (USACE, 2025; USGS, 1967), and professional judgment considering channel substrate type and floodplain and upland vegetation characteristics.

**Table 1. Roughness coefficients (Manning's n values) used in the model.**

Area Description	Roughness Coefficient (Manning's n Value)
Upper Icicle Creek Channel	0.06
Icicle Creek Channel Beside Hatchery	0.03
Lower Icicle Creek Channel	0.025
Wenatchee River	0.03
Tributary Channels	0.07
Hatchery Channel	0.02
Developed Areas	0.1
Road Surfaces	0.05
Bare Ground (<0.5 ft)	0.03
Vegetation Height 0.5-4 ft	0.07
Vegetation Height 4-12 ft	0.1
Vegetation Height 12-25 ft	0.12
Vegetation Height 25-60 ft	0.095
Vegetation Height 60+ ft	0.085



**Figure 3. Roughness values assigned to the existing conditions Icicle Creek model.**

### 2.2.2 Model Hydrology

Icicle Creek hydrology was estimated using the Icicle Creek above Snow Creek gage near Leavenworth, WA (USGS gage 12458000) (USGS, 2024a). The gage has a period of record from May 1912 to present, with data gaps from 1915 to 1936 and 1980 to 1993. All peak flows available were used to complete a Log Pearson Type 3 (USGS Bulletin 17C) peak flow analysis in HEC-SSP (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 suggested by Mastin et al. (2017). The Mastin et al. (2017) equation 11 for Region 2 in Washington was used to obtain flow estimates for the top of the project area and the mouth of Icicle Creek using a basin-area weighted conversion from the gage data. (Table 2).

Nineteen tributaries to Icicle Creek were identified within the model domain: Black Pine Creek, Boggy Creek, Jack Creek, Trout Creek, Chatter Creek, Bob Creek, Hoxsey Creek, Doctor Creek, Ida Creek, Big Slide Creek, Jay Creek, Johnny Creek, Victoria Creek, Mac Creek, 4th of July Creek, Bridge Creek, Eightmile Creek, Rat Creek, and Snow Creek. Portions of some tributaries were deemed to be poorly represented in the LiDAR and not adequate for modeling. This included areas where the lack of bathymetry resulted in no clear channel for a given tributary or where roads crossed the channel and there was no documented culvert or bridge. To streamline the hydrology and resolve these problem areas, tributaries were clumped into nine inflow boundary conditions in a representative distribution of inputs along the hydraulic model. The drainage area for each of these clumped model inputs was calculated as the difference between the drainage area of Icicle Creek directly below the downstream-most tributary confluence and the drainage area of the previous upstream input included in the model (calculated using the same method). Drainage areas were interpolated using StreamStats (USGS, 2022). The difference in flows between the top and bottom of the project area, calculated using Mastin et al. (2017) equation 11, was divided among the tributary boundary conditions based on drainage area (see Table 2).

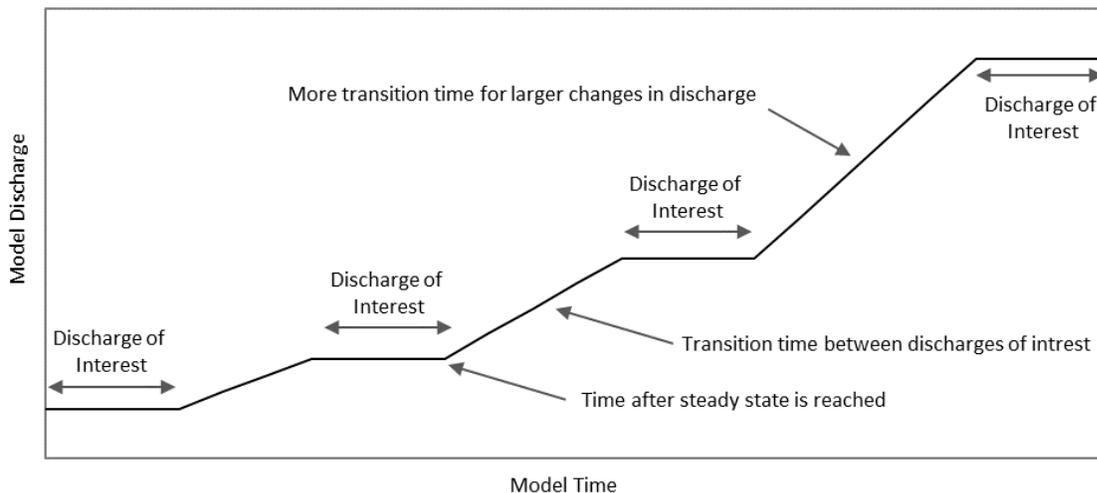
A portion of the Wenatchee River was included in the model to account for interactions between the Wenatchee River and Icicle Creek in the downstream portion of the assessment area, including backwatering from the Wenatchee into Icicle Creek during high-flow events. A gage on the Wenatchee River a couple of miles upstream of the Icicle Creek confluence (USGS 12457000) was utilized to estimate the peak flows of the Wenatchee upstream of Icicle Creek (USGS, 2024b). This gage provides peak flow data from 1911 to the present (with data missing between 1930 and 1931, and 1980 to 1989), which were used to run a peak flow analysis and basin-area correction using the same methods as described previously for Icicle Creek (Table 2).

**Table 2. Modeled flow events for the White River and tributaries used in hydraulic modeling.**

Flow Event	Icicle Creek Upstream Discharge	Black Pine Creek	Boggy Creek and Jack Creek	Trout Creek and Chatter Creek	Bob Creek, Hoxsey Creek, and Doctor Creek	Ida Creek, Big Slide Creek, and Jay Creek	Johny Creek, Victoria Creek, and Mac Creek	4th of July Creek, Bridge Creek, and Eightmile Creek	Rat Creek	Snow Creek	Wenatchee River
2 - year	1,900	170	790	110	110	160	110	980	170	370	13,580
5 - year	2,840	250	1,150	160	160	230	160	1,420	240	530	17,990
10 - year	3,570	300	1,410	190	190	280	190	1,740	290	650	20,980
25 - year	4,630	380	1,780	240	240	350	240	2,200	370	820	24,850
50 - year	5,520	440	2,090	280	280	410	280	2,570	430	960	27,810
100 - year	6,500	510	2,420	330	330	470	320	2,980	500	1,120	30,840

### 2.2.3 Model Boundary Conditions

The hydraulic model was used to evaluate existing conditions at flow events ranging from the 2-year to the 100-year flow event (Table 2). These flows are incorporated into synthetic quasi-steady state hydrographs with periods of steady flow (at the discharges of interest and other intermediate discharges) connected by smooth transition periods to create a stair-step-like pattern. The timing of all flows (Icicle Creek, its tributaries, and the Wenatchee River) are assumed to be simultaneous, which provides conservative (high) results with respect to flooding. A representative quasi-steady flow hydrograph is depicted in Figure 4. The periods of steady flow allow the model to come to a quasi-steady state condition, which facilitates the interpretation of hydraulics at specific discharges. In some cases, allowing the model to reach a steady state during large flood events may overestimate flooding results, as floodplain storage throughout the model domain must reach capacity for the outflow of the model to reach steady-state conditions. This may not occur during actual floods, especially short-duration events. Regardless, the conservative nature of this approach was deemed appropriate for this preliminary-level model.



**Figure 4. Demonstrative quasi-steady flow model input hydrograph.**

The upstream boundary condition was set to the Icicle Creek Upstream Discharge in Table 2, with an energy grade (EG) slope of 0.002 based on the terrain at the location of the upstream boundary

condition. Each of the tributary inputs (grouped as listed in Table 2) 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. In addition, a portion of the Wenatchee River was included in the downstream end of the model to account for interactions between the Wenatchee River and Icicle Creek. On the Wenatchee River upstream of the Icicle Creek confluence, an external boundary condition was added with input for the Wenatchee River. Downstream of the Icicle Creek confluence, the downstream boundary condition of the model was added as a normal depth boundary condition with a friction slope of 0.005.

#### **2.2.4 Model Calibration**

Model calibration was performed to the extent possible and within reasonable limits given the limited data available for model development and the limited data available for calibration. Data limitations were primarily related to lack of accurate channel bathymetry (i.e., use of non-bathymetric LiDAR) and lack of tributary inflow data. Despite these limitations, efforts were made to calibrate the model based on evidence of bankfull flow and floodplain inundation observed by the geomorphology team during the field assessment. These observations included bankfull channel indicators, debris lines, extent of overbank floodplain deposits, and vegetation patterns. Repeated adjustments were made to the model mesh and roughness until model results reasonably reflected the field observations. Calibration was most challenging in the downstream three reaches due to larger channel depths (compared to the steeper upstream reaches), which are not represented accurately by the LiDAR. More information on potential depth errors in the model in these lower reaches is discussed in Section 3.2.

Model results were compared to the stage readings at the USGS gaging station (USGS #12458000) near RM 6.5 to assess model accuracy at this location. This was performed by creating a high flow rating curve from the gage data using flows that had “fair” and “good” quality ratings. Modeled WSEs were shown to exceed those predicted by the rating curve by about 2 feet at the 2-year event and about 0.3 feet at the 100-year event. The greater discrepancy at the 2-year event is attributed to lack of low flow channel bathymetry in the LiDAR data. Only non-bathymetric LiDAR data were available for this assessment. These data do not capture ground elevations below water, and so the data essentially represent the water surface elevation during the LiDAR flight as opposed to the bathymetry of the channel. Even though in this case the LiDAR data were collected at relatively low flows (~331 cfs), this nevertheless equates to potentially a few feet of depth at the time of the LiDAR flight (331 cfs equates to ~3.73 ft at the gage), which is a significant portion of the channel that is not represented in the model. For these reasons, the discrepancies between modeled WSEs and actual WSEs are expected to be most pronounced in deeper channel areas, like those that occur in the lower 3 reaches, and at lower flows, where a higher percentage of the flow is contained in the low-flow portion of the channel.

### 3 Summary of Hydraulic Model Results

A summary of model results and output figures/maps are provided below. Although a wide range of flows were simulated in the model (2, 5, 10, 25, 50, and 100-year flood events), for clarity and simplicity we focus here on the 2-year, 25-year, and 100-year results.

#### 3.1 MODELED VELOCITY RESULTS

Modeled velocities for the 2-year, 25-year, and 100-year flood velocity results are displayed in Figures 5-13.

In reaches 1 and 2, the valley is wide and Icicle Creek is highly sinuous as it flows toward the Wenatchee River downstream of the hatchery canal starting at RM 3. The gradient is low and model result show low velocities here compared to most of the remainder of the assessment area. There is also much more available floodplain. In-channel velocities range from 4 to 6 ft/s during the 2-year flow event, with average floodplain velocities less than 0.5 ft/s (Figure 5). Channel and floodplain velocities increase at the 25-year flow, with channel velocities spiking to 10 ft/s near RM 2, and floodplain average velocities increasing to 0.5-2 ft/s (Figure 8). The 100-year results show portions of the channel exceeding 10 ft/s velocity, but most of the channel with velocities are between 4 and 8 ft/s, with floodplain inundation crossing the road on river right and velocities increasing slightly across the valley floor (Figure 11).

