

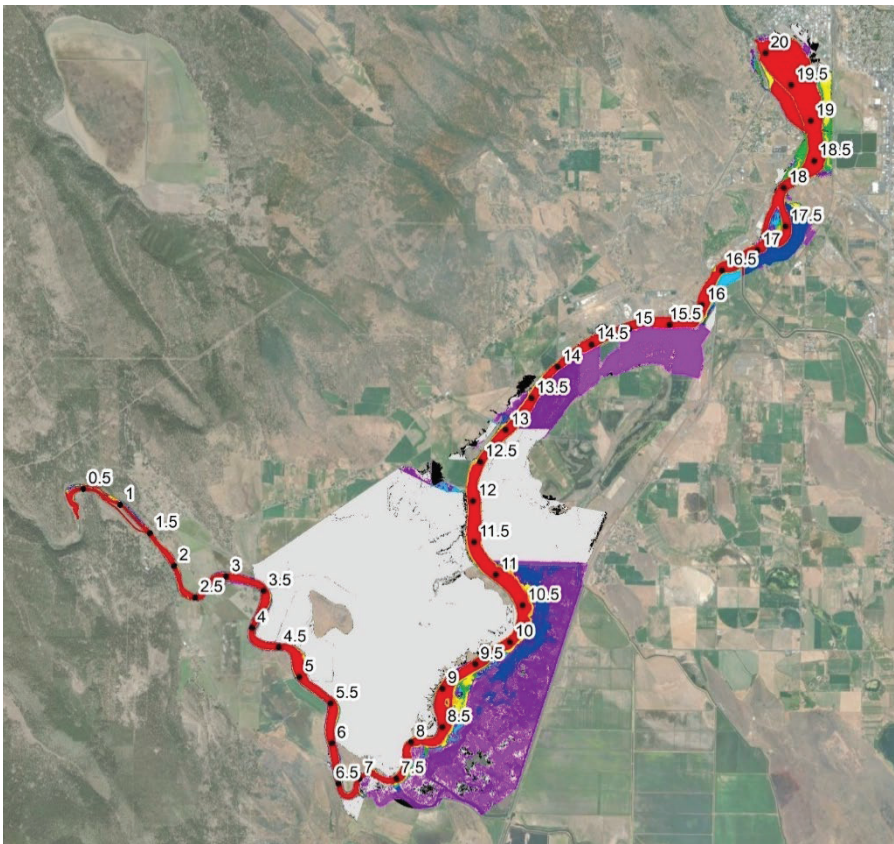


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RECLAMATION

Technical Report No. ENV-2021-118

# Hydraulic Modeling in Support of Flood Control Plan for the Klamath River Basin

Klamath Basin Area Office



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The U.S. Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated Island Communities.

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

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Klamath Basin Area Office

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## Acronyms

1D	one-dimensional
2D	two-dimensional
ac	acre(s)
cfs	cubic feet per second
DEM	digital elevation model
ft	foot (feet)
HEC-RAS	Hydraulic Engineering Center – River Analysis Software
hwy	highway
KBAO	Klamath Basin Area Office
LiDAR	Light Detection and Ranging
LRDC	Lost River Diversion Channel
NAD	North American Datum
NAVD	North American Vertical Datum
NGS	National Geodetic Survey
NGVD	National Geodetic Vertical Datum
PMF	probable maximum flood
RM	river mile
RPVD	Reclamation project vertical datum
SRH	Sedimentation and River Hydraulics
TSC	Technical Service Center



## Abstract

The Sedimentation and River Hydraulics Group (SRH) was requested by the Klamath Basin Area Office (KBAO) to update the flood control plan for the Klamath River from Lake Ewauna to Keno Dam (Keno Impoundment). To effectively update the plan two tasks were required of Technical Service Center's (TSC) SRH group: 1) conduct bathymetric survey of 20.2 miles of the Klamath River (from Lake Ewauna to Keno Dam); and 2) develop a hydraulic model to understand the relationship between flow and water surface elevation for the study reach.

A complete bathymetric survey was conducted during October 2019 from a multibeam depth sounder mounted on a boat to continuously measure water depths. The median value of each 3 ft by 3 ft grid size was extracted to build a surface to inform numerical modeling. A surface was built combining the bathymetric, 2018 topo-bathymetric Light Detection and Ranging (LiDAR), and 2010 topographic LiDAR data.

Numerical modeling was conducted in the Hydrologic Engineering Center's River Analysis System (HEC-RAS) version 5.0.7. The model combines both 1-dimensional (1D) and 2-dimensional (2D) hydraulic computations to create a hybrid unsteady flow model. The purpose of this analysis was to determine the capacity of the Klamath River. A series of discharge values ranging from 1,000 cubic feet per second (cfs) to the maximum estimated release capacity of Upper Klamath Lake (10,000 cfs) was routed into the first cross section of the model in 1,000 cfs increments. The Lost River Diversion Channel (LRDC) was modeled to account for an additional 3,000 cfs (maximum capacity of the LRDC) for all storm events.

Model results for inundation extent informed channel capacity. A water surface elevation profile informs the hydraulic drivers of the system. Model results indicate that a bedrock outcrop within the Keno Impoundment, Snow Goose Reef, serves as the hydraulic control for the upstream reach. Water surface elevation was assessed at the four modeled bridges to predict freeboard during flooding events. None of the modeled bridges are expected to be overtopped during the simulated flood events. Water surface elevation values were then compared to a 1975 study published by Pacific Power and Light Company (Pacific Power & Light Company, 1975). The difference in results between the two studies are small; thus, flood operations are unlikely to change significantly. Inundation extent indicates that marshlands begin flooding during Flood 3 (6,000 cfs exiting the model). Farmlands are not impacted until Flood 9 (12,000 cfs exiting the model), and no industrial or urban areas become inundated during Flood 10 (the largest event analyzed; 13,000 cfs exiting the model).

It should be noted that there is uncertainty associated with any numerical model as the physical processes are not completely represented by the governing equations. Uncertainties and assumptions documented in the study are associated with lack of calibration data, assumed no breaks in the levees, and model run time. Canals pulling water directly from the Klamath River were not incorporated into this study.



## Introduction

Klamath Project background and study purpose are introduced in these sections.

### Background

The Klamath Project was authorized in 1905, and currently provides irrigation water for roughly 225,000 acres of agricultural and National Wildlife Refuge lands. There are more than 700 miles of canals, drains, and diversion channels within the Klamath Project. Flow in the river has been managed to provide irrigation water as well as meeting endangered species needs throughout the watershed.

This study analyzes the reach of the Klamath River in the upper basin from Lake Ewauna (downstream of Link River Dam) to Keno Dam (Figure 1). The reach includes the confluence with the Lost River Diversion Channel (LRDC). Link River Dam was opened in 1921 just downstream of a natural bedrock control that was modified to facilitate reservoir operations. Keno Dam was built in 1967 for flood control purposes and now acts to impound water in the Klamath River upstream to Lake Ewauna. It replaced the existing wooden Needle Dam that was located on Snow Goose Reef, which was immediately upstream of present-day Keno Dam. Lost River Diversion Channel connects the Klamath River and Lost River for flood control purposes in winter months and to provide agricultural water supply for portions of the Klamath Project in summer months. Depending on operations of the surrounding dams, water can flow in both directions. Flood operations dictate that excess water from the Lost River watershed is diverted into the Lost River Diversion Channel to the Klamath River (Pacific Power Company, 2007).

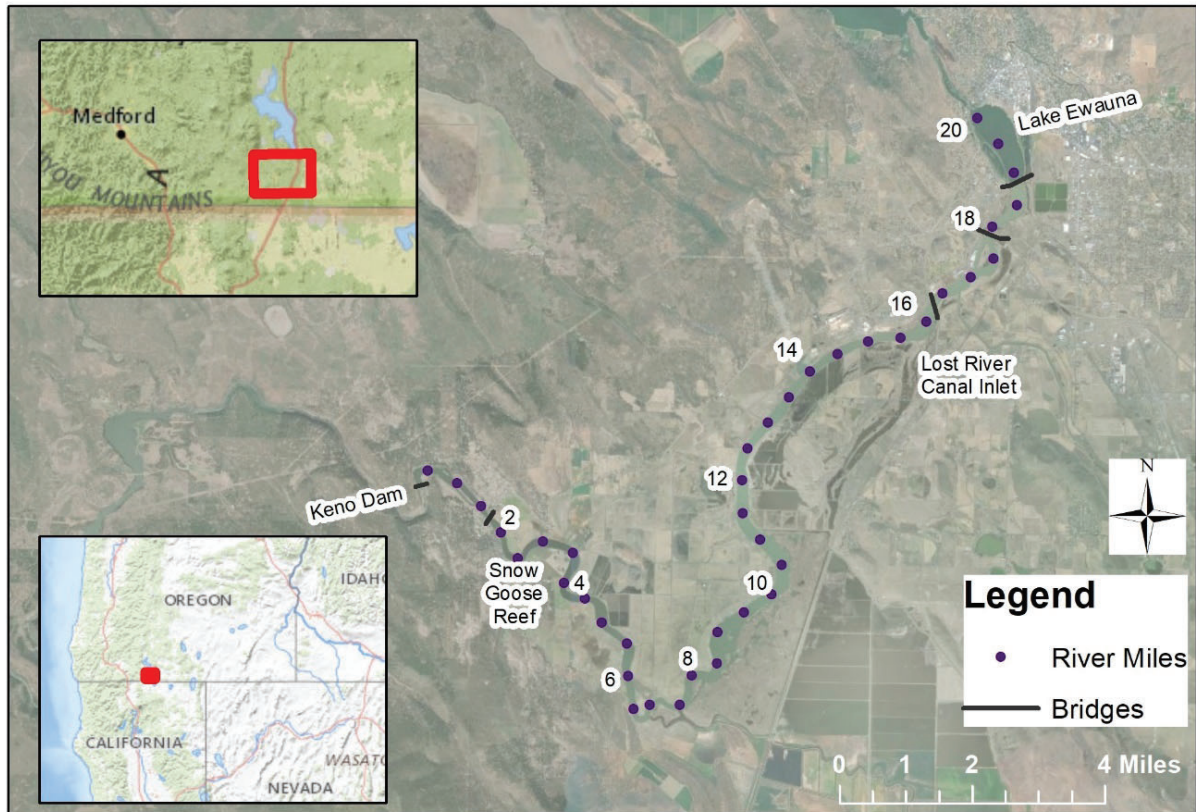


Figure 1. The model reach extends from Lake Ewauna to Keno Dam. It is in Oregon approximately 50 miles east of Medford near Klamath Falls.

As several dams are built along the Klamath River, a plan must be identified during flood events to avoid overloading a single structure and to avoid flooding of adjacent lands. Pacific Power and Light Company published a revised “Guide for High Runoff Season Operation” report in 1975. This document contains recommendations for operating Pacific Power’s Klamath River Basin Projects during high flow seasons from Upper Klamath Lake to the Iron Gate Spillway. The study provides a rating curve from Upper Klamath Lake, based on the modified upstream bedrock control, which is commonly called a “reef” (Figure 2). The study recommends maximum water surface elevation values for the Keno Impoundment corresponding to flood discharge at three bridges along the study reach. It concludes that the maximum capacity of the channel downstream of Lake Ewauna is 10,000 cfs, with an additional inflow of 3,000 cfs from the Lost River (maximum capacity of the LRDC). Therefore, the capacity of the Klamath River downstream of the Lost River Diversion Channel is reported to be 13,000 cfs. The 1975 report does not document how these values were derived. As described in more detail in the next section, the purpose of this study, as described in the following section, is to revise the flood operations plan to confirm or update the capacity of Klamath River between Lake Ewauna and Keno Dam.

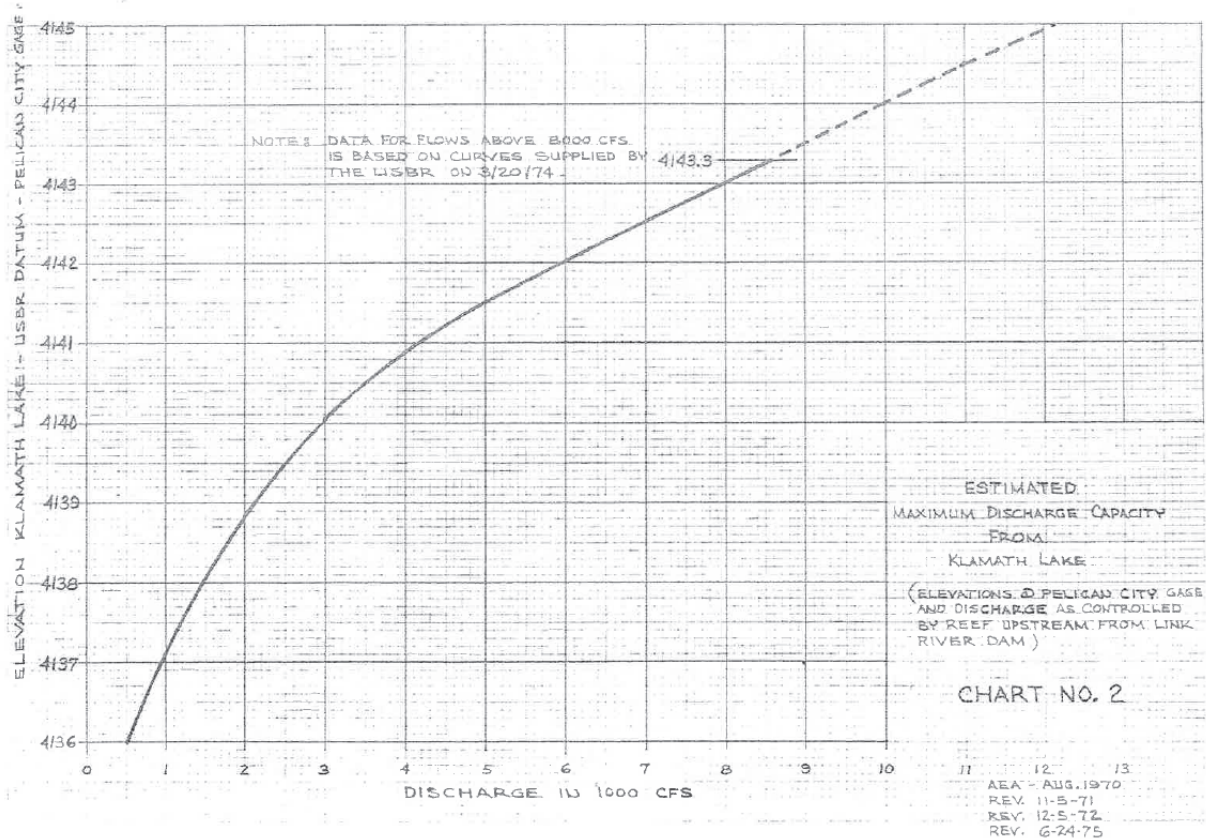


Figure 2. Chart No. 2 indicating the rating curve at the modified bedrock control upstream of Link Dam as of 1975 (Pacific Power, 1975).

