Hydraulic Analysis and Floodplain Mapping Report

Bitterroot River Floodplain Study
Missoula County, MT

May 2021

Contract Number: WO-MM-200
Mapping Activity Statement No. 2019-02

Bitterroot River, Floodplain Study

Hydraulic Analysis and Floodplain Mapping Report

Missoula County, Montana

PREPARED FOR:

Montana Department of Natural Resources and Conservation

Federal Emergency Management Agency

May 28, 2021

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I hereby certify that all work products (maps, reports, etc.) prepared for this project were done so under my direct supervision and that I am a duly Licensed Professional Engineer under the laws of the State of Montana.

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PE
Stamp

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1.0 Introduction and Background

Morrison-Maierle completed the hydraulic analysis for the Bitterroot River within Missoula County, Montana, as part of the Mapping Activity Statement (MAS) 2019-02, Missoula-Granite Physical Map Revision (PMR) (FEMA 2019). This Flood Risk Project was initiated by the Montana Department of Natural Resources and Conservation (DNRC) in partnership with the Federal Emergency Management Agency (FEMA), Missoula County and other stakeholders. The purpose of this report is to document the hydraulic analysis and preliminary floodplain mapping to provide results for incorporation into revised Flood Insurance Rate Map (FIRM) panels and a new Flood Insurance Study (FIS).

The study limits, per the MAS scope of work, consists of Bitterroot River within Missoula County with a total length of approximately 21.6 miles. The analysis approach is an Enhanced with Floodway flood study. The study approach included 1D hydraulic modeling informed by 2D hydraulic modeling of the floodplain reach. The 2D modeling was completed in a single model file. The 1D modeling was prepared in two model files to improve model run times and floodplain mapping products development. The Bitterroot River study reach of the Missoula-Granite PMR project documented in this report is summarized in Table 1 and shown on Figure 1. Both reaches were evaluated as Enhanced Level Option E models with Zone AE delineations with a floodway. The Bitterroot River is modeled from the confluence with the Clark Fork River west of Missoula, Montana upstream to the Missoula County boundary. A split flow reach along the Left Branch of Bitterroot River side of the Bitterroot Valley was included in the model to route flood flow which leaves the eastern side of the valley in Ravalli County upstream of the county boundary and flows along the eastern flow path for approximately 3.8 miles prior to rejoining the primary Bitterroot River floodplain. Approximately 2.8 miles of the Left Branch of Bitterroot River path are within Missoula County.

Table 1. Bitterroot River Model Segments

Reach	Stream	Analysis Approach	Length (miles)
1	Bitterroot River	Enhanced Level Option E	11.9
2	Bitterroot River	Enhanced Level Option E	9.7
		Total	21.6

This Summary Report presents the information and methods used to develop the one-percent annual chance (100-year) and 0.2-percent annual chance (500-year) floodplains and a floodway. This study is based on the best, currently available information including LiDAR topography, structure surveys, and a new hydrologic analysis developed specifically for this mapping update. The LiDAR was provided by Quantum Spatial Inc. in 2019 (QSI 2019). Hydrologic analysis for Missoula County Map Modernization Project was completed by the Pioneer Technical Services, Inc. in July 2020 (Pioneer 2020a) and was approved by FEMA in 2020. Hydraulic structure survey was completed by Pioneer in May of 2020 (Pioneer 2020b) and was accepted by FEMA in 2020. Bathymetric survey was completed by DOWL in October 2019 and was accepted by FEMA in 2019.