Reach 3 is also low gradient with a wide valley, but it is confined by the Leavenworth National Fish Hatchery diversion canal located on river left from RM 3 to 4. A portion of Icicle Creek's flow is diverted through this straight concrete and gravel channel, where simulated velocities are higher than the adjacent natural channel. A dam structure, "Structure 2", regulates flow between the hatchery diversion channel (canal) and the historical (natural) channel via gates that when closed direct flow into the diversion channel. However, Structure 2 is represented in the LiDAR-based model only by the abutments of the structure, not including the adjustable gates and bridge deck (as discussed in Section 2.1.3), therefore the amount of flow diverted to the hatchery diversion channel is likely being underestimated. At the 2-year flow, channel velocities in the natural channel and hatchery canal are between 2 and 6 ft/s, spiking to over 10 ft/s where flow in the natural channel is confined by water crossing and control structures downstream of the hatchery canal (near RM 4.25) and at the water control structure where flow leaves the hatchery canal and returns to Icicle Creek (near RM 3) (Figure 5). At the 25-year flow, velocities in the natural channel increase slightly, reaching 8 ft/s in some sections, while most of the hatchery canal increases to 6 to 8 ft/s (Figure 8). These velocities continue to increase at the 100-year flow, with small spikes up to 10 ft/s in the natural channel, and much of the hatchery canal reaching 8 to 10 ft/s (Figure 11). Floodplain inundation is limited in this reach by the hatchery canal on river left and the hillslopes on river right, with some activation near RM 4 and near RM 3 at higher flows, with velocities generally less than 1 ft/s.

In the upstream portion of the project area, Icicle Creek flows through a steep and confined valley. A dramatic increase in gradient and channel confinement distinguished Reaches 4 to 18 from these lower reaches. The steep gradient coupled with the confined channel and greater prevalence of cobbles and boulders in this part of the study area results in much more turbulent and high velocity flows. At the 2-year flow, the in-channel velocities generally span from 6 to 10 ft/s, though often exceed 10 ft/s in steep sections (Figure 5 to 7). For the 25-year and 100-year flows, velocities in these reaches generally exceed 10 ft/s (Figure 8 to 11). Floodplains are limited in these reaches. There are two key areas that stand out from this trend, a small portion of Reach 10 (near RM 10.5) and Reach 15. These areas have lower gradient than upstream and downstream areas, with floodplain inundation occurring at the 25-year and 100-year flows, and velocities generally between 4 and 8 ft/s, not exceeding 10 ft/s.

Upstream of this steep section, reaches 19 and 20 have slightly lower gradients and are less confined than the downstream canyon reaches, resulting in lower channel velocities and more floodplain inundation. At the 2-year flow, channel velocities range from 2 to 6 ft/s and small areas of floodplain inundation have velocities from <0.05 to 2 ft/s (Figure 7). Channel velocities increase to 2 to 8 ft/s at the 25-year flow and there is more floodplain inundation, with velocities between 1 to 2 ft/s (Figure 10). Velocities continue to increase at the 100-year flow, ranging from 4 to 8 ft/s in channel with some small areas between 8 to 10 ft/s, and 0.5 to 4 ft/s modeled in the floodplain (Figure 13).

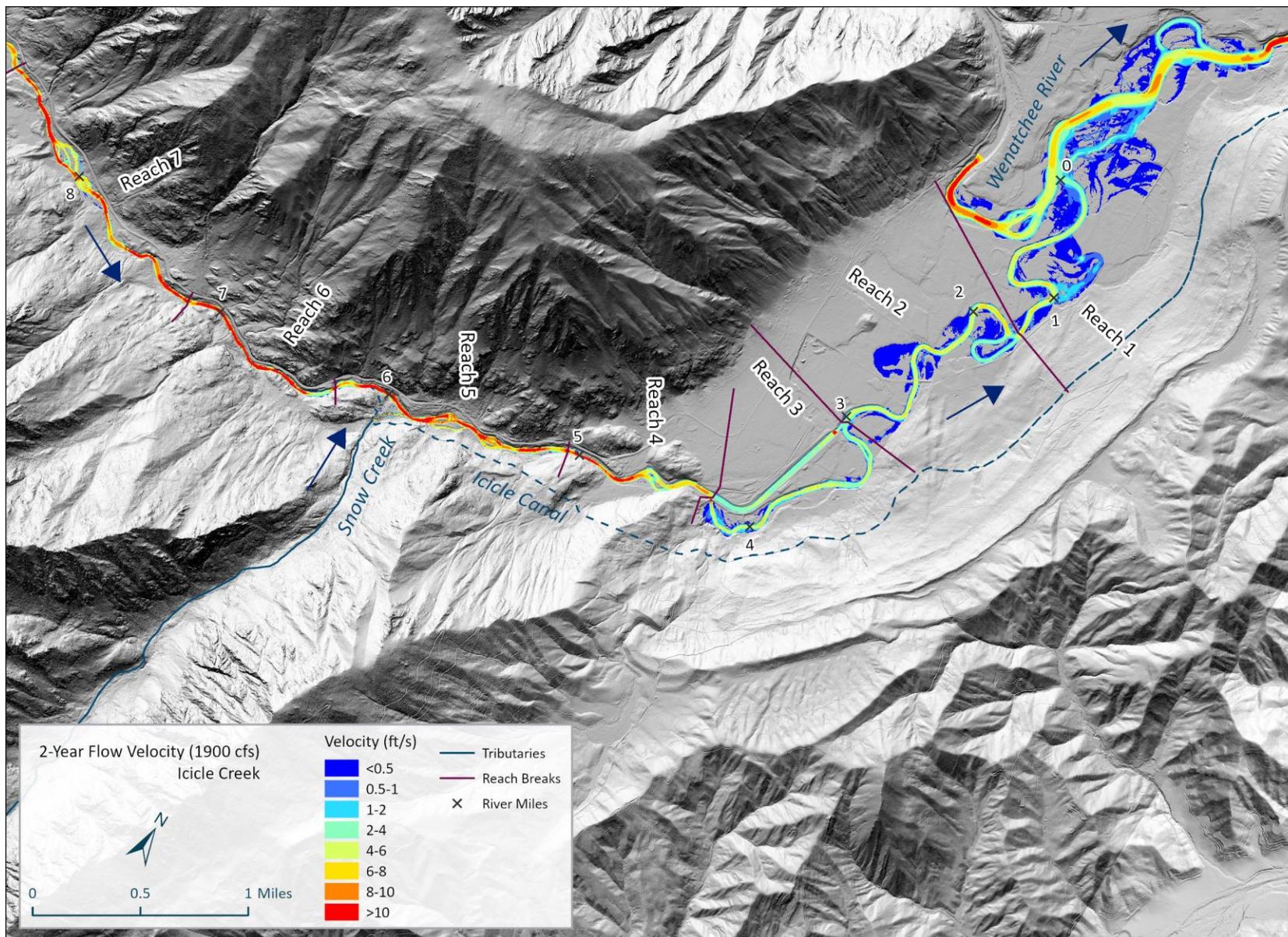


Figure 5. Modeled 2-year flood velocity for Reaches 1 to 7, labeled with flow input at the upstream end of the model.

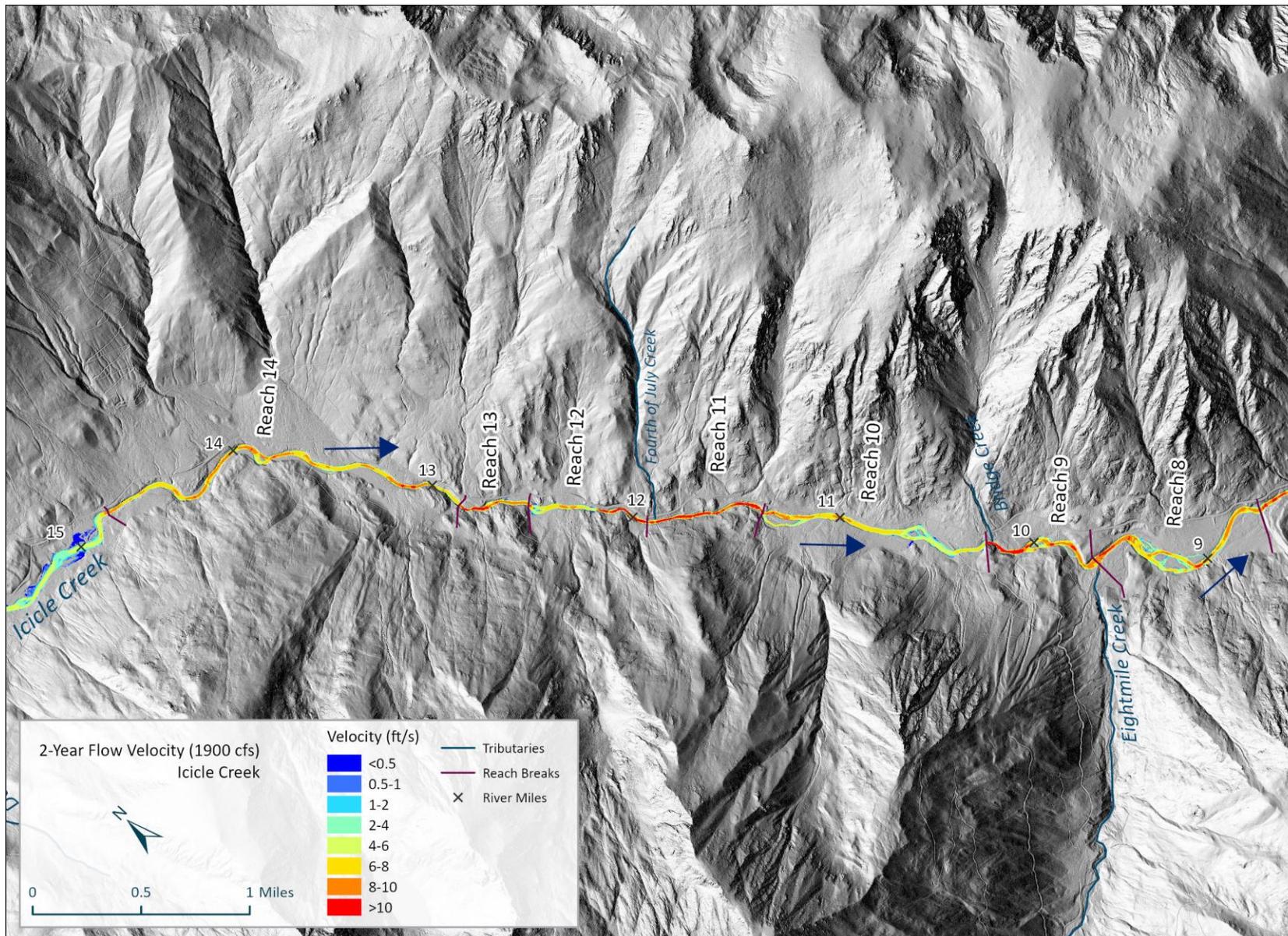


Figure 6. Modeled 2-year flood velocity for Reaches 8 to 14, labeled with flow input at the upstream end of the model.