## Study Purpose

Changes in operation and the potential for Reclamation to assume control of Link River Dam and ownership/control of Keno Dam have created a need to update the flood control plan for Upper Klamath Lake and the Klamath River from Lake Ewauna to Keno Dam. Furthermore, four lower dams (Iron Gate, Copco No. 1, Copco No. 2, and J.C. Boyle Dams) are expected to be decommissioned in 2023. Dam decommissioning and removal will substantially change river hydraulics below Keno Dam, resulting in potential changes in water management in upstream impoundment (Upper Klamath Lake and Keno Impoundment). Reclamation's KBAO requested that Reclamation's TSC assist to update the flood operations plan. As part of this assistance several studies are being conducted simultaneously by TSC. The studies include the following tasks. Items #3 and #4 (in bold) are documented in this report.

1. Develop initial flood scenarios based on existing data,
2. Conduct a bathymetric survey of Upper Klamath Lake to develop a relationship between stage and pool capacity,

3. **Conduct bathymetric survey of the Klamath River from Lake Ewauna to Keno Dam,**
4. **Develop a hydraulic model to develop a relationship between flow and water surface elevation for the study reach,**
5. Analyze the release capacity from Upper Klamath Lake,
6. Refine flood scenarios, and
7. Develop a final flood control plan.

## Field Methods

A complete bathymetric survey was conducted during October 2019 from a boat using a multibeam depth sounder to continuously measure water depths. The horizontal position of the moving boat was continuously tracked using real-time kinematic (RTK) global positioning system (GPS). All bathymetric and GPS points were collected in the following datum:

- Horizontal: North American Datum (NAD 1983) and State Plane coordinates Oregon South (international feet) and
- Vertical: North American Vertical Datum 1988 (NAVD 1988), Geoid 12A

The bathymetric survey was conducted from 10/24/2019 to 10/29/2019. During this survey, millions of bathymetric data points were collected. The median value of each 3 ft by 3 ft grid size was extracted to develop a continuous bathymetric surface of the Klamath River that is the basis of the numerical modeling (Figure 3).

During this period, daily river water surface elevations were measured by two Pacific Corps gages, located at the Highway (Hwy) 97 Bridge and Keno Dam. These two locations are approximately 16 river miles apart and daily water surface elevation differed by less than 0.1 feet. The water surface elevation ranged from 4085.4 ft to 4085.8 ft (NAVD88) throughout the duration of the survey. As the difference between the gages was minimal, we assume that the water surface elevation was uniform along the entire length of river. The average water surface elevation was 4085.6 feet (NAVD 88) at both Pacific Corps gages. More details on survey methodology are included in Appendix A — Hydrographic Survey Equipment and Methods.

Hydraulic Modeling in Support of Flood Control Plan for the Klamath River Basin

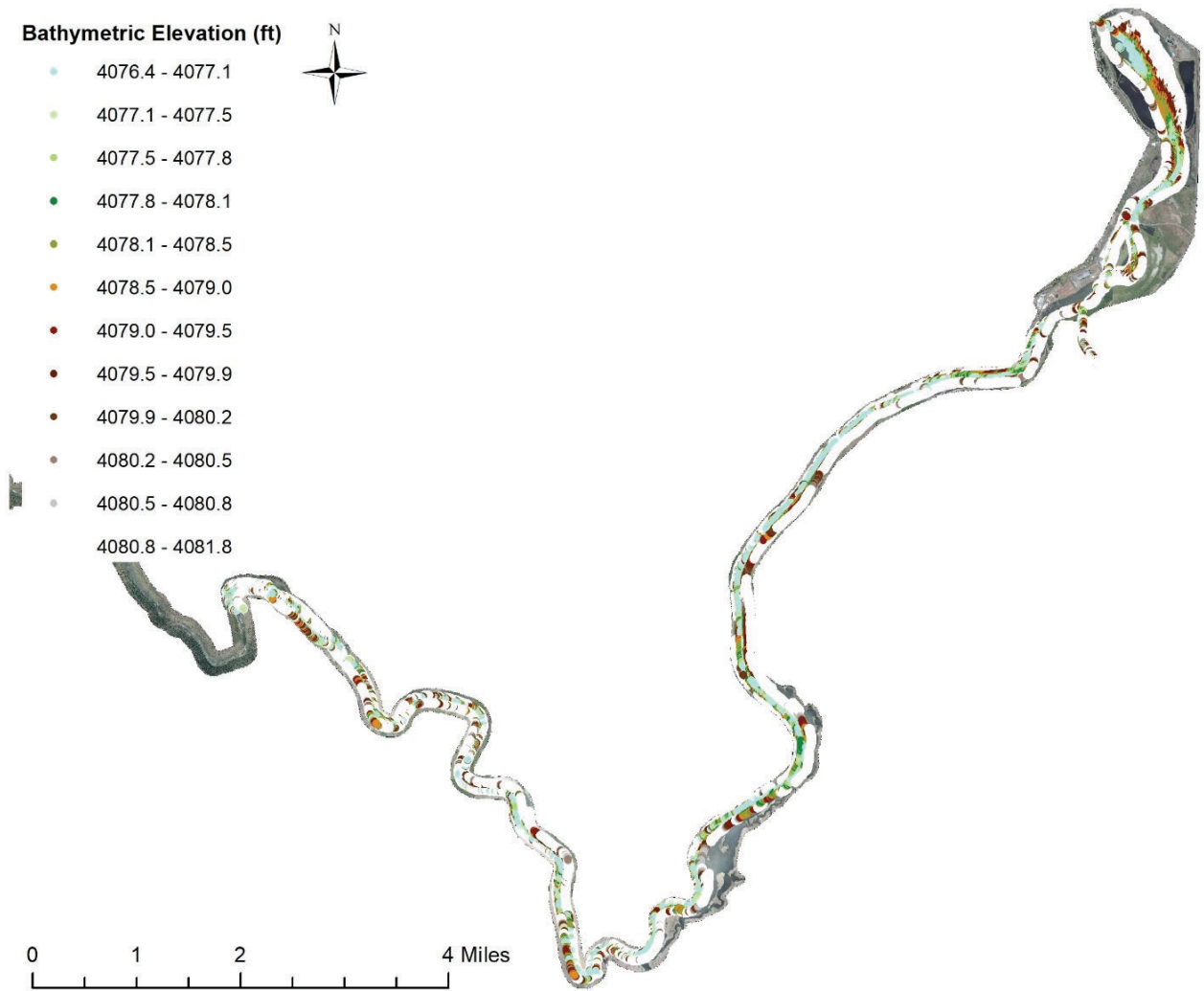


Figure 3. Spatial extent of the data points collected on the bathymetric survey on a 3 ft by 3 ft grid.

# Modeling Methodology

The following section provides details on how the model was development, including an overview of the applied model and data.

## HEC-RAS Model Overview

HEC-RAS 5.0.7 was applied to analyze channel capacity of the Klamath River between Lake Ewauna and Keno Dam (Figure 4). HEC-RAS can perform 1D and 2D hydraulic calculations to simulate a system of channels, levees, and floodplain areas. The 1D and 2D hydraulic computations can also be combined to create a hybrid unsteady flow model, which was applied to this study.

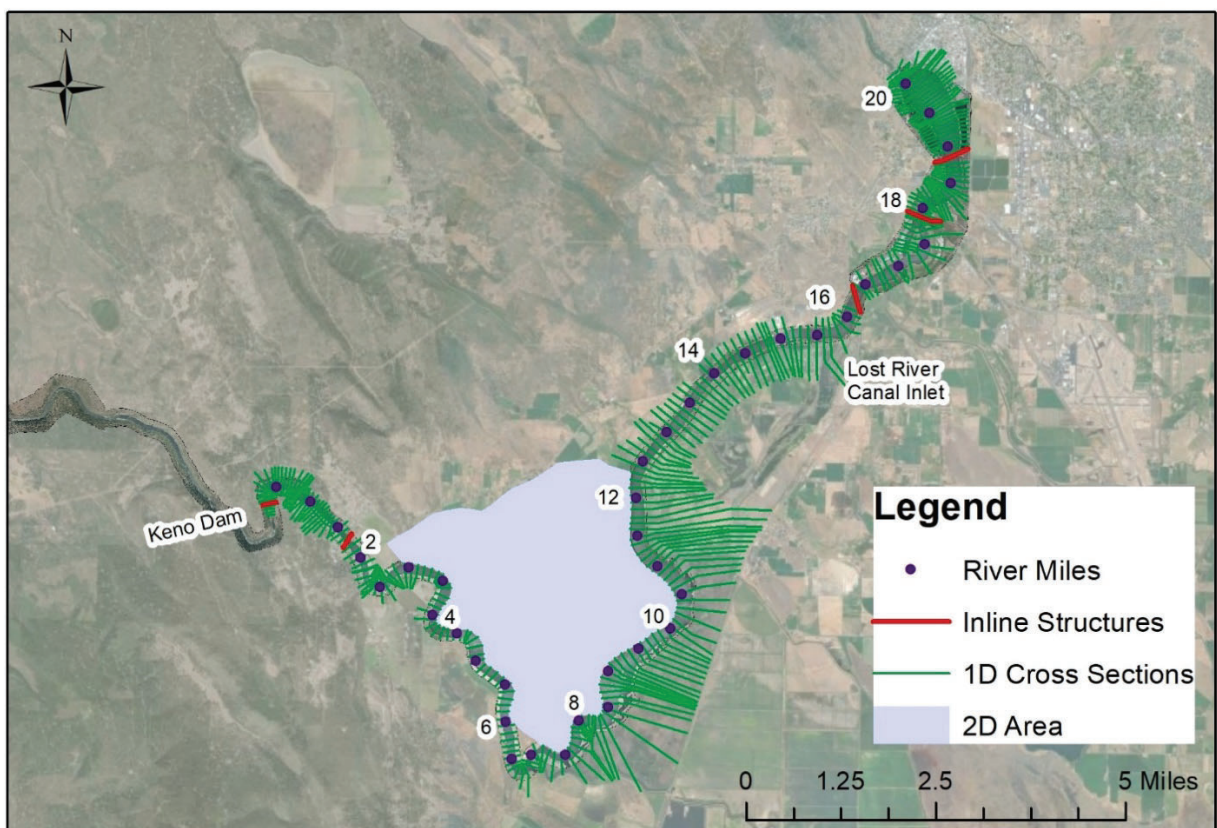


Figure 4. The HEC-RAS model extends from the inlet upstream of Lake Ewauna to just below Keno Dam. Much of the model was built using 1D cross-sections; however, 2D analysis was required in the west floodplain, between RM 3.5 and RM 12. Modeled cross-sections are represented with green lines. River miles are marked every two miles in purple dots and black text. Keno Dam occurs at RM 0.2 (station 866). Lost River Diversion Channel inflow occurs at RM 16.5 (cross section 87912) Station 0 is at the downstream model boundary.

### **One-Dimensional Modeling**

One-dimensional modeling was applied to the entire river reach in the channels and most of the overbanks. Areas that were not included in the one-dimensional analysis were represented with a 2D area. Water surface elevation is calculated using the energy equation following the standard step procedure assuming gradually varied flow (Brunner, 2016). The 1D cross-sections were connected to the 2D analysis area through two lateral structures.

### **Two-Dimensional Modeling**

HEC-RAS 2D is an unsteady flow model that calculates water surface elevation by applying the Saint-Venant Equations using an implicit finite volume algorithm. A feature that is unique to HEC-RAS 2D is that cells do not have a uniform elevation, rather the detail of the underlying terrain is applied to the mesh, known as a “high resolution subgrid model” (Casulli, 2009). In other words, the full resolution of the underlying terrain is used to calculate a single water surface elevation in any given cell.

## **Hydrology**

The purpose of this analysis was to determine the capacity of the Klamath River and update the flood operations plan. This study is part of a larger effort that needs to be compared to the original 1975 flood operations plan. Updated flood hydrology (annual exceedance probability, seasonal and typical hydrographs) are being developed concurrently with this hydraulic modeling effort. A series of discharge values ranging from 1,000 cfs to 10,000 cfs were simulated in 1,000 cfs increments. This approach was selected to compare water surface elevations to those calculated during the 1975 study and to quantify when flows spill outside of the channel. The upstream boundary corresponds to approximately 400 feet upstream of Lake Ewauna (RM 20.2). The LRDC is located within the project reach, RM 16.5 (Cross Section 87912). A steady discharge of 3,000 cfs was selected for flood conditions, based on the original Flood Operations Plan and the Standing Operating Procedures (Pacific Power, 1975 and Pacific Power Company, 2007). This was entered as a lateral inflow, applying only one significant figure. Therefore, a total of 4,000 cfs to 13,000 cfs exits the model downstream of Keno Dam (Table 1). As a reference, the peak inflow for the probable maximum flood (PMF) is 58,600 cfs exiting Link River Dam, upstream of the Lost River Diversion Channel (Pacific Power Company, 2007). The PMF is defined as a hypothetical flood event resulting from a combination of the most severe meteorological and hydrologic conditions that could occur in an area (United States Federal Energy Regulatory Commission, 2001). This flood was not simulated as extensive flooding is expected during such an unlikely event.

Table 1. Modeled Flood Scenarios

<b>Flood Scenario Name</b>	<b>Upstream Flow Boundary Condition (cfs)</b>	<b>Lateral Inflow at Lost River Diversion Canal (cfs)</b>	<b>Total Flow Exiting the Model (cfs)</b>
Flood 1	1,000	3,000	4,000
Flood 2	2,000	3,000	5,000
Flood 3	3,000	3,000	6,000
Flood 4	4,000	3,000	7,000
Flood 5	5,000	3,000	8,000
Flood 6	6,000	3,000	9,000
Flood 7	7,000	3,000	10,000
Flood 8	8,000	3,000	11,000
Flood 9	9,000	3,000	12,000
Flood 10	10,000	3,000	13,000

## Model Extent & Surface Generation

The model domain includes 20.2 miles of the Klamath River from approximately 400 feet upstream of Lake Ewauna to 800 feet downstream of Keno Dam. Three datasets were merged to build the surface for this model (Figure 5):

- 1) bathymetric multi-beam data collected in October of 2019 (discussed under Field Methods),
- 2) 2018 topo-bathymetric LiDAR digital elevation Model (DEM; QSI Corvallis, 2019), and
- 3) 2010 topographic LiDAR data (Watershed Sciences Inc., 2011).

The bathymetric data were extracted from millions of points to a 3 ft by 3 ft point grid, to match the existing LiDAR data resolution. These points were summarized as a 3.28-foot (1 meter) grid raster before being integrated into the LiDAR data. The bathymetric data were used to represent the channel while LiDAR data represented areas of the channel too shallow to survey and floodplain areas where overland flow would be anticipated during high flow events.

Both LiDAR datasets were originally collected in Universal Transverse Mercator (UTM) coordinates, which is in meters. The 2018 LiDAR dataset was a 3.28-foot (1 meter) grid raster. The 2010 LiDAR dataset that was available to the TSC was a 3-foot grid raster. Both LiDAR datasets needed to be projected to the project coordinate system (NAD 1983 State Plane Oregon South) and converted to imperial units (feet). The three datasets could then be mosaiced together to maintain the extent and grid spacing of the 2018 LiDAR DEM. There were locations where the datasets overlapped, especially in the channel. In these locations, the

mosaic operation went in the following order: 2019 bathymetry, 2018 LiDAR and 2010 LiDAR. Therefore, the bathymetry data took precedence over the 2018 LiDAR data as the error associated with bathymetric sonar data is considered more reliable than that of green LiDAR data. Where the 2018 and 2010 LiDAR datasets overlapped, the more recent (2018) LiDAR took precedence over the 2010 LiDAR.