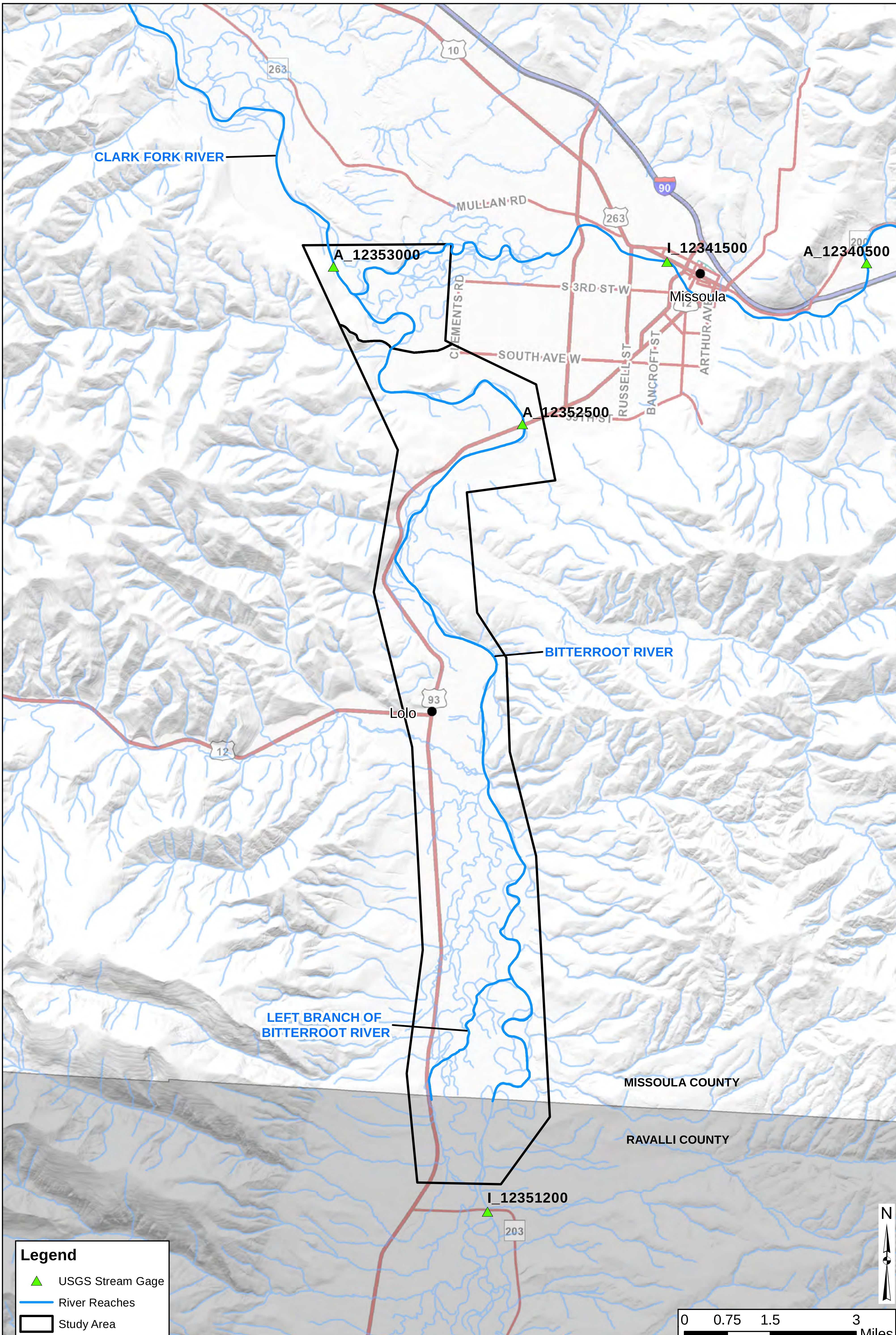
The hydraulic analysis for the Bitterroot River study reaches include the 10%, 4%, 2%, 1%, 0.2%, and 1% plus annual-chance (AC) flood events. The 1% plus event is defined as a flood event using flood flow rates that include the average predictive error for the discharge calculation for the floodplain study. This flow rate is calculated to provide a confidence range within which the actual 1% annual-chance discharge is likely to fall, given the uncertainty that often exists with estimating discharges (FEMA 2016b). The DNRC and the professional service contractor Morrison-Maierle have completed this study using guidelines and standards published in the FEMA Resource and Document Library to ensure the study complies with the requirements of the National Flood Insurance Program.

1.1 Bitterroot River Basin Description

The Bitterroot River watershed is west of the Rocky Mountain continental divide in western Montana. The Bitterroot River is a major tributary to the Clark Fork River in the upper Columbia River basin. Tributaries to the Bitterroot River originate in the Bitterroot and Lolo National Forests and in the Anaconda-Pintler Wilderness. The watershed is bounded on the east and south by the Sapphire Mountain Range and by the Bitterroot Mountain Range to the west. The main stem of the Bitterroot River is formed by the confluence of the East Fork and West Fork Bitterroot Rivers near Darby, Montana. The Bitterroot River flows north for approximately 84 miles before its confluence with the Clark Fork River below Missoula, Montana. The Bitterroot River watershed encompasses approximately 2,859 square miles (Pioneer 2020a). The terrain varies from a high alpine environment in its headwaters to a broad inter-mountain valley in Missoula County.