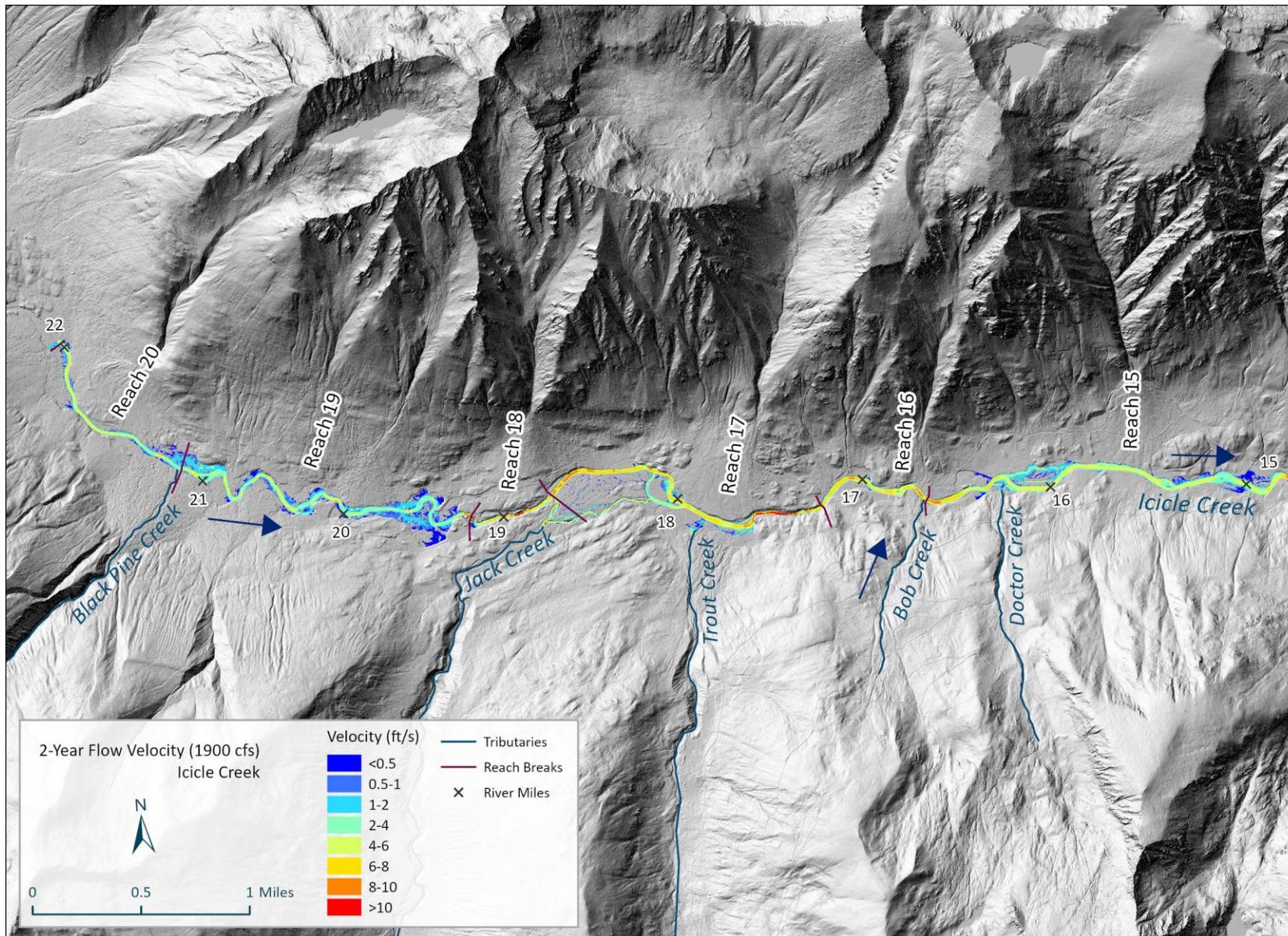


Figure 7. Modeled 2-year flood velocity for Reaches 15 to 20, labeled with flow input at the upstream end of the model.

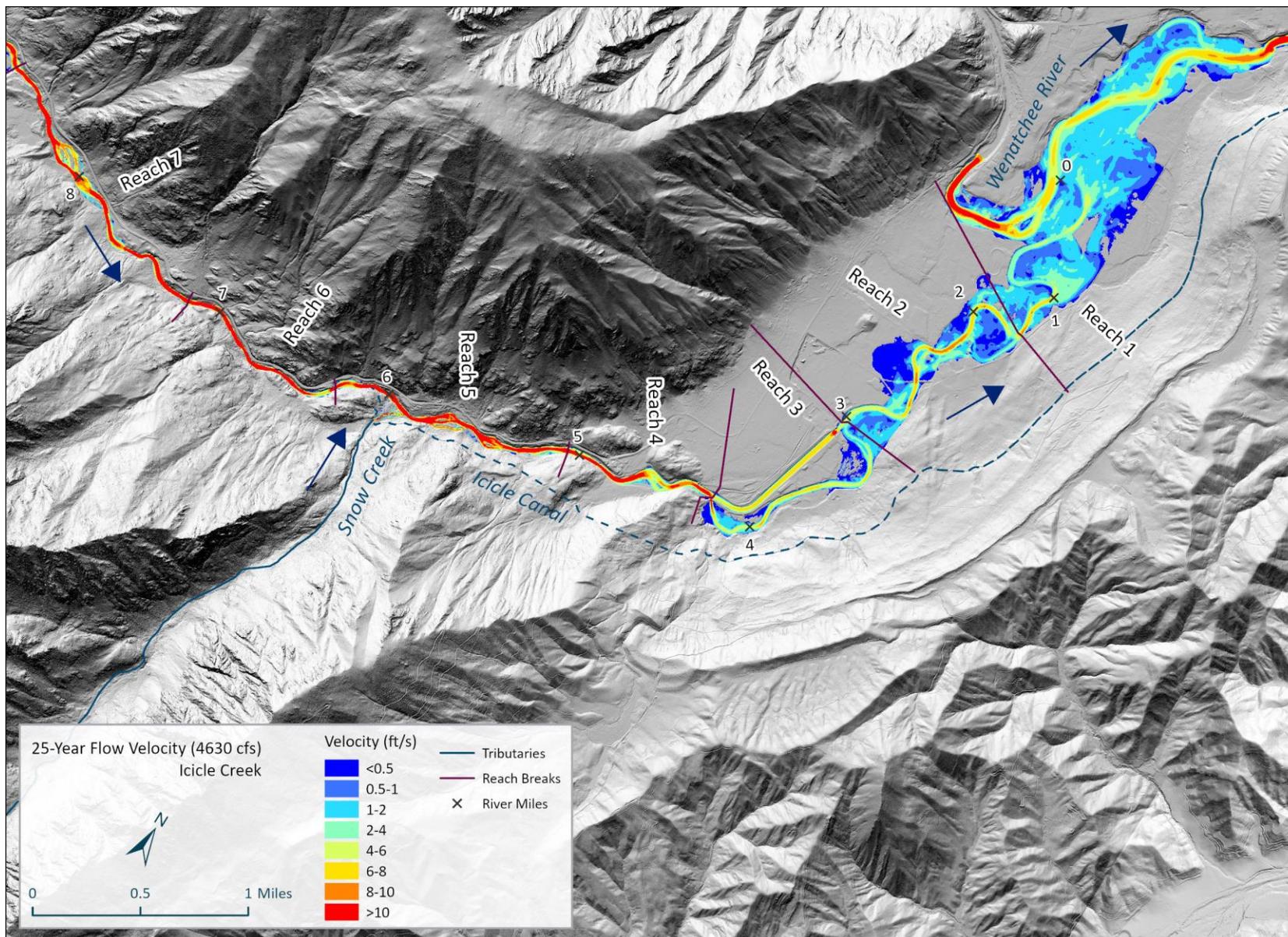


Figure 8. Modeled 25-year flood velocity for Reaches 1 to 7, labeled with flow input at the upstream end of the model.

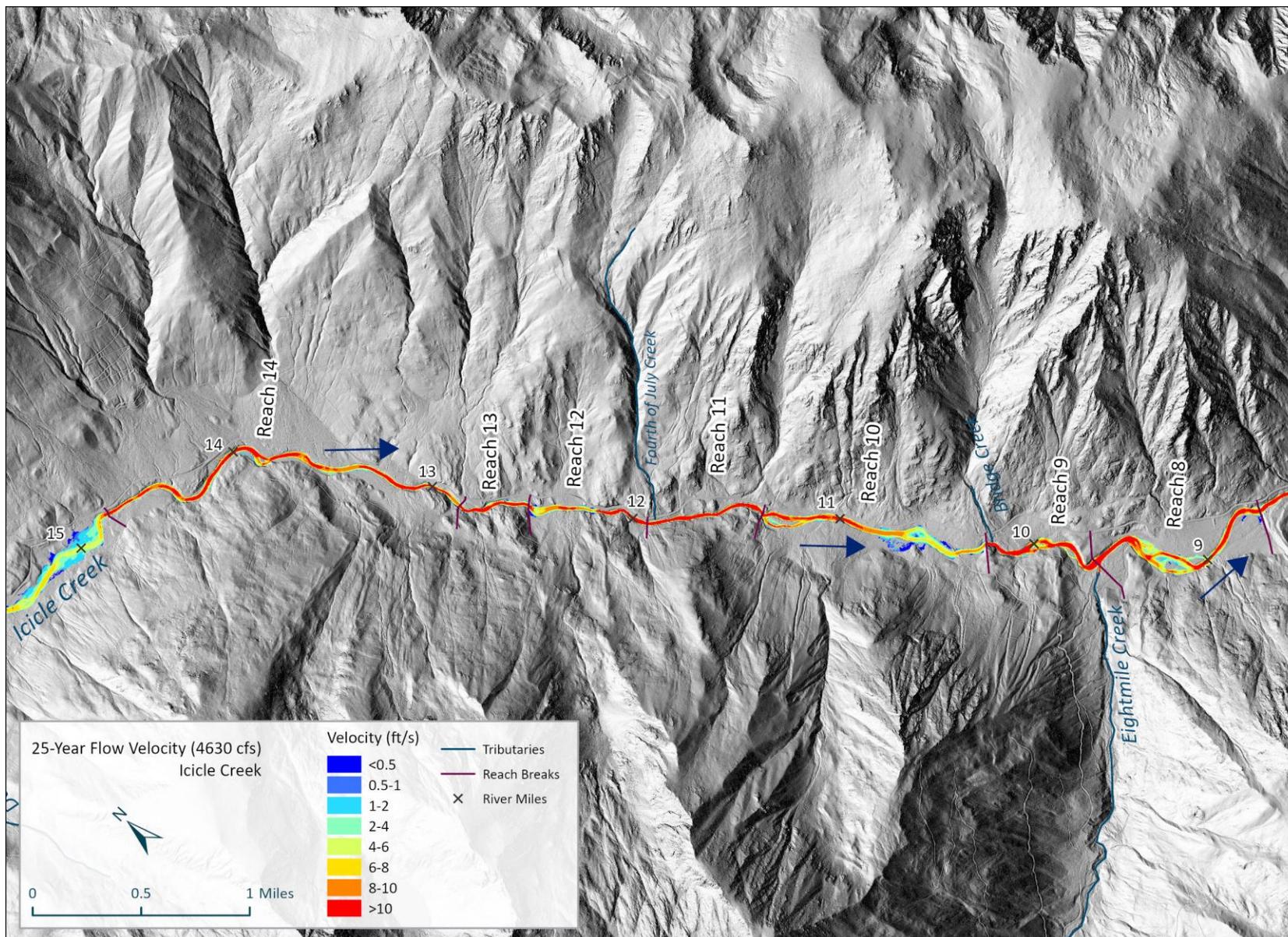


Figure 9. Modeled 25-year flood velocity for Reaches 8 to 14, labeled with flow input at the upstream end of the model.