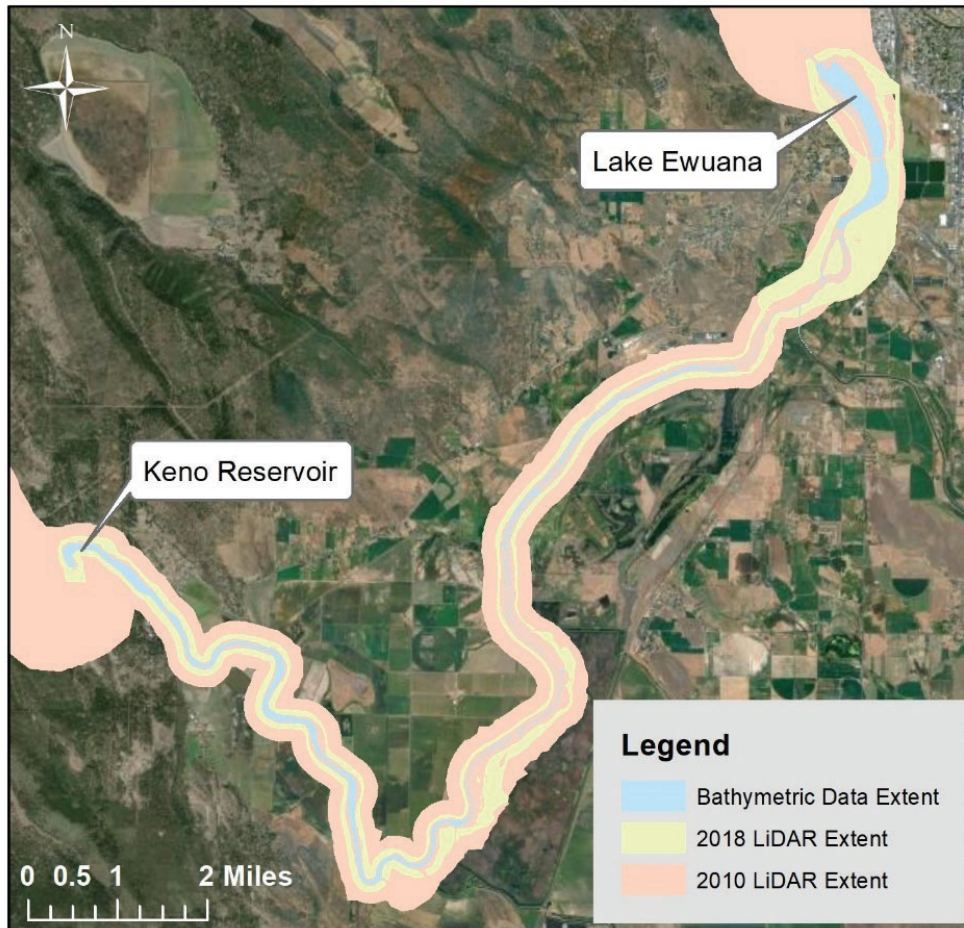


Figure 5. Spatial extent of the three datasets used to build the model surface.

## Model Geometry

The following sections describe how the project reach was represented in the HEC-RAS model through cross sections and structures.

### Cross Sections

Cross sections were digitized approximately every 500 feet unless greater detail was required to represent channel and overbank geometry. Areas of greater detail include sharp changes in channel width (contractions or expansions), bridges, sharp meander bends, or flow splits near exposed islands. A total of 301 cross sections were required to represent the 20.2 miles of the Klamath River and surrounding floodplain. Where possible, the cross sections were drawn to

contain the flow of the largest flow (10,000 cfs upstream of LRDC and 13,000 remaining downstream river). However, this was not possible in the west overbank 3 to 12 miles upstream of Keno Dam (cross section 64828 through 15458) due to the sharp meander bend and flat overbank topography. Two-dimensional modeling was applied in this area (Figure 4).

Bank stations throughout the project were delineated to best separate the channel and floodplain for Manning's  $n$  roughness characterization. A combination of topography and aerial imagery were used to approximate the bank location. Bank location does not necessarily identify the top of overbank to define flooding.

### ***Manning's Roughness***

A conservative, uniform Manning's roughness was assigned based on literature and professional judgement. A value of 0.035 was selected within the channel as a clean, straight main channel (Chow, 1959). Documentation from the 1975 study indicates that Manning's roughness values ranged from 0.025 to 0.035 (letter to Mr. C.D. Lawrence from A.E. Alspaugh, July 20, 1972). Coincidentally, the floodplain roughness was also selected to be 0.035 as a floodplain, with pastures, no brush and high grass (Chow, 1959). This is reasonable to represent the agricultural lands surrounding the river. Furthermore, the purpose of hydraulic modeling is to determine channel capacity; therefore, a detailed delineation of floodplain was outside of this scope of work.

At the time of this report, no calibration data were available for this modeling effort. While water surface elevation and flow data are available from the 2019 survey, these data cannot be applied for calibration for the following reasons:

- 1) The model is intended to simulate flood conditions; flow conditions were low, less than 1,000 cfs, during the survey to the point that the change in water surface elevation throughout the 20-mile reach was less than 0.1 feet.
- 2) Gate operations at Keno Dam served as a hydraulic control for the river reach during the survey. To simulate flood scenarios, gates at Keno Dam were fully opened to shift the hydraulic control upstream to Snow Goose Reef, which was not the case during the survey. Gates were mostly shut during the survey for the safety of the crew and for water operations purposes. It should be noted that leaving the gates fully open was done for numerical modeling purposes and would not be practical or advisable for operational purposes.

### ***Ineffective Flow Areas***

Ineffective flow areas were added to the model for two purposes:

- 1) to delineate ineffective flow zones upstream/downstream of structures such as bridges and Keno Dam.
- 2) to render flow that overtopped the levees as ineffective (Figure 7).

The areas outside the levees could become wet but assumed to have zero conveyance and velocity. This was done to calculate the depth of inundation if there were seepage underneath



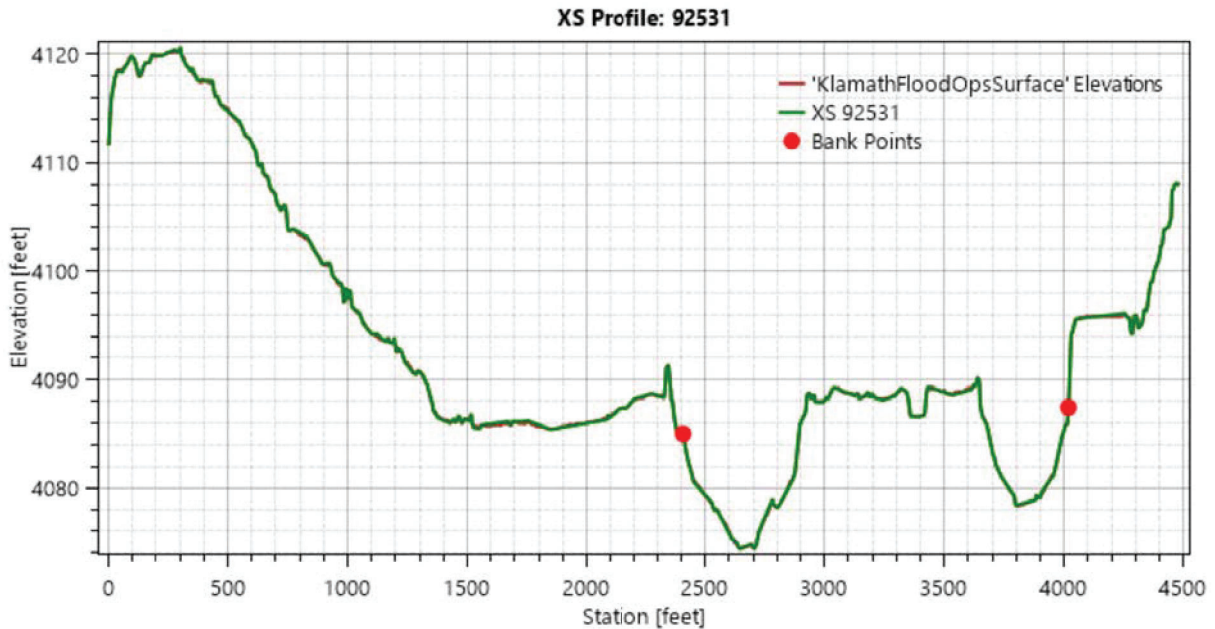


Figure 7. Representation of the island centered at RM 17.5 as a single cross section, with bank points on the far side of either channel.

### Inline Structures

Four bridges and one dam are located within the model domain:

1. Railroad bridge crossing at the downstream extent of Lake Ewauna (RM 18.8, Station 99252),
2. Southside Expressway Bridge (RM 17.8, Station 94113),
3. Dallas California Highway Bridge (RM 16.2, Station 85683),
4. Greensprings Highway Bridge (RM 1.7, Station 8941)
5. Keno Dam (RM 0.2, Station 865.5)

The four bridges were represented in the model as inline structures (two examples are presented in Figure 7). Bridge deck elevation, and pier width and location were digitized based elevations and stationing on available design drawings. All drawings were developed before 1993, when NAVD88 was released; therefore, we assume that all elevations are in NGVD29. The SRH team converted the elevation data into NAVD88 using the National Geodetic Survey (NGS) VERTCON datum shift calculator. Drawings were available for all but the railroad bridge at RM 18.8. No data were available for the railroad bridge crossing. The bridge was built making assumptions based on LiDAR topography and site photos. The bridge deck was assumed to include the cross beams highlighted in Figure 8.

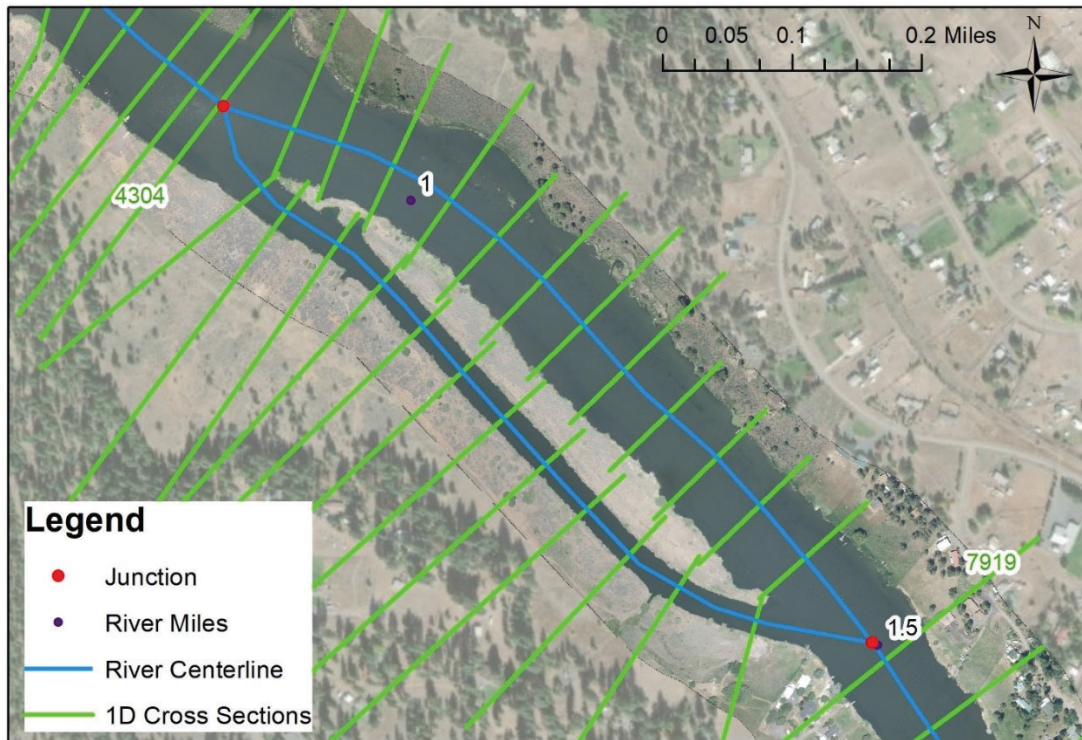


Figure 8. One split flow location was modeled between RM 0.5 and RM 1.5. Two junctions were placed in between cross sections 7919 and 4304.

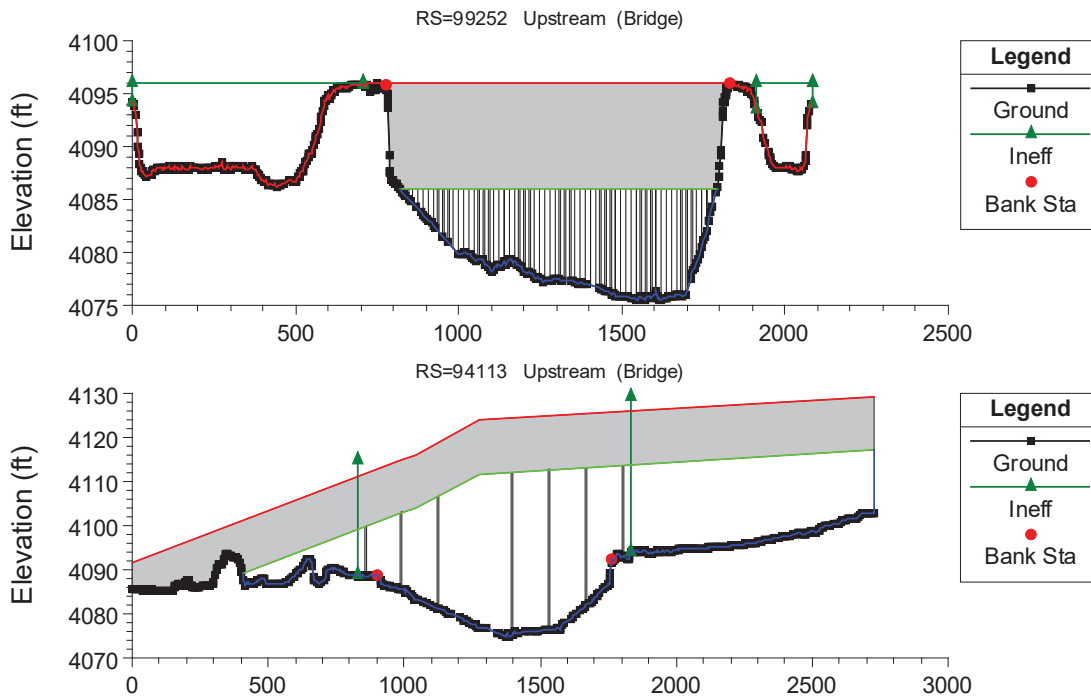


Figure 9. Examples of how bridges are represented in HEC-RAS as a one-dimensional structure. Both panels show the upstream geometry. The top panel depicts the railroad bridge at RM 18.8, while the bottom panel delineates Southside Expressway at RM 17.8.



Figure 10. Site photo of the railroad bridge downstream of Lake Ewauna. Note that the piers are numbered to inform model input data. The cross, beams highlighted in the site photo, were assumed to be part of the bridge deck.