The hydrology of the watershed is primarily snowmelt driven, although spring and early summer rainfall runoff also contributes to flood risks. The upper portion of the watershed includes mountain peaks over 10,000 feet in elevation. Valley floor elevations for the Missoula County study reach range from 3,190 feet at the southern county boundary to 3,100 feet at the confluence with the Clark Fork River. The mean slope of the Bitterroot River in the study reach is 4.16 feet per mile, which is relatively flat for western Montana rivers and streams.

Land use in the study reach varies from forests in the mountainous areas of the upper basin to extensive agricultural use in the Bitterroot River valley from Conner to Missoula. The upper portions of the watershed are largely rural with small communities along tributaries to the Bitterroot River. The Bitterroot River valley below Darby is, for Montana, moderately settled. Notable communities in the Bitterroot River valley include Hamilton, Stevensville, Florence, Lolo, and the City of Missoula at the confluence with the Clark Fork River. Of the communities noted, Lolo and Missoula are within the Missoula County study reach. Highway 93 (US 93) runs north along the Bitterroot River valley. The Bitterroot River mainstem study reach and the Left Branch of Bitterroot River are shown on Figure 1.



Morrison Maierle engineers · surveyors · planners · scientists 1 Engineering Place Helena, MT 59602 Phone: (406) 442-3050 Fax: (406) 442-7862 COPYRIGHT © MORRISON-MAIERLE, INC., 2020	DRAWN BY: BNC CHK'D BY: LDC APPR. BY: LDC DATE: 3/26/2021	Bitterroot River Study Area Missoula-Granite PMR Bitterroot River Floodplain Study	PROJECT NO. 1447.054 Figure 1

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2.0 Previous Mapping

Flood Insurance Rate Maps (FIRM's) were completed for the Bitterroot River in Missoula County, MT in 1983. The FIRM panels were updated in 1988 and again in 2015. The 2015 FIRM update included the conversion to digital data, revision of elevations to the NAVD88 vertical datum, and mapping revisions based on topographic data at a two feet contour interval resolution. The flood hazard currently mapped for Bitterroot River is Zone AE with a floodway for the entire Missoula County reach. A Floodplain Insurance Study (FIS) accompanied the FIRM panels published in 1983. This Floodplain Study will be a component of the Missoula County FIS report updates for both the Bitterroot River and other streams in Missoula County as part of the larger county-wide floodplain study update project.

The existing Zone AE flood maps were developed with coarser topographic data for both hydraulic modeling and flood map delineation. This floodplain study will improve flood risk estimates and communication by incorporating better topographic data quality and by updating the flood risk analysis to capture current stream alignment and land use within the floodplain.

3.0 Hydrology

The study included a comprehensive peak flood flow analysis for the Bitterroot River as shown on Figure 1. The Bitterroot River study includes a 21.6-mile reach of the mainstem river, and several miles of flood flow split from the mainstem below the southern Missoula County border. In total, 2,859 square miles of the drainage area contribute to the Bitterroot River in Missoula County. As part of the Missoula-Granite PMR project, the Montana Department of Natural Resources and Conservation (DNRC) contracted Pioneer Technical Services to complete a comprehensive peak flow hydrologic analysis, including flood flow frequency calculations for all ungaged flow node locations (Pioneer 2020a).

3.1 Bitterroot River

The Bitterroot River watershed lies within the Bitterroot Mountains and the Sapphire Mountains. Within the study reach, 4 locations were identified as having significant changes in streamflow or being at a critical location in the Pioneer Technical Services Hydrology Report. Of the 4 flow nodes, 1 is located at an active United States Geological Survey (USGS) stream gage site and 3 ungaged flow nodes are located at Hydrology Unit Code 12-digit (HUC 12) watershed boundaries along the mainstem of the Bitterroot River (Pioneer 2020a).

3.1.1 Bitterroot River Gage Analysis

At the gaged site, all peak flow discharges were derived from gage data using Bulletin 17C methodologies. Peak flow discharge estimates at the Bitterroot River gages were conducted using the systematic gage data peak flow flood frequency analysis by the USGS. To address non-congruent periods of records between the gages, the USGS performed a MOVE.3 analysis, which extended the records of the gages. The extended record values were used in this analysis. Two active USGS gaging stations are located in the area of the Bitterroot River mainstream and the summary data for these gages are listed in Table 2. The gage near Florence is upstream of the Missoula County boundary, outside the study area.