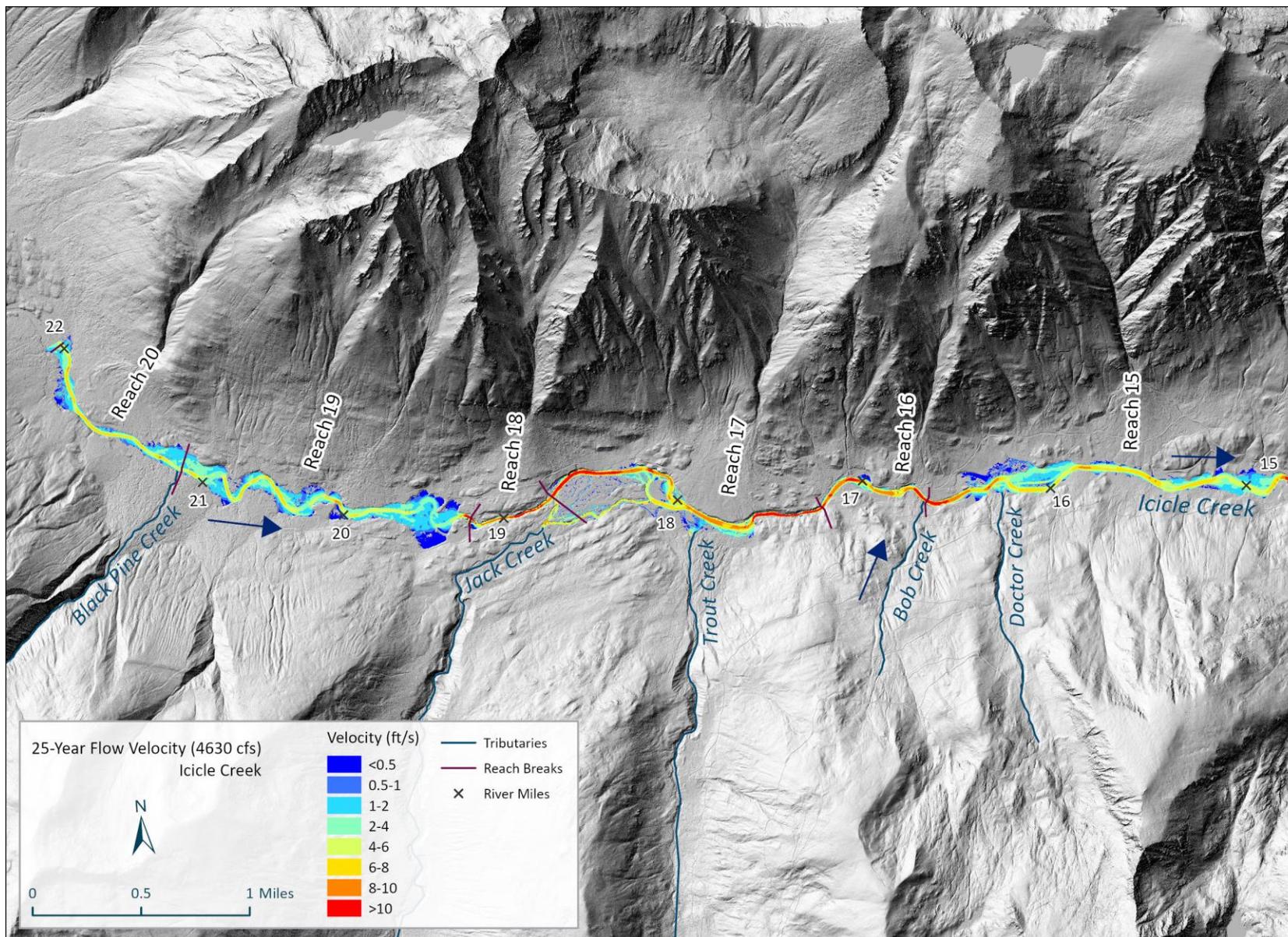


Figure 10. Modeled 25-year flood velocity for Reaches 15 to 20, labeled with flow input at the upstream end of the model.

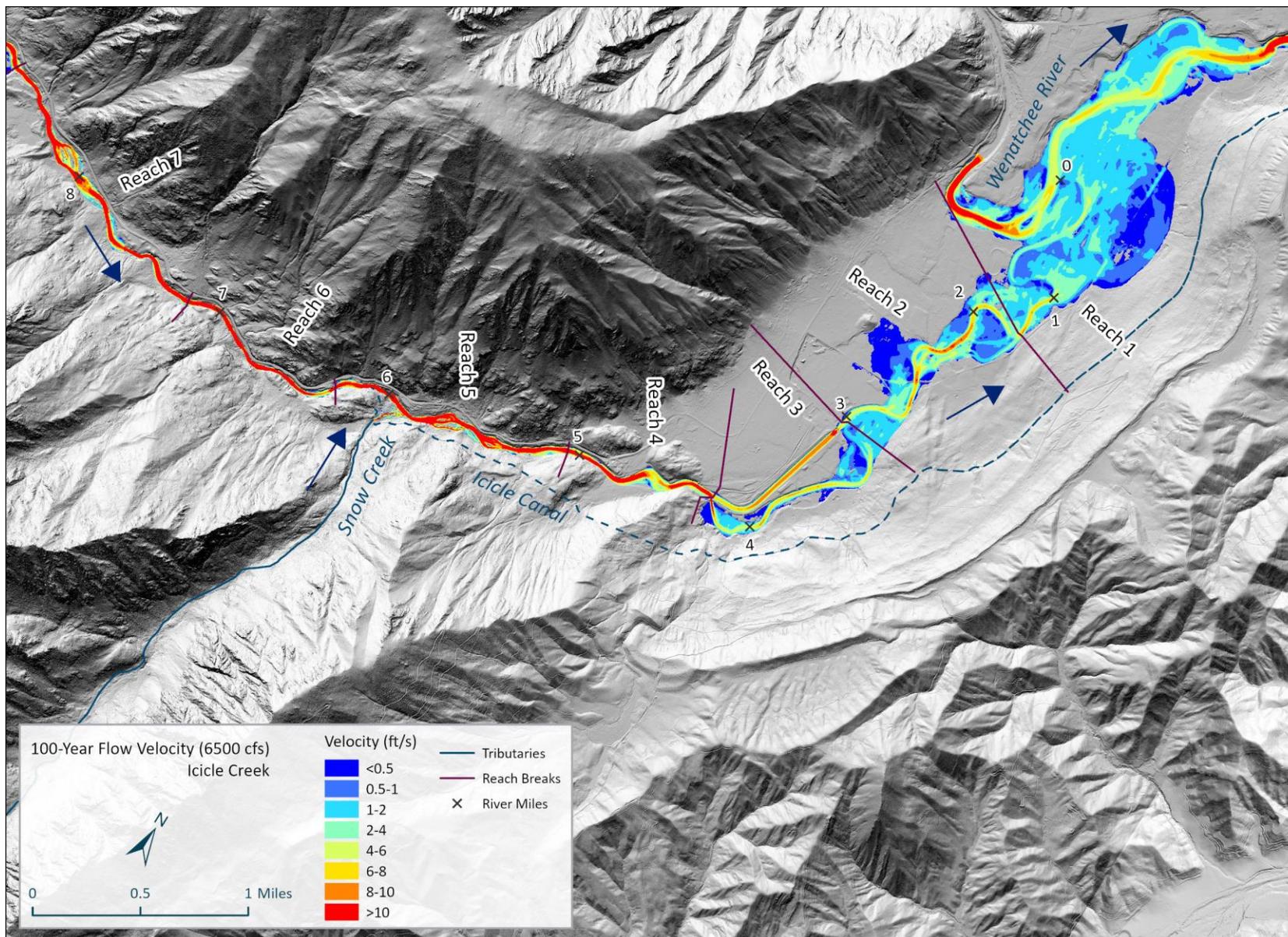


Figure 11. Modeled 100-year flood velocity for Reaches 1 to 7, labeled with flow input at the upstream end of the model.