Keno Dam was represented as an inline structure (Figure 9). Drawings from 1965 to 1967 were available for Keno Dam. The drawings informed the embankment elevation and gate locations and dimensions. Elevations were assumed to be in NGVD29 and converted them to NAVD88 using the NGS VERTCON datum shift calculator.

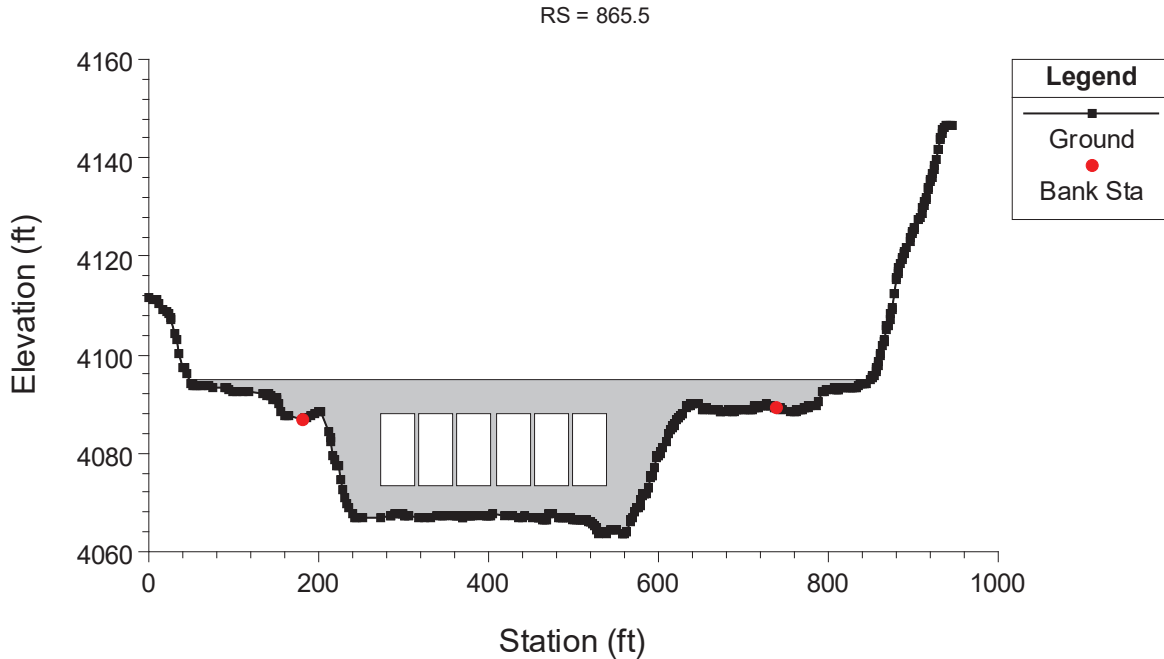


Figure 11. Keno Dam digitized as an inline structure at RM 0.2.

### Lateral Structures

Two lateral structures were added to the model to connect the 1D channel and 2D overbank area. The first extends from cross section 64828 (RM 12.3) to beyond cross section 37713 (RM 7.1), approximately 5.1 miles (26,760 feet) in length (Figure 10). The second lateral structure extends from upstream of cross section 31813 (RM 6.0) to 90 feet downstream of cross section 15458 (RM 2.9), approximately 3.3 miles in length. Both embankment crests were set to match the LiDAR topography. The standard weir equation for a broad crested weir was applied to both structures with a weir coefficient of 0.5. The tailwater connections for both lateral structures are the 2D overbank area previously discussed.

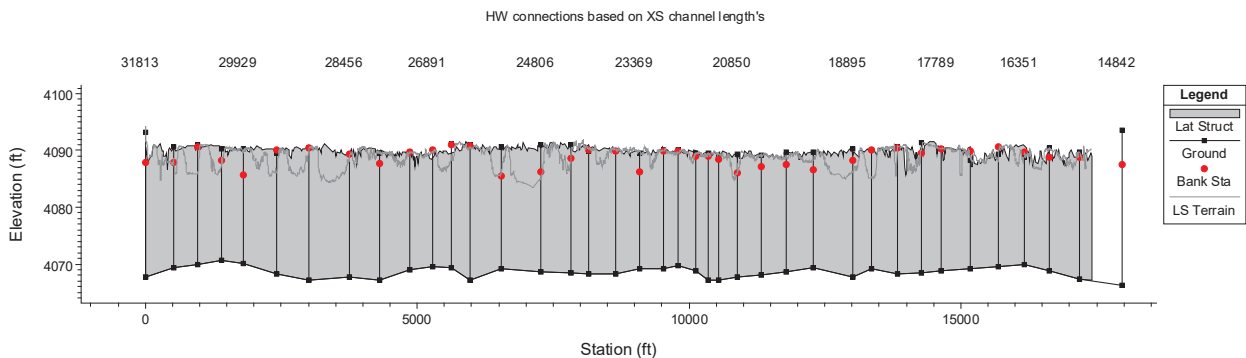


Figure 12. Lateral structure to connect the 1D channel and 2D overbank at RM 12.3.

## Boundary & Initial Conditions

Model boundary conditions are required at the upstream and downstream edges of the model. If there are any additional flow input locations, an additional boundary condition can be added. If there are any flow split locations, an initial discharge estimate is required for each channel. HEC-RAS does have a flow optimization option that allows the program to determine appropriate flow allocations based on water surface elevation calculated by the governing equations.

Discharge volume was the upstream boundary condition to the model. Flow was incrementally increased at the model inlet (cross section 106397; north and upstream of Lake Ewana) by 1,000 cubic feet per second (cfs). A constant inflow of 3,000 cfs was distributed at cross section 87912 (RM 16.5) to represent LRDC. The model reach contains one flow split which required initial conditions between RM 0.5 and 1.5 (Figure 6). The initial conditions were set to split the flow in half between the two channels. Then the upstream junction was optimized using the HEC-RAS “Flow Optimization” tool to determine the appropriate flow allocation to each channel (Table 2).

Keno Dam serves as a downstream hydraulic control of the modeled reach. Flow goes through critical depth at Keno Dam, which means that flow conditions downstream of the dam will not impact the water upstream of the dam. Therefore, the downstream boundary condition will not impact hydraulic model results upstream of Keno Dam if the flow still goes through critical depth at the dam. As the 800 feet of channel downstream of Keno Dam do not significantly impact this study, it is appropriate to set the downstream boundary condition to critical depth. All six gates at Keno Dam were open to their maximum height (14.5 ft) to best analyze the capacity of the upstream channel.

Table 2. Flow Optimization for split flow between the main and excavated channel between RM 0.5 and RM 1.5 (cross section 7919 and 4304)

Flood Scenario	Total Flow (cfs)	Flow Percentage between Bypass Channel and Main Channel	
		Bypass Channel (River Left)	Main Channel (River Right)
Flood 1	4,000	86%	14%
Flood 2	5,000	83%	17%
Flood 3	6,000	82%	18%
Flood 4	7,000	80%	20%
Flood 5	8,000	79%	21%
Flood 6	9,000	77%	23%
Flood 7	10,000	76%	24%
Flood 8	11,000	75%	25%
Flood 9	12,000	75%	25%
Flood 10	13,000	74%	26%

## Results & Discussion

Hydraulic model results were assessed to develop a relationship between flow and water surface elevation and inform channel capacity. High water surface elevations within the channel can put channel spanning structures at risk. There are four such structures discussed in this section. Channel capacity was analyzed to determine at what flood event does overtopping occur. Much of the overbank areas consist of marshlands and farm fields. However, there are some areas where flooding would risk surrounding infrastructure. Overtopping flows and their extent and impact will be discussed.

### Water Surface Elevation

Water surface elevation was extracted along the channel profile for each modeled flow scenario (Figure 9). Results show that the bedrock outcrop, referred to as Snow Goose Reef, at approximately station 12,500 ft (RM 2.5) serves as the hydraulic control for the upstream reach. This means that any changes made below the bedrock outcrop will not significantly affect the water surfaces in the channel upstream. It also means that the water surface elevation for the entire upstream reach, through Lake Ewauna is dictated by this feature. Should the water surface elevation within the upstream channel need to be decreased given the same volume of water, the bedrock outcrop could be lowered, notched, or bypassed.

Water surface elevation was assessed at the four modeled bridges to predict freeboard during flooding events. Of the four modeled bridges, only the railroad bridge is impacted by floodwaters. While floodwaters reach the lower cross beams, water is not expected to overtop the bridge deck, which is approximately 10 ft higher than the cross beams. The freeboard of the other three bridges ranges from 8.4 to 10.6 feet during Flood 10, the highest modeled flood event (Table 4). As discussed in Inline Structures Section, drawings for the railroad bridge could not be obtained. Therefore, all elevation values were estimated. Furthermore the bridge was represented using a very conservative approach. The bridge, including the cross members, were assumed to be a solid structure, not representing the permeability through the gaps between the cross members, which were assumed to be part of the bridge deck. Therefore, it is likely that water is not pressurized, but flowing through the cross beam members. This bridge is not overtopped, even during Flood 10 conditions.

## Hydraulic Modeling in Support of Flood Control Plan for the Klamath River Basin

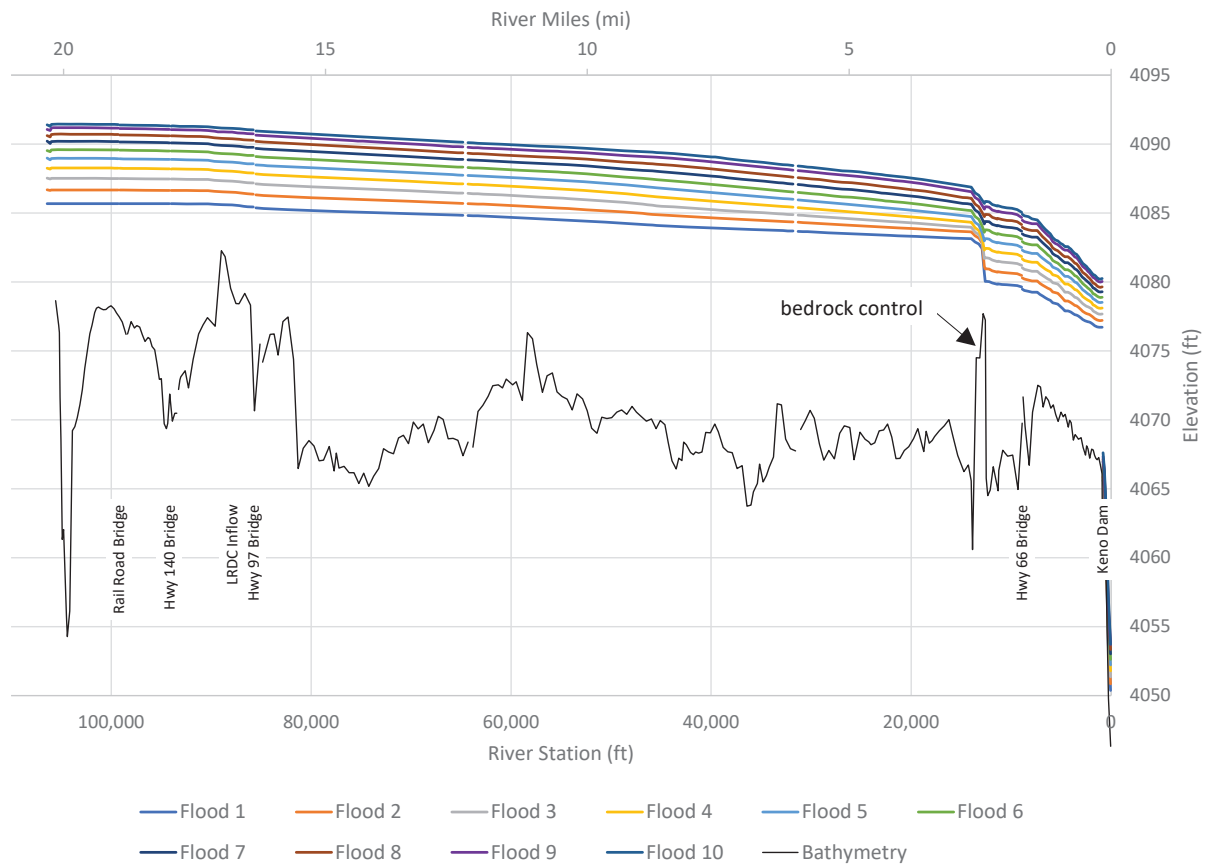


Figure 13. Water surface elevation profile along the model reach. River and cross section stationing (in feet) is labeled on the bottom x-axis, while river miles are labeled on the top x-axis. The bedrock control is located around RM 2.5.

The flood water surface elevation values were then compared to the flood stages reported in the 1975 flood operations plan. The plan identified water surface elevations for two flow events: 1) 7,000 cfs from Lake Ewauna and 3,000 cfs from Lost River Diversion Channel and 2) 10,000 cfs from Lake Ewauna and 3,300 cfs from Lost River Diversion Channel. While Flood 10 simulated a total of 13,000 cfs (rather than 13,300 cfs), the additional 300 cfs accounts for only 2% of the flow. Therefore, it is still reasonable to compare results of the two similar flow events. This plan predicted flood stage at three locations:

- 1) Hwy 140 bridge (cross section 94184; RM 17.8),
- 2) Highway 97 Bridge (cross section 85789; RM 16.2), and
- 3) Keno Dam (cross section 885; RM 0.2; Figure 10)

Table 3. Freeboard values at four bridges for all modeled floods. Negative freeboard indicates that the bottom of the bridge deck is submerged

<b>Bridge Name</b>	<b>Railroad Bridge</b>	<b>Hwy 140 Bridge</b>	<b>Highway 97 Bridge</b>	<b>Hwy 66 Bridge</b>	
Cross Section Station (ft)	99252	94113	85683	8941	
River Mile	18.8	17.8	16.2	1.7	
Top of Bridge Deck Elevation (ft)	4096.0	4114.92	4107.66	4100.13	
Bottom Deck Elevation (ft)	4086.0	4102.75	4098.89	4095.13	
Discharge (cfs)	Freeboard (ft)		Discharge (cfs)	Freeboard (ft)	
1,000	0.3	17.1	4,000	13.5	15.7
2,000	-0.8	16.0	5,000	12.6	14.8
3,000	-1.5	15.3	6,000	11.8	14.1
4,000	-2.2	14.6	7,000	11.1	13.5
5,000	-2.9	13.9	8,000	10.4	12.8
6,000	-3.6	13.3	9,000	9.8	12.2
7,000	-4.2	12.7	10,000	9.2	11.7
8,000	-4.7	12.2	11,000	8.8	11.3
9,000	-5.1	11.7	12,000	8.3	10.9
10,000	-5.5	11.3	13,000	7.8	10.1

The difference in results between the two studies are relatively small, less than 1 ft, except at Keno Dam (Table 3 and Figure 11). It should be noted that the 1975 flood operation study provides little documentation how these values were calculated. The Manning’s n values ranging from 0.025 and 0.035 were applied to the channel in the 1975 flood operation study. However, little data are provided on the calculation methodology, channel geometry and structure representation. Therefore, it is difficult to assess or quantify the accuracy of the previous study. The analysis documented in this report predicts a lower water surface elevation at Keno Dam for Flood 7 (10,000 cfs), but comparable results for Flood 10 (13,300 cfs). The current study consistently predicts a higher water surface elevation at Highway 97 bridge. This could be due to the sedimentation along the 20.2-mile reach or discrepancies calculation methods. Finally, results were comparable at bypass bridge.