Table 2. Bitterroot River Mainstem USGS Gaging Station

USGS Station Number	Station Name	Regulation Status as of 2018	Period of Record	Number of Record Peaks	Drainage Area (square miles)
12352500	Bitterroot River near Missoula, MT	U	1899-1901, 1903-1904, 1990-2018	2	2,814
12351200	Bitterroot River near Florence, MT	U	1958-1965, 1972, 1974, 1982, 2003-2011	2	2,354

U: Unregulated stream.

3.1.2 Bitterroot River USGS Gage Station Regression Equations Analysis

The USGS performed a gage analysis and a weighted with Regional Regression Equations analysis for the Bitterroot River Gaging Station (Pioneer 2020a). Results of the Annual Equivalent Peak (AEP) discharges for systematic and weighted flood frequency estimates with regional regression equations for the gage located on the Bitterroot River Mainstem are presented in Table 3.

Table 3. Bitterroot River Mainstem USGS Gage Flood Frequency Estimates

USGS Gage Station Number	Station Name	Peak Flood Frequency Method	AEP Peak Discharge (cfs) for indicated exceedance probability (%)					
			50	10	4	2	1	0.2
			Peak Discharge (cfs), for indicated return interval (years)					
			2	10	25	50	100	500
12351200	Bitterroot River near Florence, MT	At-Site	15,100	20,900	23,600	25,600	27,500	31,800
		MOVE.3	14,100	20,100	23,000	25,100	27,200	32,000
12352500	Bitterroot River near Missoula, MT	At-Site	14,400	23,100	27,200	30,100	32,900	39,200
		MOVE.3	14,700	22,700	26,400	28,900	31,400	36,900

MOVE.3: Regional Regression Weighted and Maintenance of Variance Extension, Type III

3.1.3 USGS Gage 1%+ Peak Flow Analysis

The 1%+ AEP event was calculated by USGS in accordance with FEMA guidance (FEMA, 2019) to provide a confidence range that the 1% flood frequency peak flow estimates are likely to fall within (Pioneer 2020a). The upper 84% confidence limit calculated in the gage analysis was used by USGS to determine the 1%+ flood frequency peak flow estimates (FEMA, 2016b). The Bitterroot River Mainstem 1%+ flood frequency peak flow estimates for the gages located on the Bitterroot River Mainstem are listed in Table 4.

Table 4. Bitterroot River Mainstem USGS Gage 1%+ Peak Flow Analysis

USGS Gage Station Number	Station Name	Drainage Area (sq. mi)	1% + AEP Peak discharge, At-Site (cfs)	1% + AEP Peak discharge, MOVE.3 (cfs)
12352500	Bitterroot River near Missoula, MT	2,814	38,400	36,600
12351200	Bitterroot River near Florence, MT	2,354	32,300	32,400

MOVE.3: Regional Regression Weighted and Maintenance of Variance Extension, Type III

3.1.4 Bitterroot River Mainstem Flow Nodes

For Bitterroot River Mainstem, hydraulic models were developed using geometric and streamflow data prepared by Pioneer Technical Services. A review of the study area was performed to identify potential flow change locations and at each flow node, a drainage basin area was delineated. A total of four flow nodes were identified including 1 gaged location and 3 ungaged locations.

Using ArcGIS, Bitterroot flow nodes were located just upstream of each tributary confluence with Bitterroot River. The ungaged flow nodes were assigned the nearest GNIS hydrographic feature name and the gaged flow node was assigned the USGS gage number. The flow node locations and corresponding watershed areas are summarized in Table 5 and shown on Figure 2. Station number 12351200 is a USGS gage outside of the study of reach, therefore, it was noted but not used as a flow node for this analysis.

Pioneer noted that Nodes 300 and 400 were located between USGS gaging stations and, therefore, the two-site logarithmic interpolation method was a more relevant method for estimating the peaked flows at these ungaged flow nodes. Bitterroot River flow nodes used in this study are summarized in Table 5 and Bitterroot River mainstem flow nodes and sub-basin locations are shown in Figure 2.