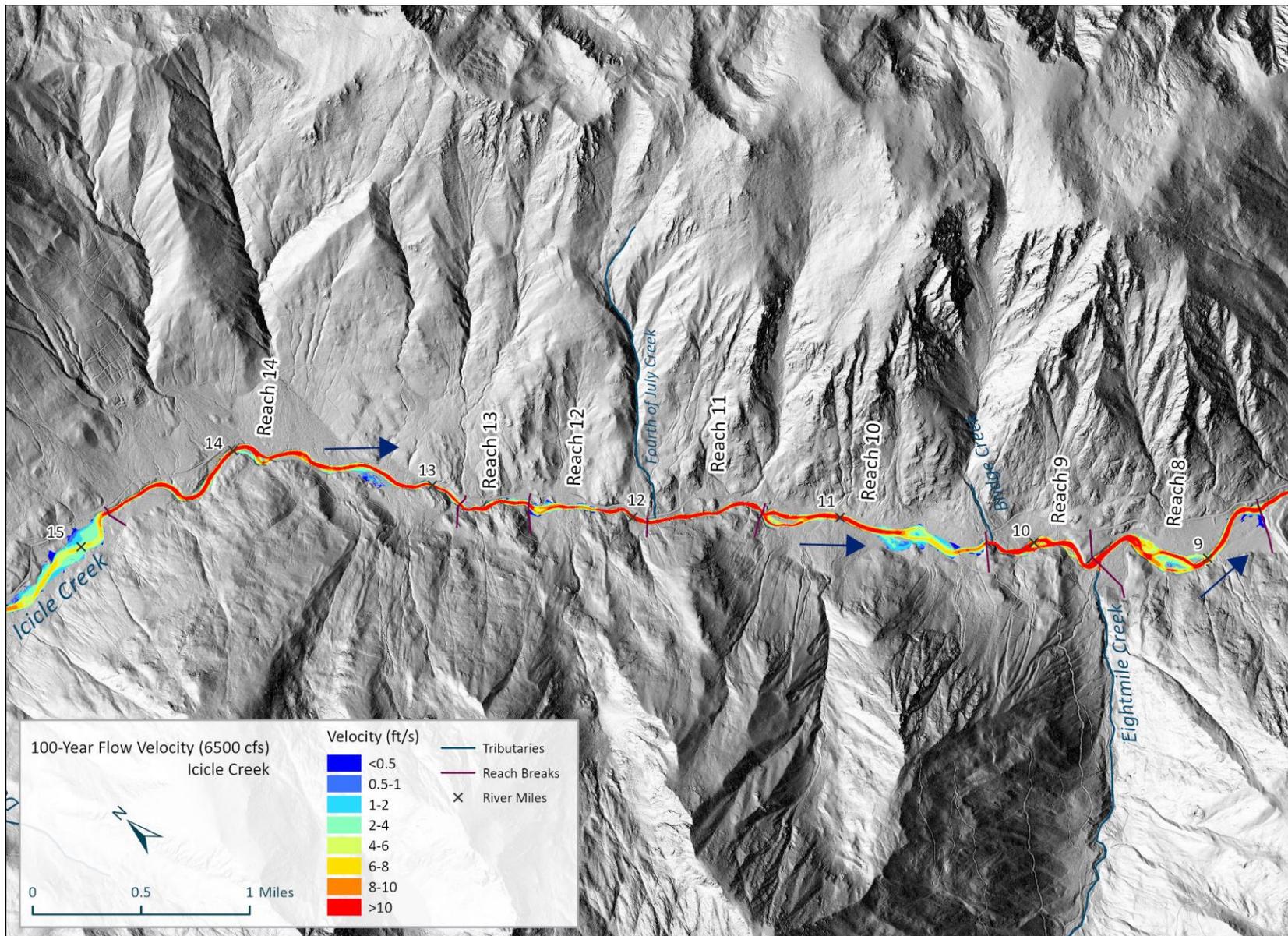


Figure 12. Modeled 100-year flood velocity for Reaches 8 to 14, labeled with flow input at the upstream end of the model.

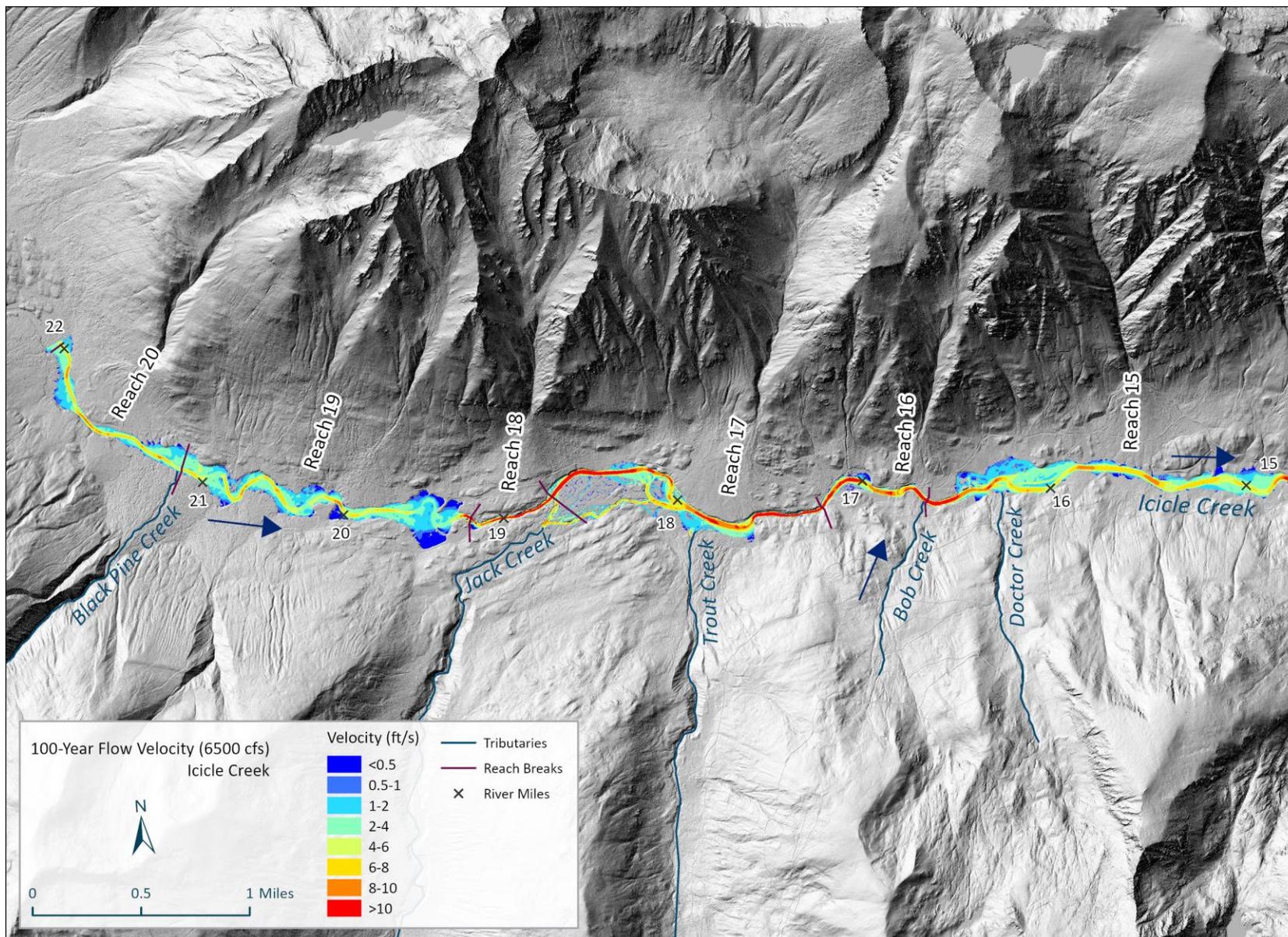


Figure 13. Modeled 100-year flood velocity for Reaches 15 to 20, labeled with flow input at the upstream end of the model.

### 3.2 MODELED DEPTH RESULTS

Modeled depths at the 2-year, 25-year, and 100-year floods are included below in Figures 14-22. As previously described, The LiDAR used in the model terrain does not include bathymetry, which means there is error and uncertainty in the channel conveyance and model depths, and an overall underestimation of depths and conveyance. For reference, the habitat surveys recorded residual pool depths of between 0.5 and 18 feet in the lower three reaches of the assessment area, depths that would not be captured by the LiDAR. The model is believed to be more accurate in upstream reaches due to shallower channels at hydraulic controls (e.g., riffle crests). Despite these caveats, the model is nevertheless believed to provide useful information on relative depths and conveyance at the reach-scale and for comparing conditions among reaches and across flow levels.

In the portion of the assessment area around Leavenworth (Reaches 1 to 3), channel depths for the 2-year flow range from 8 to 10 feet, while floodplain depths vary from 0.5 to 4 feet (Figure 14). As flows increase to the 25-year event, channel depths exceed 10 feet, ranging from 10 to 12 feet, and floodplain depths increase to between 2 and 6 feet (Figure 17). For the 100-year flow event, downstream channel depths further increase to 11 to 15 feet, with floodplain depths ranging from 2 to 8 feet (Figure 20). The model results show that the hatchery canal experiences lower depths than the natural channel beside it, which can be 2 to 4 feet deeper (Figure 14, 17, and 20). Structure 5 (a low bridge with gates crossing the historic channel) is not explicitly represented in the model (see section 2.1.3). Therefore, the model would not fully represent backwatering effects caused by the structure. Floodplain inundation in the downstream area increases with large flow events and appears to result in the road on river right being overtopped between RM 0 and 1.

In the upstream section of the assessment area (Reaches 4 to 20), water depths for the 2-year flow generally range from 4 to 6 feet, with occasional deep pockets reaching 8 to 12 feet (Figure 14 to 16). For the 25-year flow, depths increase to 6 to 10 feet, with some isolated pockets reaching 12 to 18 feet (Figure 17 to 19). During the 100-year flow event, depths further increase, ranging from 6 to 11 feet, with the deepest pockets extending to 15 to 20 feet (Figure 20 to 22).

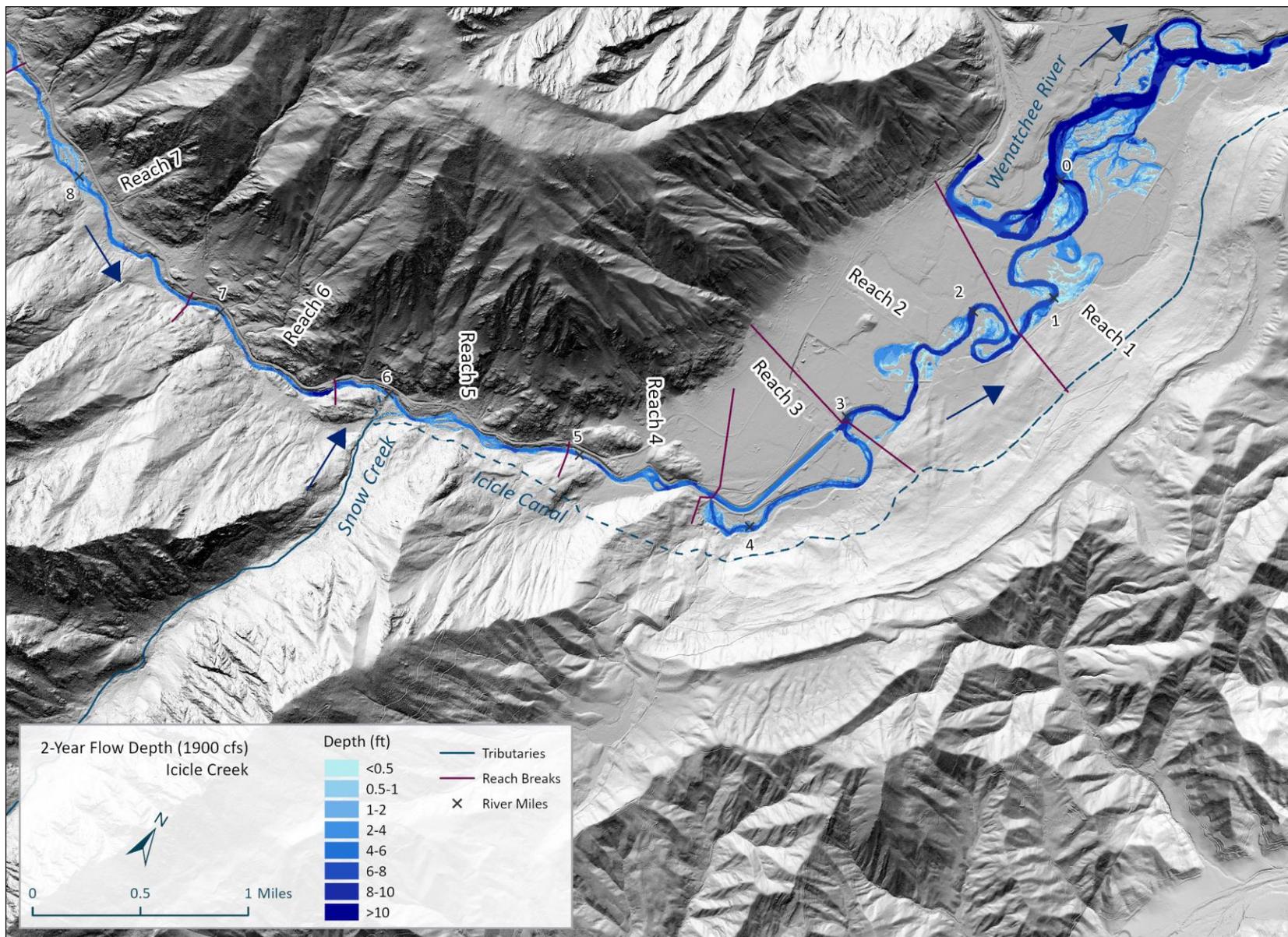


Figure 14. Modeled 2-year flood depth for Reaches 1 to 7, labeled with flow input at the upstream end of the model.