Table 4. Water surface elevation comparison between the 1975 Flood Operations study and the results from the current hydraulic modeling effort

	<b>Bypass Bridge</b>	<b>Weed Bridge (Highway 97 Bridge)</b>	<b>Keno Dam</b>
Cross Section Station (ft)	94113	85683	866
Water surface elevation at 10,000 cfs 1975 Flood Operations Plan (ft)	4090.09	4089.09	4081.09
Water surface elevation for Flood 7 (ft)	4090.09	4089.76	4079.29
Difference (ft)	0.00	0.67	-1.80
<hr/>			
Water surface elevation at 13,300 cfs 1975 Flood Operations Plan (ft)	4091.49	4090.34	4080.29
Water surface elevation for Flood 10 (ft)	4091.41	4091.10	4080.37
Difference (ft)	-0.08	0.76	0.08

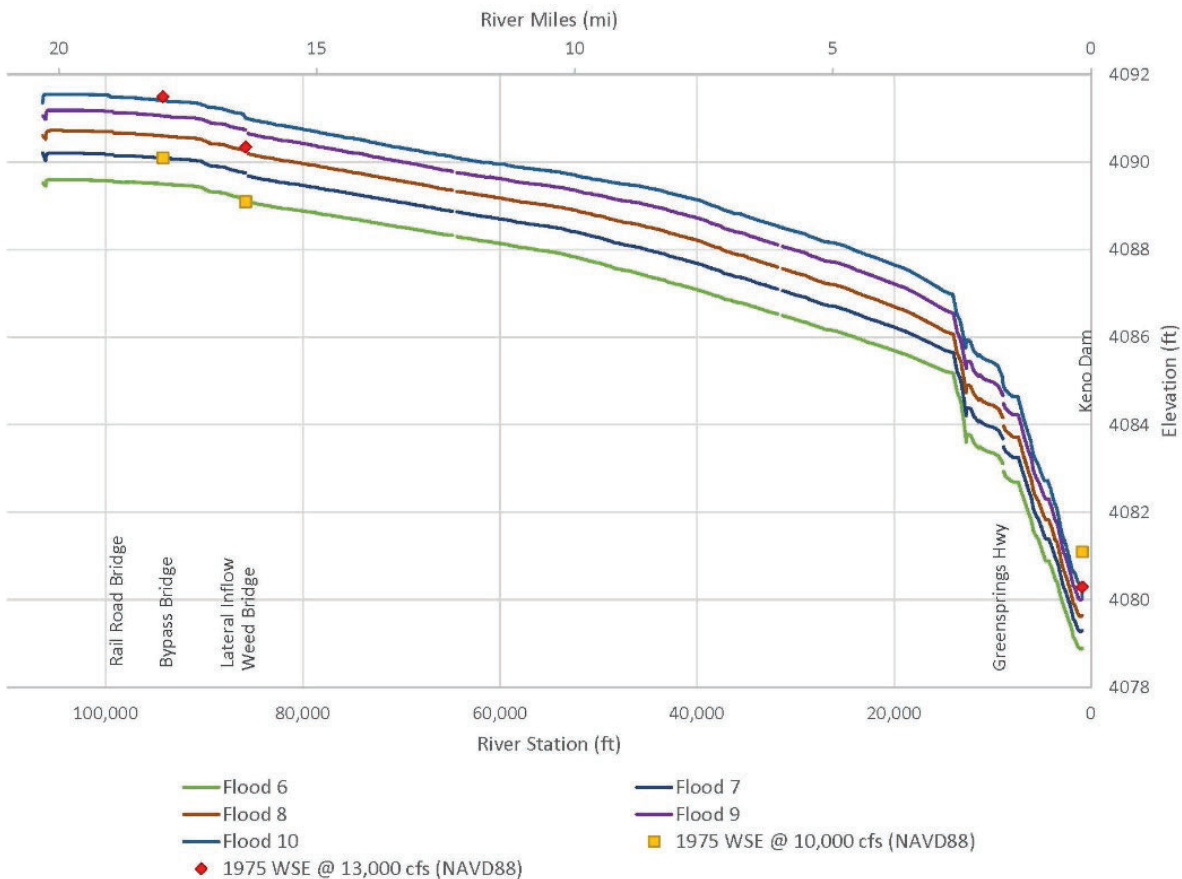


Figure 14. Water surface elevation profiles comparing current model results to the 1975 Flood Operations recommendations. The water surface elevation from Pacific Corps (1975) are in yellow squares for Flood 7 (7,000 cfs into Lake Ewauna and 3,000 cfs from Lost River Diversion Channel) and red diamonds for Flood 10 (10,000 cfs into Lake Ewauna and 3,000 cfs from Lost River Diversion Channel).

## Channel Capacity

Channel capacity was assessed based on flood overtopping and inundation extent. Inundation extent is based on steady state conditions, meaning that the flow, water surface elevation, and all other hydraulic parameters do not change over time. Therefore, this may not accurately represent a storm event, where flow volume quickly increases to a peak and slowly decreases over time. It is a conservative approach that shows the maximum flood inundation extent for a given flow rate. Manual editing of inundation extents of all simulated floods was required to eliminate disconnected wetted areas. There are several disconnected inundated areas surrounding Lake Ewauna that are known to hold water (Figure 12). The property to the west of Lake Ewauna is a fallow agricultural field that has ponded water. It is unofficially serving as additional waterfowl habitat. The property to the east of Lake Ewauna is a remnant wetland that became disconnected from the Klamath River when the railroad was constructed.

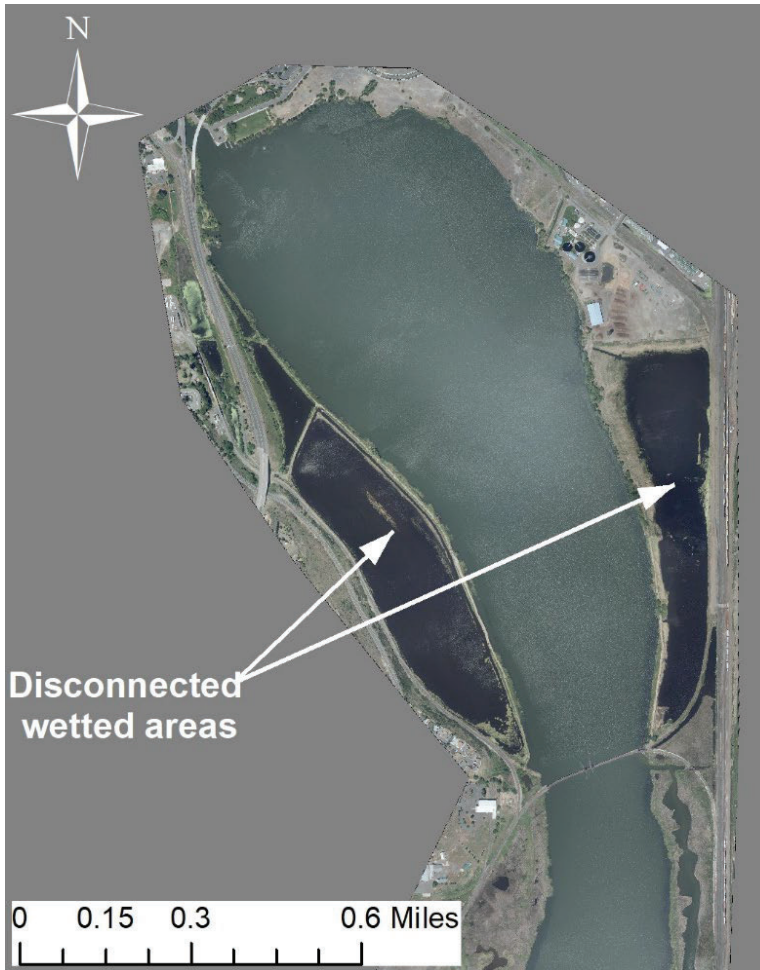


Figure 15. Disconnected wetted areas that were not removed from inundation extents.

Inundation extent maps are presented in Appendix B – Inundation Maps with an overview provided in Figure 13. Results show that overtopping flows begin during Flood 3 in the marshy areas, near RM 9. Some of the marshlands downstream of Lake Ewauna, RM 18.5, begin to inundate during Flood 4. The channel overtops the southern levees downstream of Lost River Diversion Channel (RM 16.5) during Flood 5. During Flood 6, inundation begins in the marshland to the east of the river between RM 11 and 7 and again surrounding RM 17.5, east of the large island. By Flood 8, most of the marshland within the project reach are inundated. Farmland does not begin to inundate until Flood 9. Once the levees overtop, most of the farmland becomes inundated; thus the largest change in inundation area occurs between Floods 8 and 9 (Figure 14). The inundation area differences between Flood 9 and 10 are minor. Despite the wide-spread inundation of Flood 10, no urban or industrial areas become flooded.

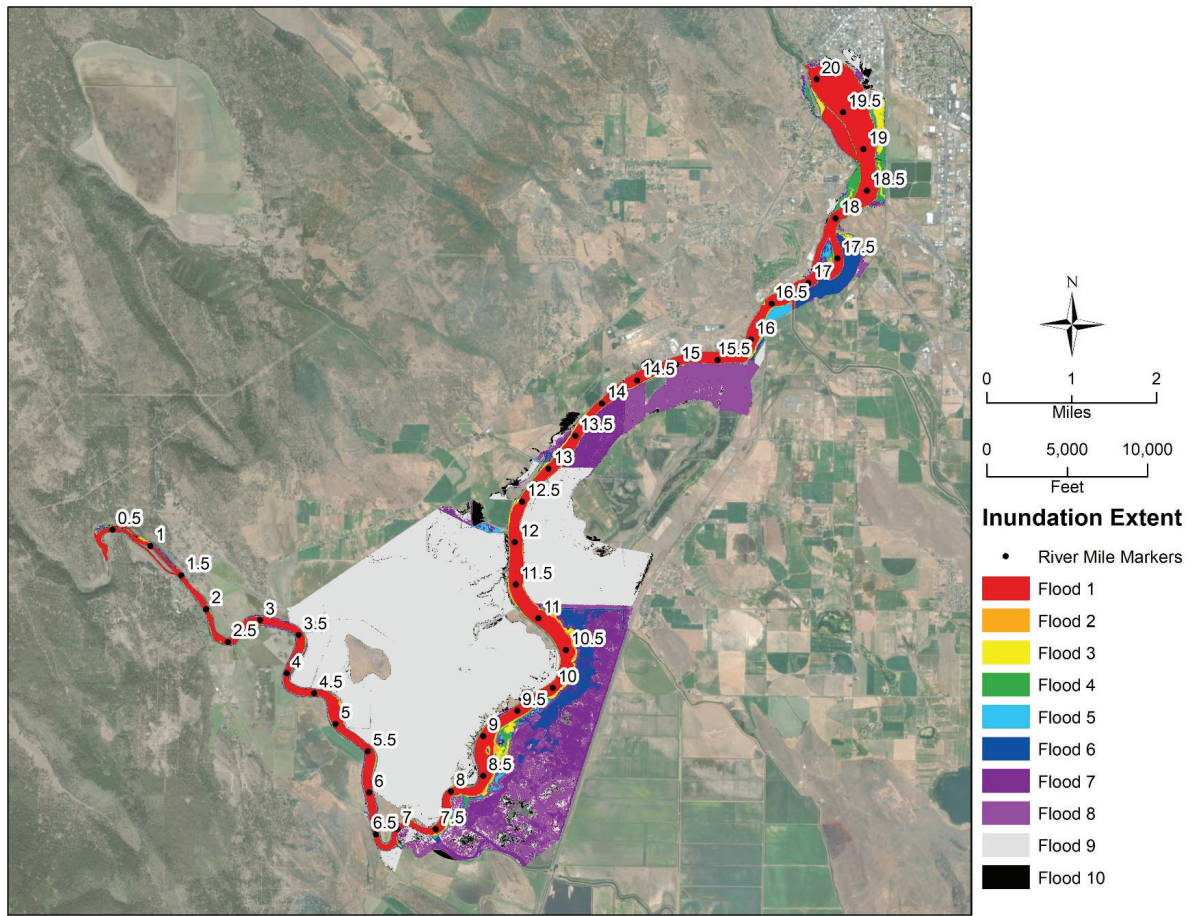


Figure 16. Overview map showing inundation extent for the modeled reach.

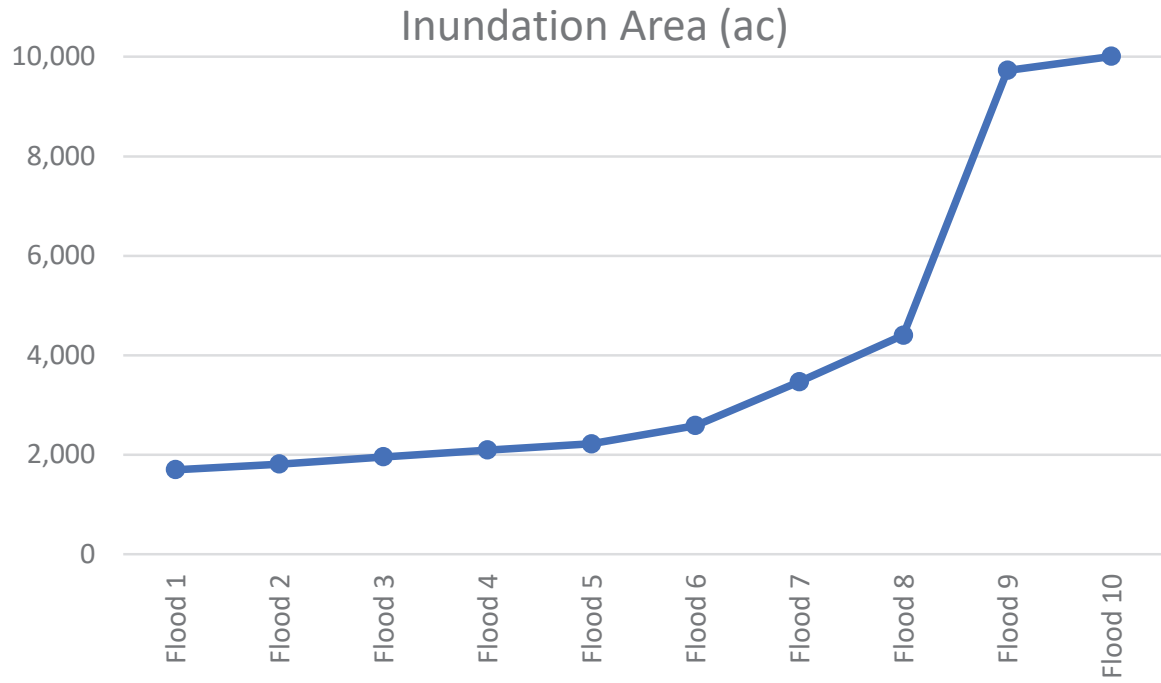


Figure 17. Inundation area for modeled floods in acres (ac).