Table 5. Bitterroot River Mainstem Flow Nodes

Node/USGS Station ID	Location Description	River Mile Where Accumulated Flow Computed[1]	Calculated Basin Area[2] (sq. mi)	Study Reach	Hydraulic Model River Station (feet)
12351200*	Bitterroot River near Florence, MT	NA	2,340	Bitterroot River	N/A
400**	Bitterroot River-North Woodchuck Creek	14.3	2,414	Bitterroot River / Left Branch of Bitterroot River	111,361 / 14,432
300	Lower Lolo Creek	9.8	2,742	Bitterroot River	71,002
12352500	Bitterroot River near Missoula MT	5.9	2,821	Bitterroot River	47,149
100	Bitterroot River at junction with Clark Fork River	0.1	2,857	Bitterroot River	26,592
1000	Clark Fork upstream of Bitterroot River	29.6	6,149	Clark Fork River	23,768
12353000	Clark Fork below Missoula MT	28.9	9,007	Clark Fork River	14,637

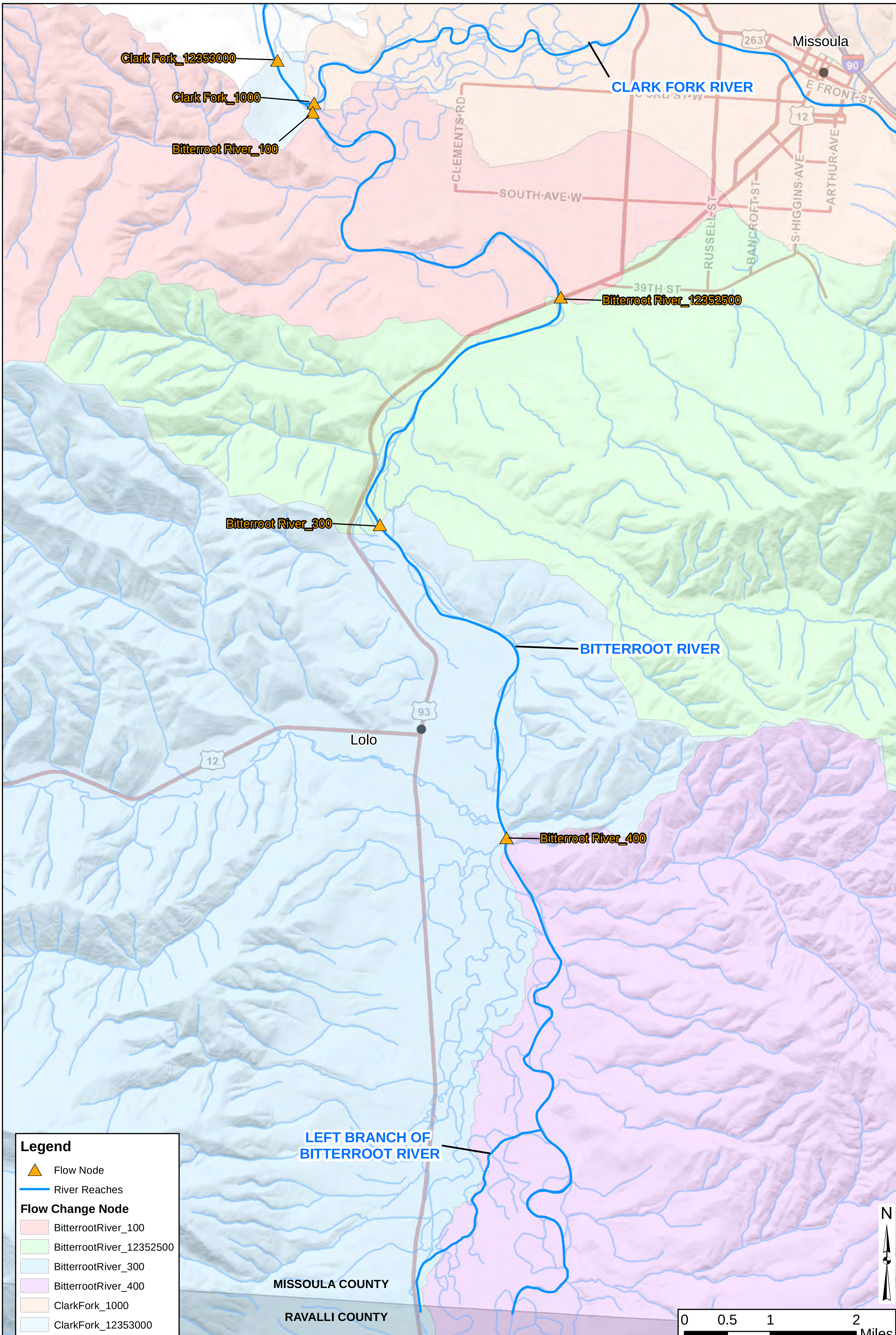
1. River miles start at the downstream extent of each study reach
2. Source: Esri ArcGIS
* Denotes USGS gage outside of study reach, not used as a flow node in this analysis
** Flow split between Bitterroot River and Left Branch of Bitterroot River flood reaches
USGS: U.S. Geological Survey