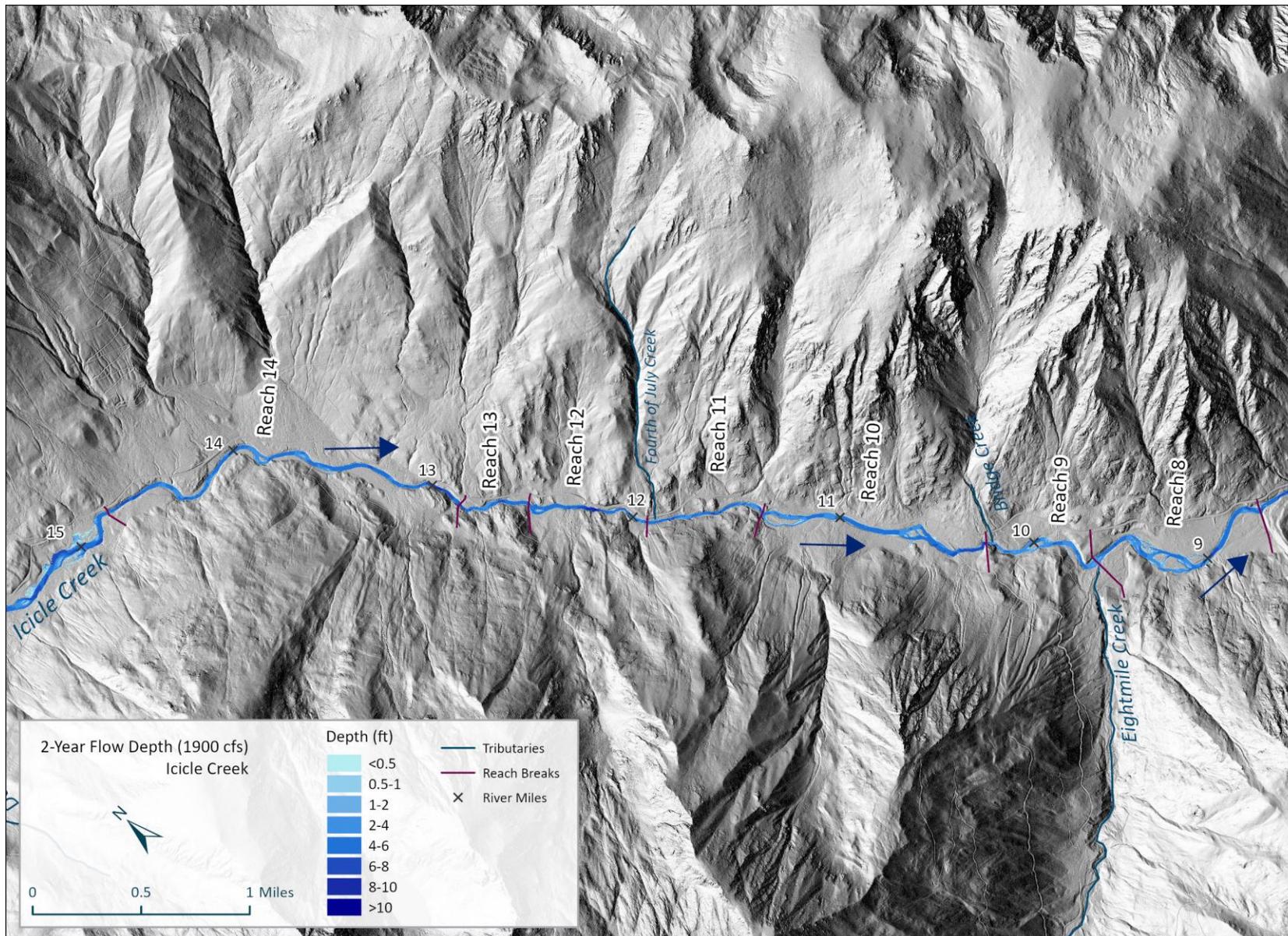


Figure 15. Modeled 2-year flood depth for Reaches 8 to 14, labeled with flow input at the upstream end of the model.

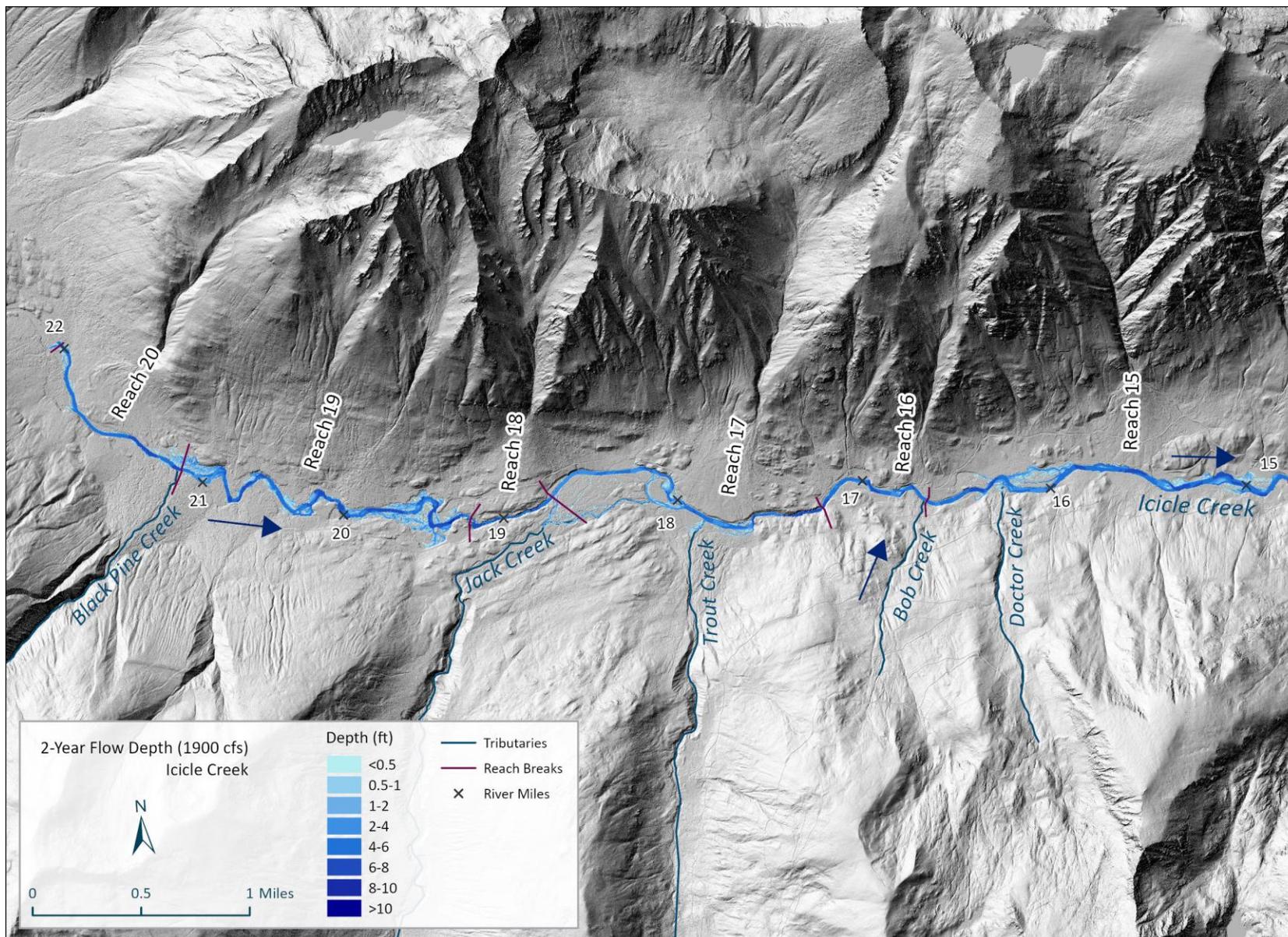


Figure 16. Modeled 2-year flood depth for Reaches 15 to 20, labeled with flow input at the upstream end of the model.