## Model Sensitivity & Limitations

There is uncertainty associated with any numerical model as the physical processes are not completely represented by the utilized governing equations and model assumptions. A roughness sensitivity analysis was conducted to constrain the uncertainty associated with deviation in the modeled Manning's  $n$  value.

### Limitations

The HEC-RAS 1D and 2D model provided water surface elevations which indicate channel capacity and inundation extent of various floods. The model results are subject to the following limitations:

1. A single, spatially average Manning's  $n$  value was assigned for each material type (floodplain and channel). Material roughness is not uniform through any mapped material and will likely vary between seasons, especially in agricultural areas.
2. As no calibration data were available the roughness values were based on literature (Chow, 1959). A sensitivity analysis was conducted to understand the variability associated with these assumptions.
3. Flood inundation extent assumes steady state conditions, meaning an infinite duration of the high flow event. This may be an overly conservative estimate, assuming that the flood duration is long enough to fill all accessible areas. A flood event will be a hydrograph of finite duration, beginning at base flow and increasing to a peak flood flow. The peak flow will have a short duration and decrease as flood water recede. The inundation extent will be dependent on the duration of the peak and the rate of flow decrease on the falling limb of the hydrograph.
4. Flood inundation extent is based only on Klamath River channel capacity. Several canals pull water off the river throughout this reach. Canal capacity and overtopping flows through these canals was not included in this assessment. Therefore, additional areas could inundate during flood events if canal levees have failed.

### Roughness Sensitivity Analysis

Roughness sensitivity was tested throughout the model reach by decreasing the roughness values by 0.01 in the river and floodplains. This value was a conservative estimate based on values widely reported in literature (Chow, 1959).

A higher roughness will result in a higher water surface elevation, especially at high flows (Figure 13). The sensitivity analysis clearly shows that the reach is controlled by Snow Goose Reef, located at RM 2.5. The maximum difference in water surface elevation during Flood 7 is 1.77 feet, showing that Manning’s roughness has a measurable impact on the water surface elevation of the flood. During the Flood 10 simulation, the modeled roughness creates a high enough water surface elevation for flood waters to spill out of the main channel into the farmland on the right overbank between RM 12.3 and 2.9. However, at a lower Manning’s  $n$  value of 0.025, water remains in the main channel for Flood 10 instead of inundating the right overbank. Therefore, the change in water surface elevation due to lowering Manning’s roughness has a large impact with the largest change being a decrease in water surface elevation of 1.67 ft within Lake Ewauna.

Based on the results of the sensitivity analysis, we can assume that a change in model roughness of 0.01 will impact the discharge at which farmland becomes inundated. However, we recommend using the results at a Manning’s roughness of 0.035 for operational releases. Collection of water surface elevation data during high flows will improve the model accuracy.

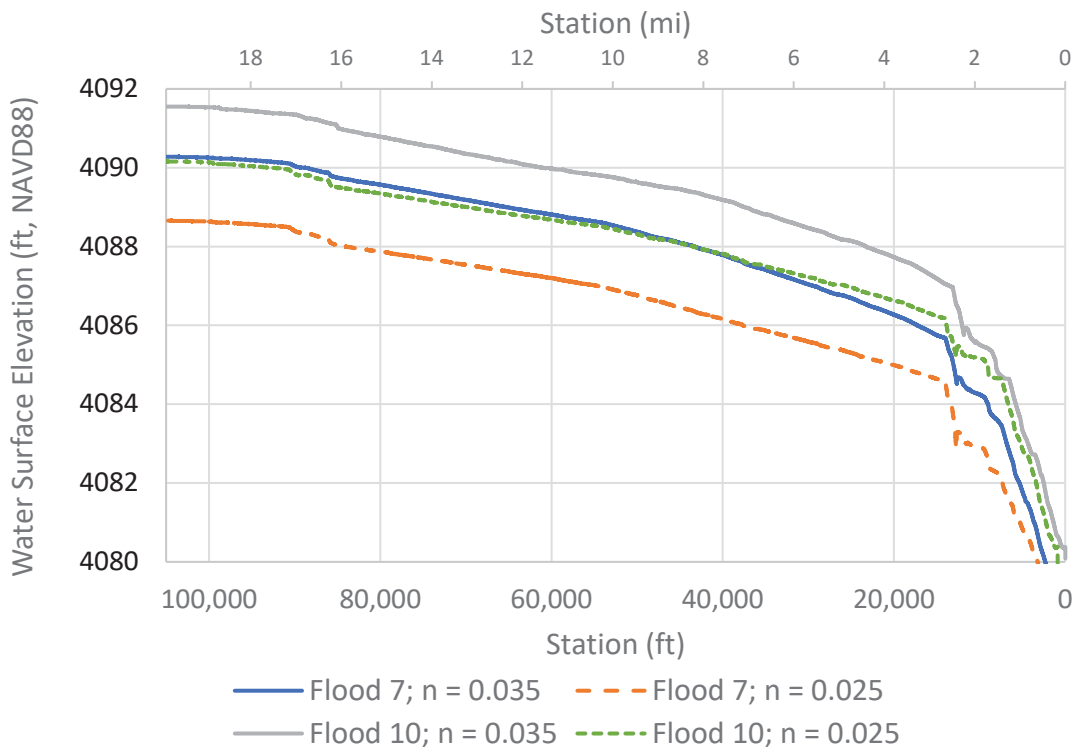


Figure 18. Differences in water surface elevations along the longitudinal profile of the study reach. The low  $n$  values ( $n = 0.025$ ) are represented by dotted and dashed lines, while the modeled  $n$  (0.035) values are represented by solid lines.

## Conclusions & Future Work

As part of a comprehensive flood control plan update for the Klamath Project, KBAO has requested TSC's technical assistance in updating the flood control plan of the Klamath River from Lake Ewauna to Keno Dam. The purpose of this study is to: 1) conduct a bathymetric survey of the study reach and 2) determine a relationship between flow and water surface elevation for the study reach.

A complete bathymetric survey was conducted in October of 2019 of the 20.2-mile study reach. These data were merged with two LiDAR datasets to create a comprehensive surface for hydraulic analysis via numerical modeling in HEC-RAS. The results from the HEC-RAS model were analyzed to develop a relationship between flow and water surface elevation to inform channel capacity.

The water surface elevation results compared well to the 1975 Flood Operations Plan. The flood stages in the 1975 Plan were reported at three structures for Flood 7 and Flood 10 (Bypass Bridge, Weed Bridge, and Keno Dam). The largest difference in water surface elevations was 1.8 feet at Keno Dam for Flood 7. The difference in water surface elevation at all other locations and floods was less than 1 foot.

The water surface elevation profile indicated that a bedrock outcrop at RM 2.5, also known as Snow Goose Reef, serves as the hydraulic control for the entire upstream reach. This means that the reef elevation determines the water surface elevation between RM 20.2 and 2.5. Lowering the top elevation of the reef would decrease the water surface elevation upstream for all modeled floods. This could be beneficial as flood waters could potentially impact the Railroad Bridge at RM 18.8. As no drawings were available, Railroad Bridge measurements were based on photographs and assumptions. TSC recommends surveying this bridge to confirm that it floods during storm events. All other bridges had a freeboard >7.8 feet for Flood 10 scenario.

Finally, channel capacity was assessed based on flood overtopping and inundation extent. Results indicate that overtopping occurs within the surrounding marshlands during Flood 3 and all marshlands are inundated by Flood 8. Farmland does not begin to inundate until Flood 9; however, that results may vary based on assumed channel and overbank roughness. No urban or industrial areas become inundated in any of the modeled flood events.

## Future Work

To better understand flood impacts within the model reach, the SRH team will need the products of concurrent studies. Once those products are available, the SRH team recommends the following:

- 1) Collect water surface elevations during a high flow event,
- 2) Model a storm hydrograph,
- 3) Complete a levee survey, and
- 4) Survey Railroad Bridge.

Modeling a representative storm hydrograph or series of hydrographs would establish a better understanding of flood performance within the study reach. The current study assumes steady state conditions, which determines the inundation extent for an indefinite flood. The model run time was comparatively very long to allow for the surrounding floodplain to inundate. This means that the reported results represent the maximum expected inundation extent. Modeling a representative storm hydrograph would give a better understanding of the inundation extent, flood routing, and maximum water surface elevation of flood events.

A levee survey would inform KBAO of any low points within the approximate 40.4 miles of levees surrounding the project reach. The current model assumes that the cross sections represent the lowest points in the levee. In other words, all levees surrounding the modeled cross sections are assumed to be higher. If there is an undocumented low point within the levee, flood waters will breach the levee, resulting in unexpected inundated area. The levee survey would better constrain the flood inundation extent and the expected water surface elevation for flood scenarios.

Finally, drawings were available for all modeled bridges except the Railroad Bridge at RM 18.8. This is the only bridge that is assumed to be impacted by flood events in the project reach. Surveying the bottom deck elevation, pier locations, pier widths, and cross beam dimensions would allow better representation of this structure in the numerical model. Better representation would lead to a better understanding of how this bridge is impacted by flood flows.

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## **Appendix A – Hydrographic Survey Equipment and Methods**

The bathymetric survey was conducted from 10/24/2019 to 10/29/2019. During this period, daily river water surface elevations were measured USGS gage on Link River at Klamath Falls (11507500). Two Pacific Corps gages are located at the Highway (Hwy) 97 bridge and Keno Dam. These two locations are approximately 16 river miles apart and daily water surface elevation differed by < 0.1 feet. Therefore, we can assume one value represents the water surface elevation throughout the river reach. The water surface elevation ranged from 4085.4 ft to 4085.8 ft (NAVD88) with an average of 4085.6 ft.

The survey was conducted along a series of cross section, longitudinal, and shore line survey lines (Figure 8). The survey lines were spaced close enough for adequate interpolation between multi-beam depth data.

The survey employed an 18-foot, flat-bottom aluminum Wooldridge boat powered by outboard jet and kicker motors (Figure 15). Reservoir depths were measured using multibeam echo sounder which consisted of the following equipment:

- variable-frequency transducer with integrated motion reference unit,
- near-surface sound velocity probe,
- two GPS receivers to monitor the boat position and heading,
- an external GPS radio, and
- processor box for synchronization of all depth, sound velocity, position, heading, and motion sensor data.



Figure 19. Wooldridge boat with RTK-GPS and multibeam depth sounder system.

The multibeam transducer emits up to 512 beams (user selectable) capable of projecting a swath width up to 120 degrees in 100 feet (30 meters) of water. Sound velocity profiles were collected over the full water depth at various locations throughout the reservoir. These sound velocity profiles measure the speed of sound through the water column, which can be affected by multiple characteristics such as water temperature and salinity. These sound velocity profiles were used to correct the depth measurements.

RTK GPS survey instruments were used to continuously monitor the survey boat position and measure other ground control points. The GPS base station and receiver was set up on a tripod over a point overlooking the reservoir (Figure 8). The coordinates of this point were computed using the Online Positioning User Service (OPUS) developed by the National Geodetic Survey (NGS) ([www.ngs.noaa.gov/OPUS/](http://www.ngs.noaa.gov/OPUS/)). During the survey, position corrections were transmitted to the GPS rover receivers using an external GPS radio and UHF antenna (Figure 16). The base station was powered by a 12-volt battery.

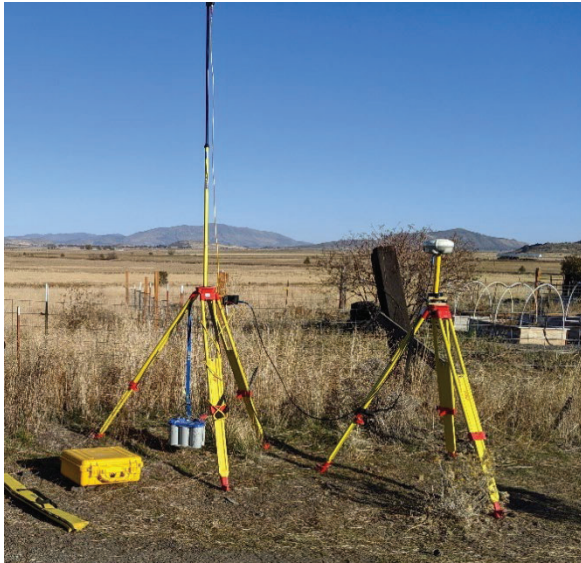


Figure 20. The RTK-GPS base station set-up used during the Klamath River Survey in Oregon is typical of the set up used for other bathymetric surveys.

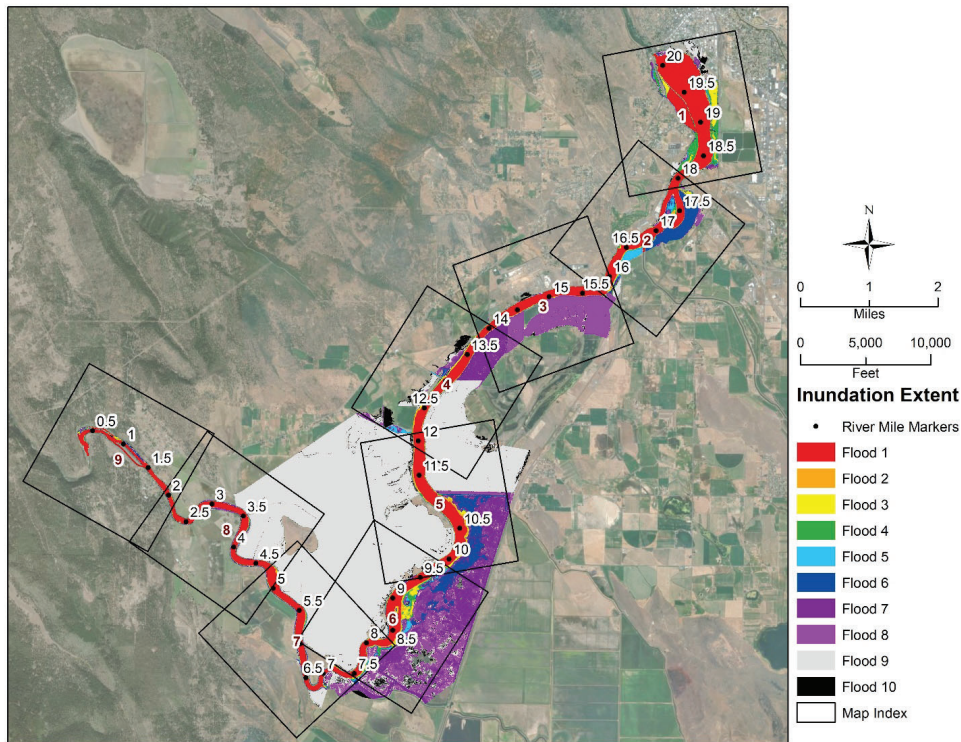
The GPS rover receivers include an internal radio and external antenna mounted on a range pole (ground survey) or survey vessel (bathymetric survey). The rover GPS units receive the same satellite positioning data as the base station receiver, and at the same time. The rover units also receive real-time position correction information from the base station via radio transmission. This allows rover GPS units to measure accurate positions with precisions of  $\pm 2$  cm horizontally and  $\pm 3$  cm vertically for stationary points and within  $\pm 20$  cm for the moving survey boat.

During the bathymetric survey, a laptop computer was connected to the GPS rover receivers and echo sounder system. Corrected positions from one GPS rover receiver and measured depths from the multibeam transducer were transmitted to the laptop computer through cable connections to the processor box. Using real-time GPS coordinates, the HYPACK software provided navigational guidance to the boat operator to steer along the predetermined survey lines.

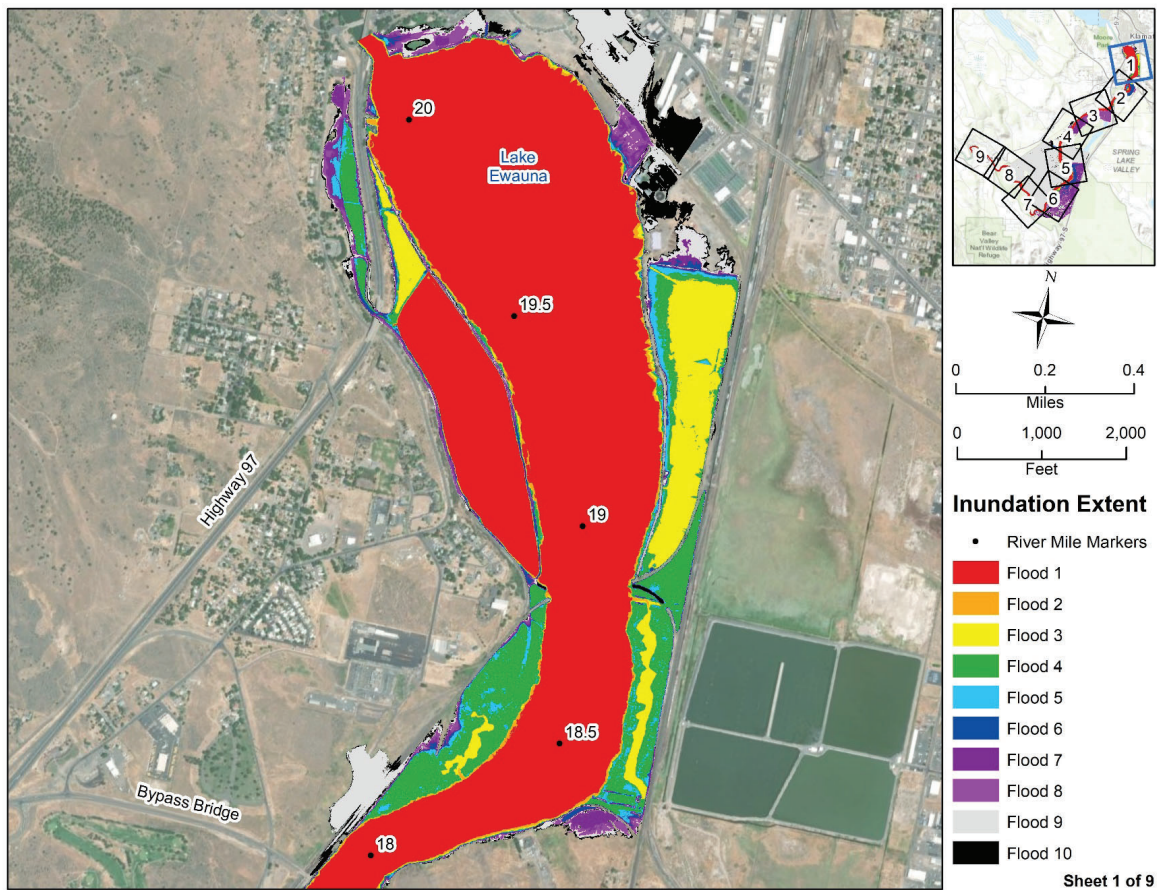
The HYPACK hydrographic survey software was used to combine horizontal positions and depths to map the reservoir bathymetry in the user selected coordinate system, NAD 1983 State Plane, Oregon South. Water surface elevations from dam gage records and RTK GPS measurements were used to convert the sonar depth measurements to reservoir-bottom elevations in the NAVD88. The multibeam depth sounder generates millions of data points. Sometimes fish, underwater vegetation, or anomalies mean that a small portion of depth measurements do not represent the reservoir bottom and these data are deleted during the post processing. Final processing of the bathymetric data resulted in 2.5 million data points used in the development of the reservoir surface. Filtering of this large data file is necessary, so a raster is created in GIS (e.g. 1-foot square cells). For each raster cell, the reservoir bottom elevation is assigned equal to the median elevation of all available data points within that raster cell. The use of the median value reduces the influence of the highest and lowest elevations within the cell.