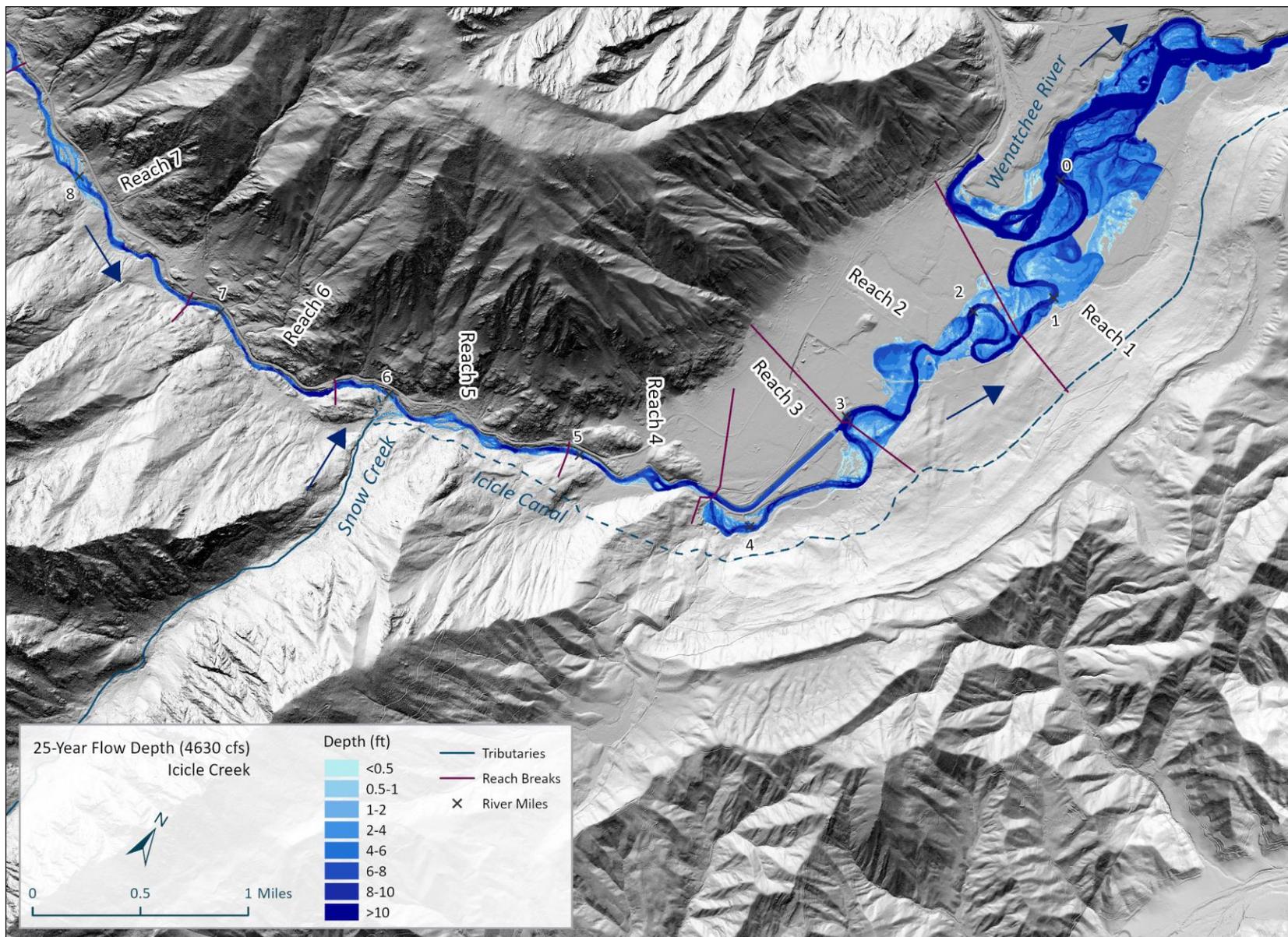


Figure 17. Modeled 25-year flood depth for Reaches 1 to 7, labeled with flow input at the upstream end of the model.

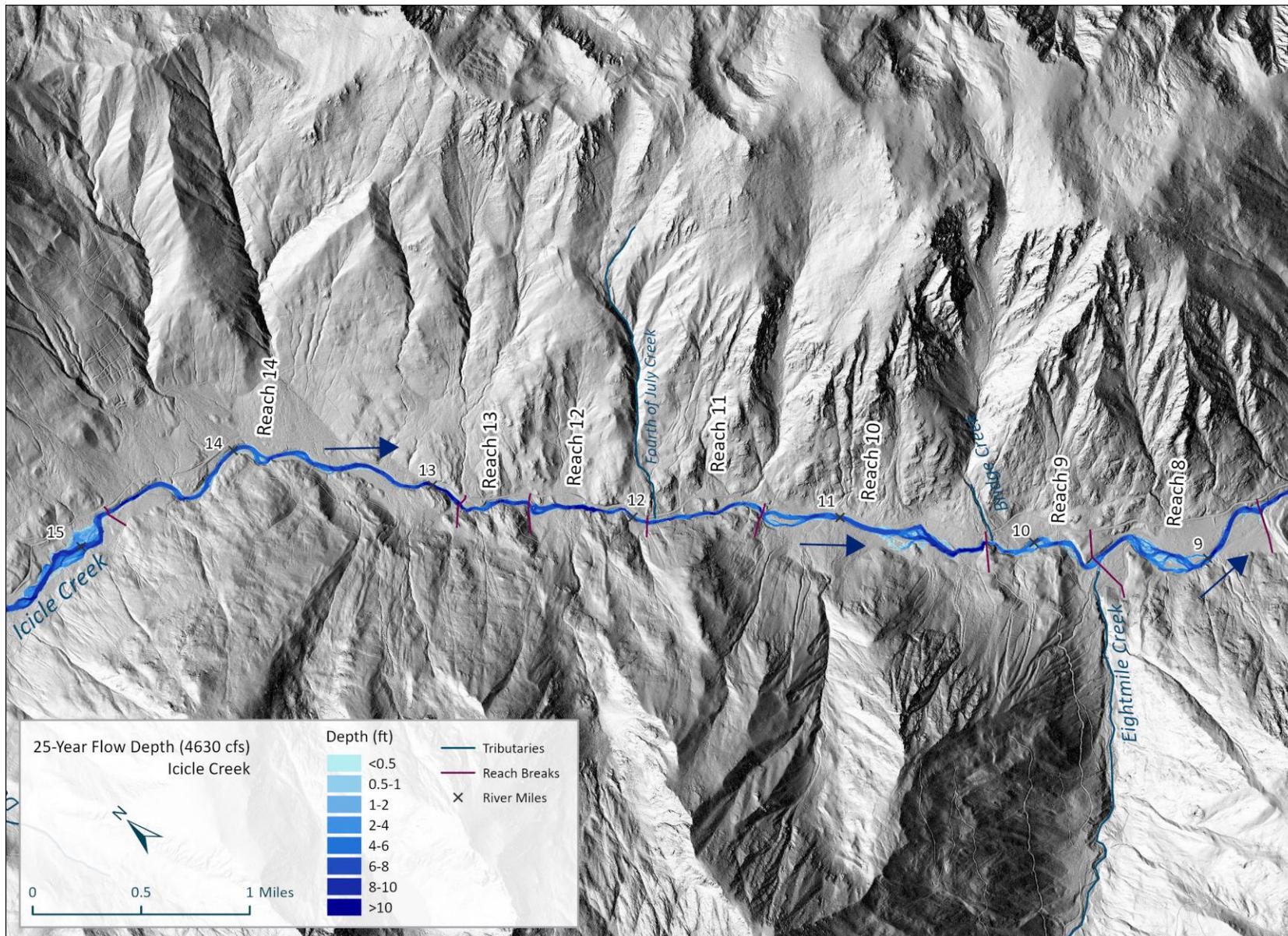


Figure 18. Modeled 25-year flood depth for Reaches 8 to 14, labeled with flow input at the upstream end of the model.

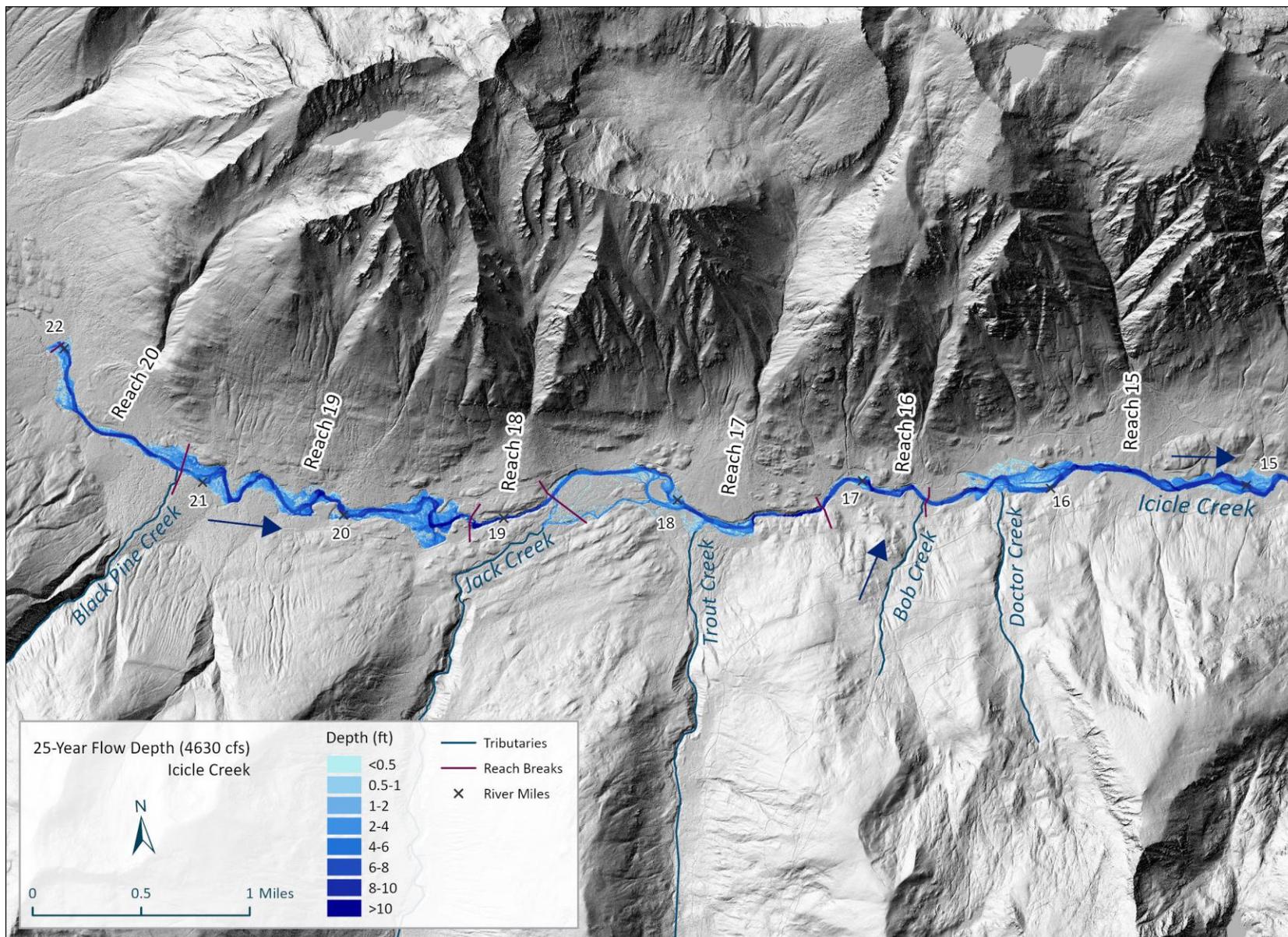


Figure 19. Modeled 25-year flood depth for Reaches 15 to 20, labeled with flow input at the upstream end of the model.

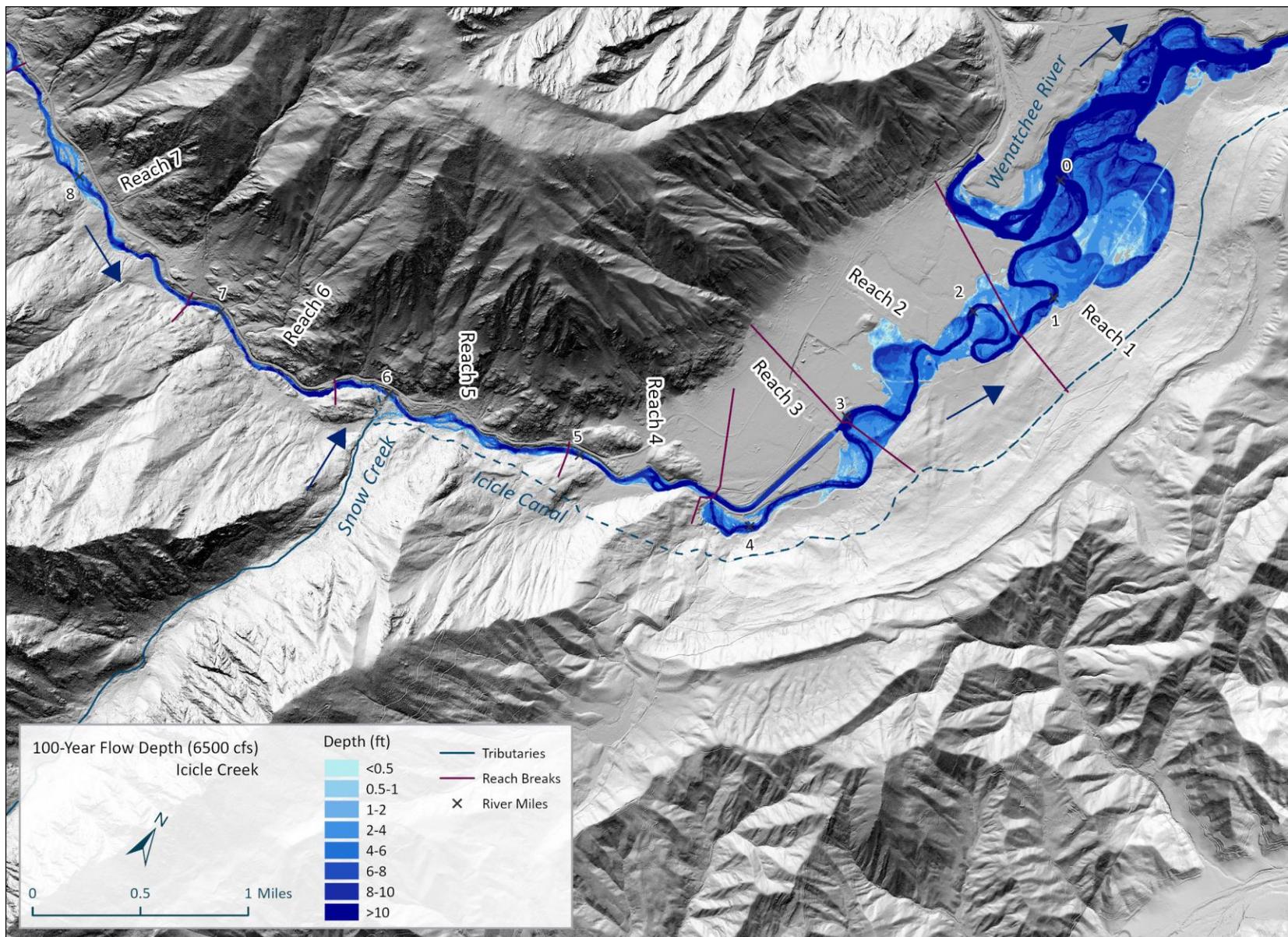


Figure 20. Modeled 100-year flood depth for Reaches 1 to 7, labeled with flow input at the upstream end of the model.

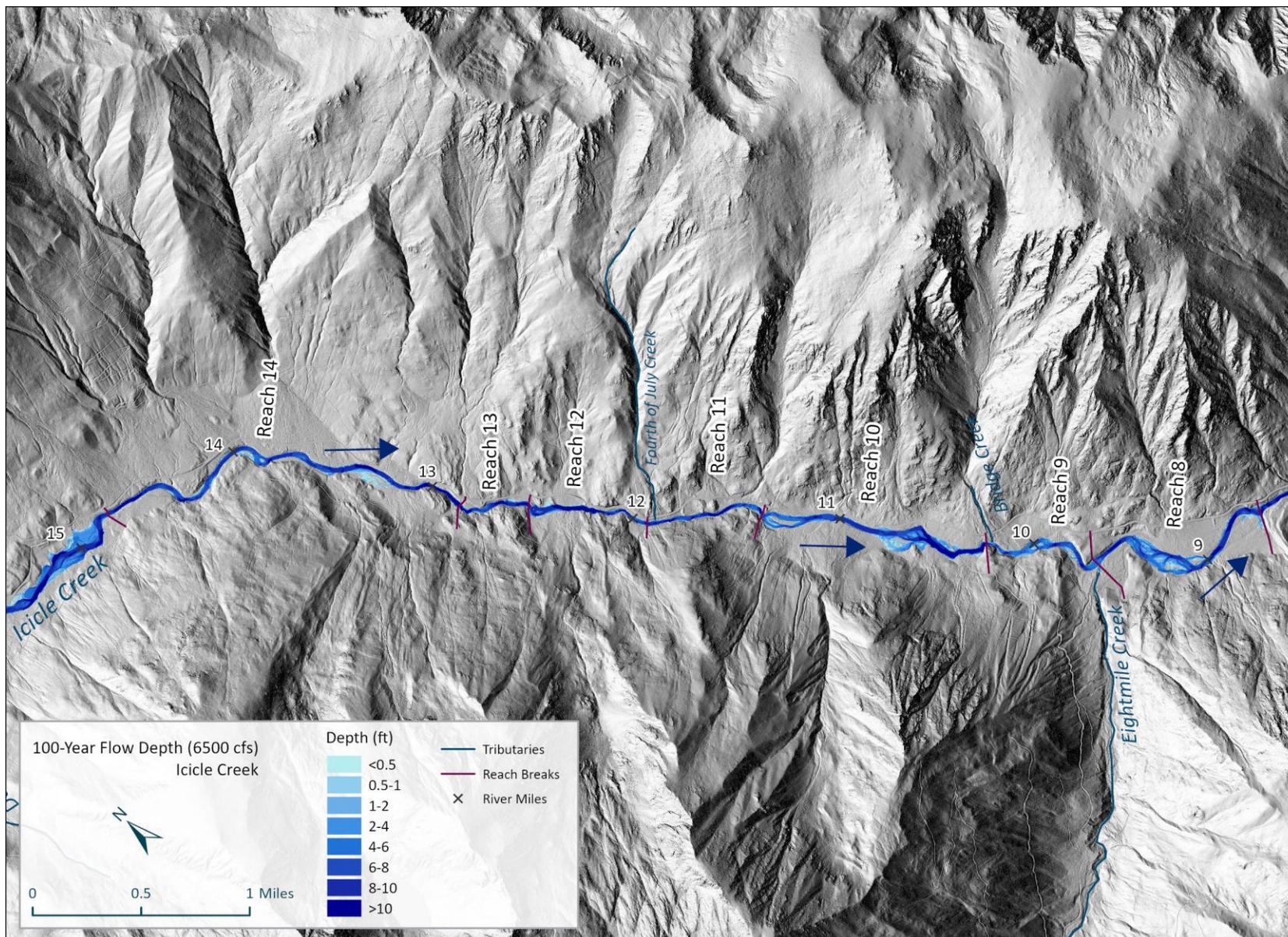


Figure 21. Modeled 100-year flood depth for Reaches 8 to 14, labeled with flow input at the upstream end of the model.

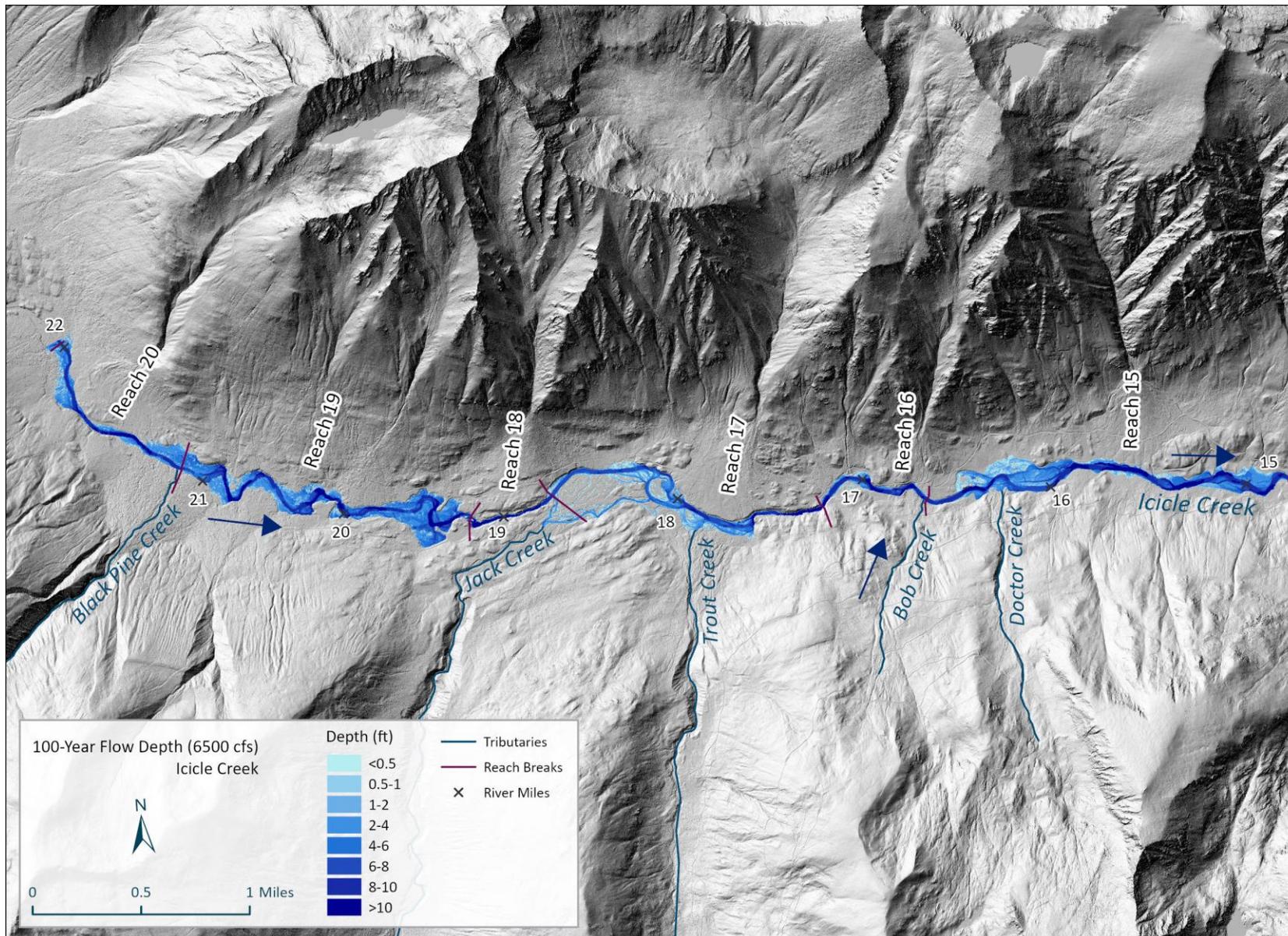


Figure 22. Modeled 100-year flood depth for Reaches 15 to 20, labeled with flow input at the upstream end of the model.

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