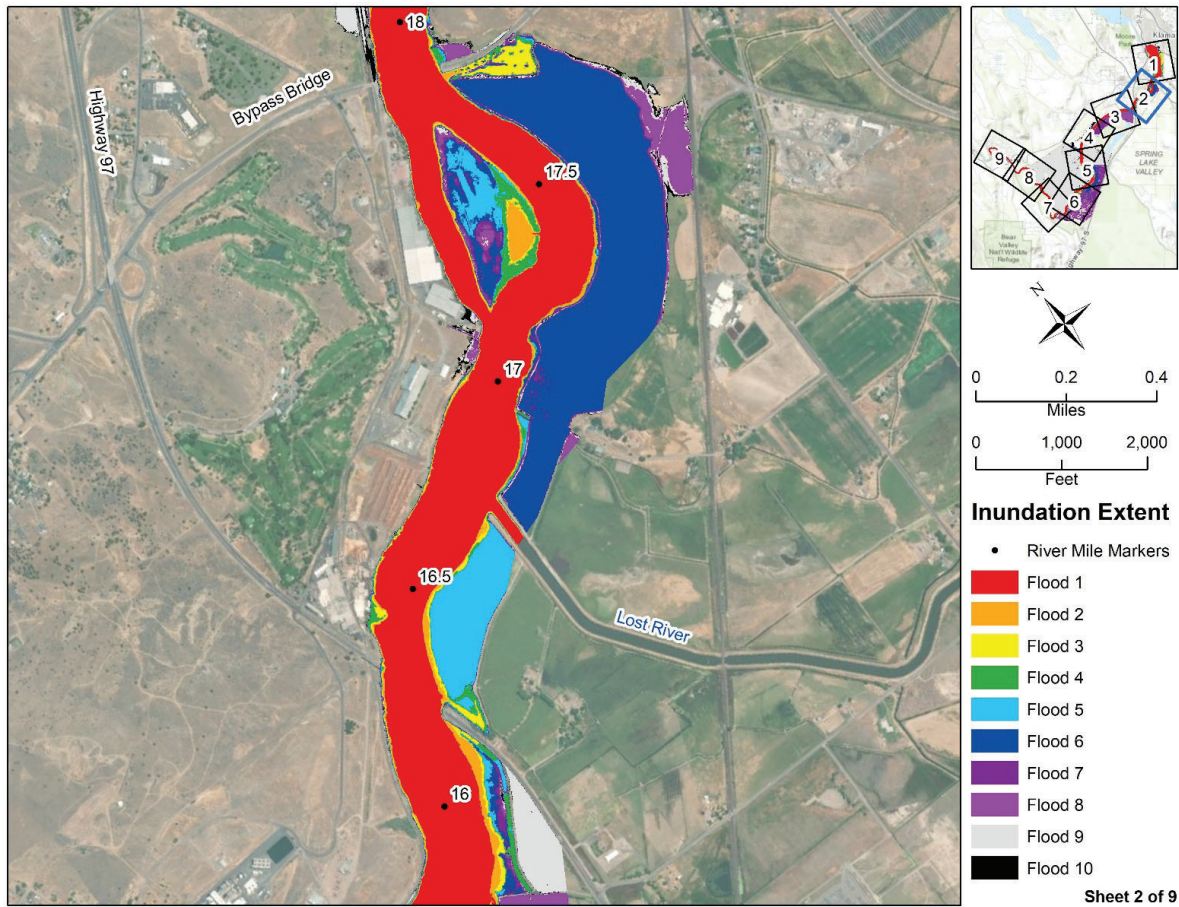
## Appendix B – Inundation Maps



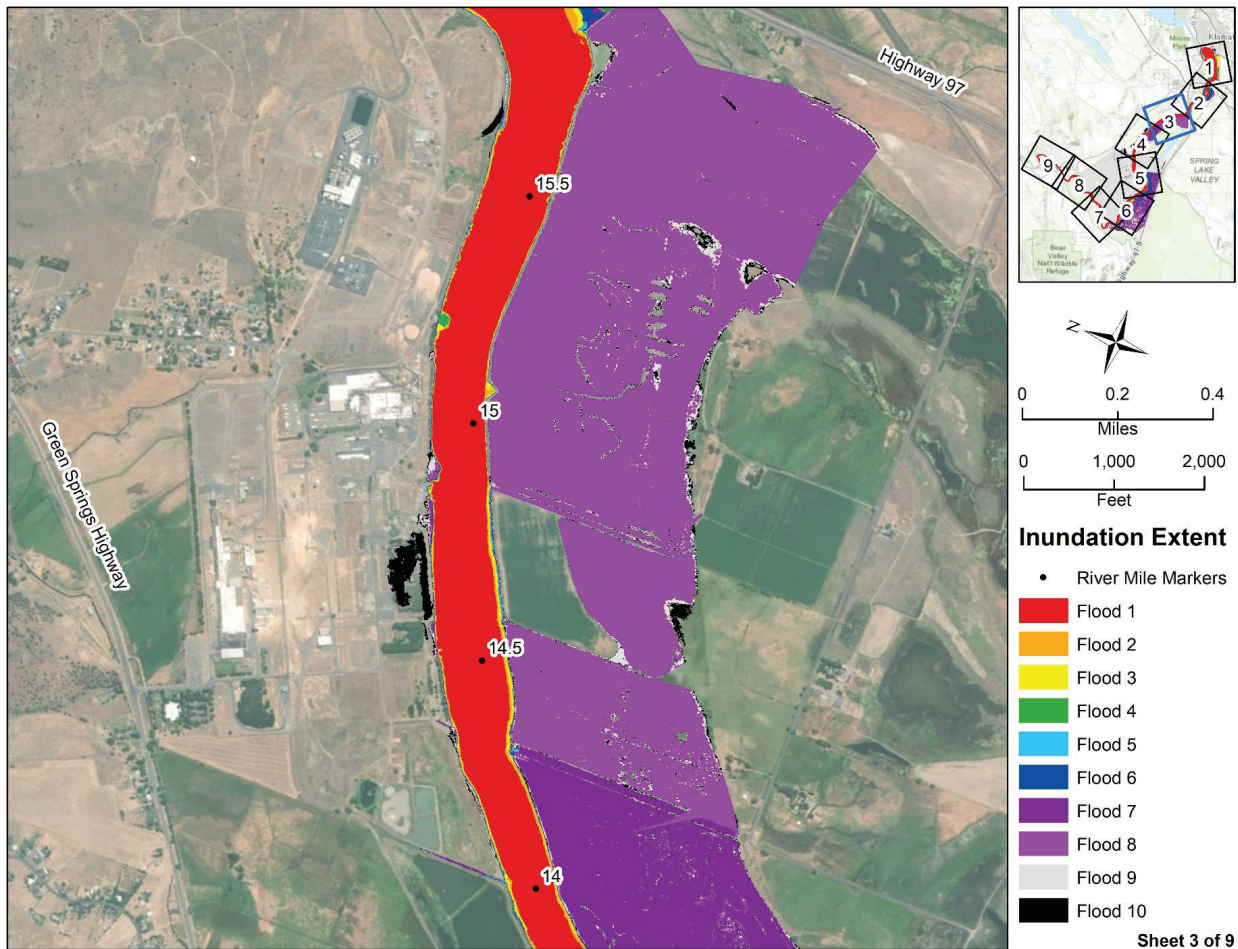
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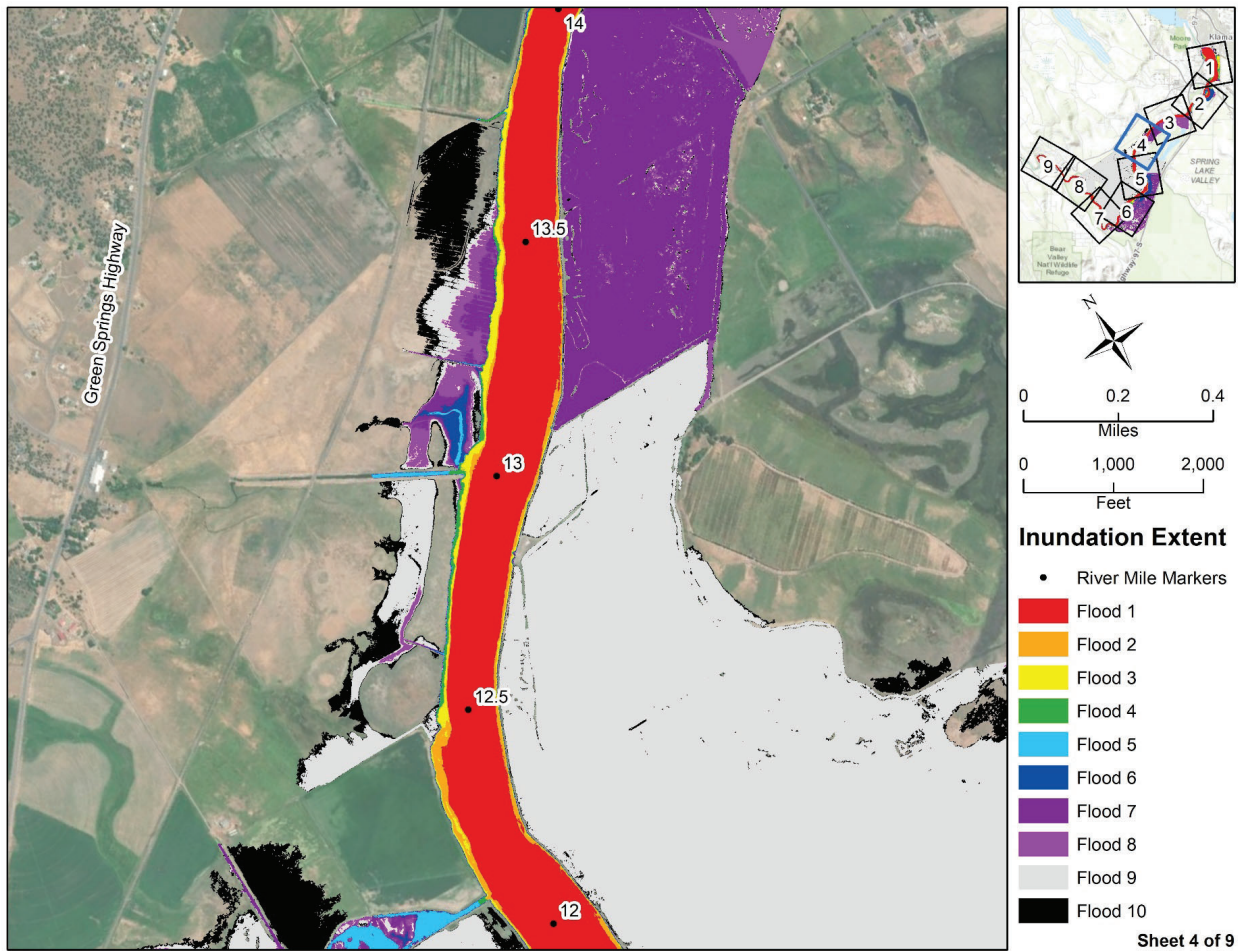
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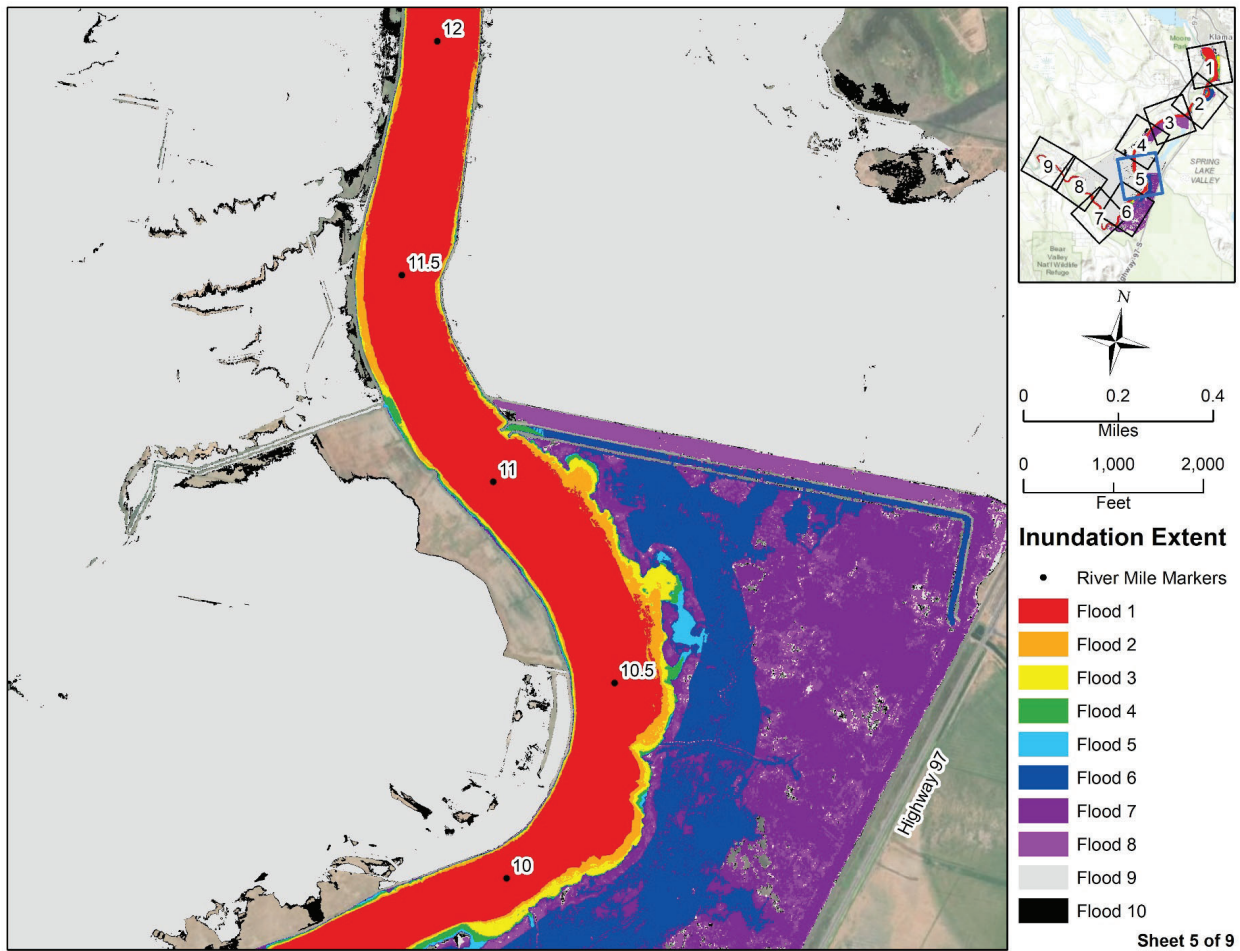
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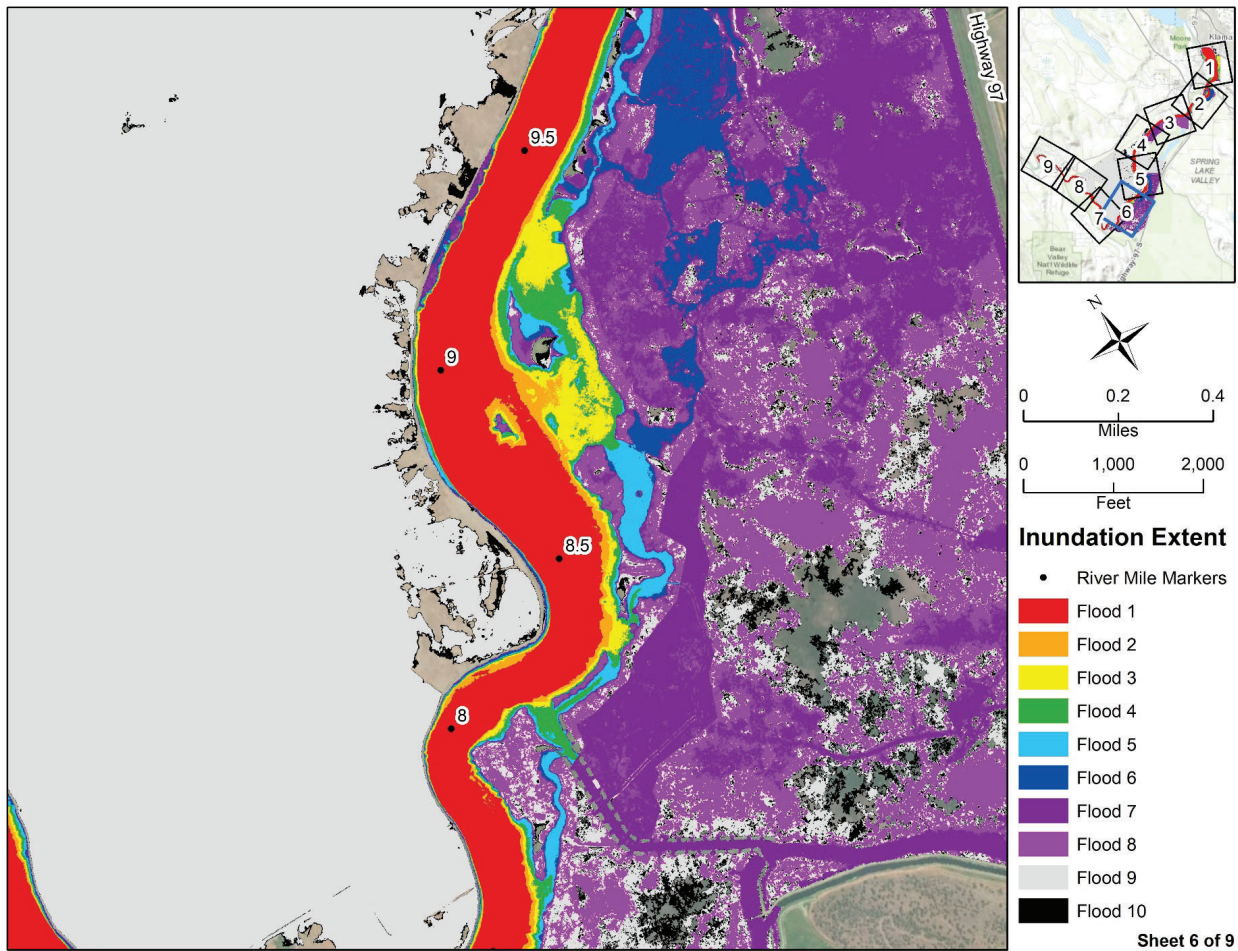
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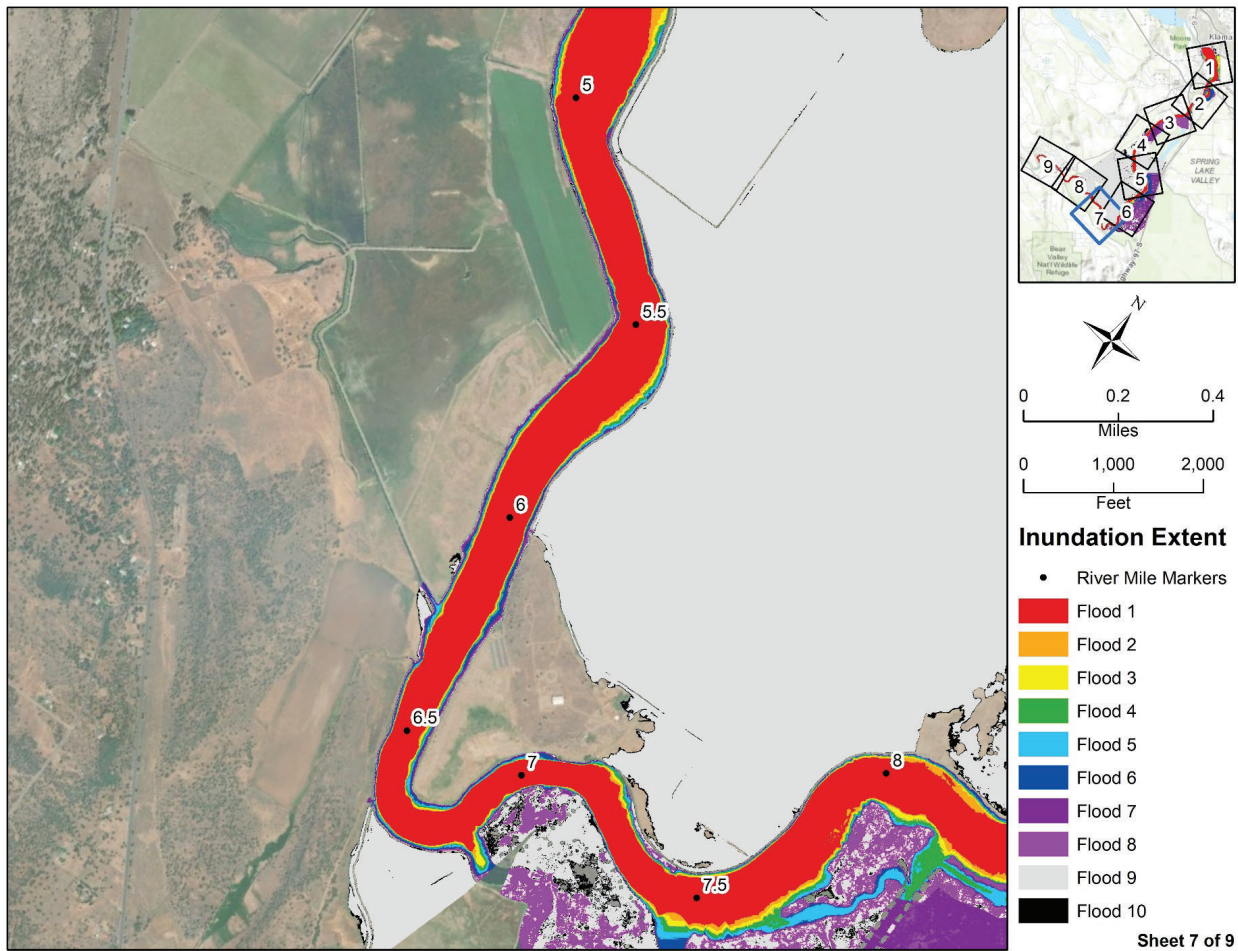
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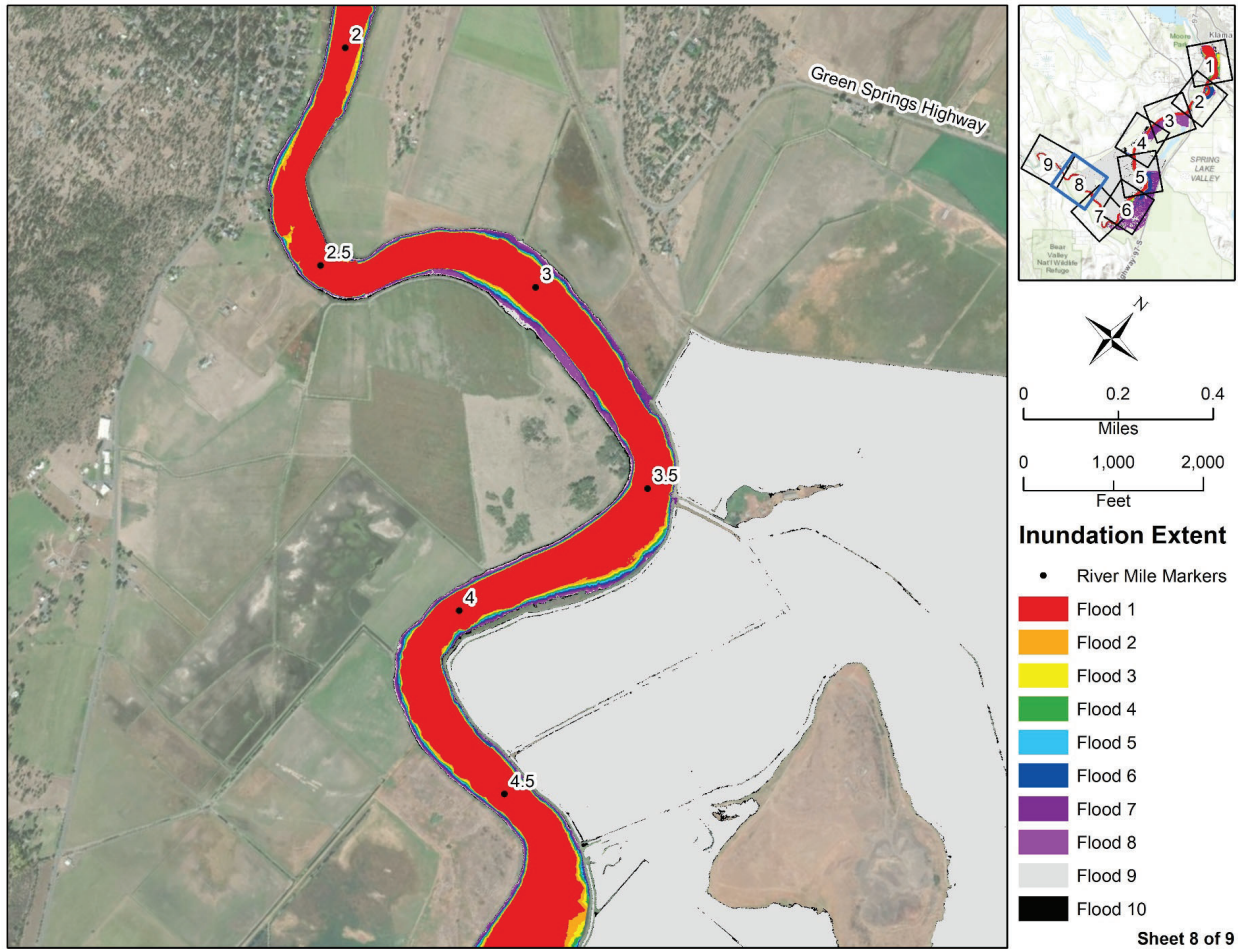
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