In the confluence area of the Bitterroot and Clark Fork Rivers, the Clark Fork River splits into two primary channels around Kelly Island (Figure 4). Bitterroot flow node 100 was geographically placed at the confluence of the Bitterroot River with the northern channel of the Clark Fork River. The Bitterroot River floodplain/valley mouth begins to separate from the Clark Fork River floodplain above the confluence of the Bitterroot River with the

Clark Fork River channel on the south side of Kelly Island. The two main channel confluence points are approximately 3,700 feet apart along the southern channel streamline and approximately 2,000 feet apart when measured along the center of Clark Fork River floodplain.

Flood flows between the two flood sources begin to comingle at the confluence between the Bitterroot River and the Clark Fork River southern channel. Therefore, the location of the flood flow change was shifted from the northern channel confluence to the southern channel confluence for the Bitterroot River hydraulic model development to better represent the geographic location where full flood flow from both flood sources would be routed by the Clark Fork River floodplain. This approach yields a reasonably conservative coincident peak boundary condition for flooding along the Bitterroot River upstream of the confluence.

FEMA floodplain studies are generally prepared using hydraulic models which simulate steady-state conditions. The steady-state option is used for 1D model development and 2D model development is prepared to approximate steady-state conditions by running the peak flow for a duration sufficient to approach a steady-state condition where inflow and outflow at the model boundaries are equal. In steady-state models, the peak flow rate calculated for each flow node is projected to the next upstream flow node.



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Bitterroot River
Flow Node Locations

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Figure 2

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3.1.5 Bitterroot River Creek Mainstem Discharges

Pioneer conducted a peak discharge frequency analysis for the Bitterroot River mainstem study reach (Pioneer 2020a). The study reach extends 21.6 miles from the confluence with the Clark Fork River (CFR). As noted above, flood frequency flow estimates were developed for both gaged and ungaged sites. The results were compared with previous studies.

The hydrologic analysis results provided in Table 6 and shown on Figure 3 represents the recommended discharges at each flow node location throughout the study reach. In comparing the flood discharges, the current discharges are less than or equal to the existing mapped values except for node 100. Given that node 100 was the only node within the recommended transfer method drainage area ratio between 0.5 and 1.5, the transfer method was conducted and utilized to produce a more accurate peak discharge estimate. The methods for hydraulic analysis are accepted based on the Bitterroot River mainstem basin and this hydrologic analysis conforms to the FEMA standard for enhanced level studies and was approved by FEMA in 2020. Note that the statistically derived flow for the 1%-plus flow profile is higher than the 0.2% AC flow profile at Bitterroot_400 and less than the 0.2% flow profile for the downstream flow nodes. The shift in relationship between these flows creates a crossing profile just upstream of the location where the flow change occurs.

Table 6. Bitterroot River Flooding Source Summary of Discharges

		Estimated Discharge (cfs)						
		50% Annual Chance	10% Annual Chance	4% Annual Chance	2% Annual Chance	1% Annual Chance	0.2% Annual Chance	1% + Annual Chance
Node/USGS Station ID	**Location Description**	**2-year**	**10-year**	**25-year**	**50-year**	**100-year**	**500-year**	**100-year-plus**
400	Bitterroot River-North Woodchuck Creek	14,200*	18,500*	21,000*	23,900*	26,100*	32,800*	33,100*
300	Lower Lolo Creek	14,600	21,900	25,300	27,900	30,400	36,100	35,900
12352500	**Bitterroot River near Missoula MT**	**14,700**	**22,700**	**26,400**	**28,900**	**31,400**	**36,900**	**36,600**
100	Bitterroot River at junction with Clark Fork River	15,200	23,500	27,300	29,800	32,400	38,000	37,800

* Includes flood flows routed by Left Branch of Bitterroot River split flow reach

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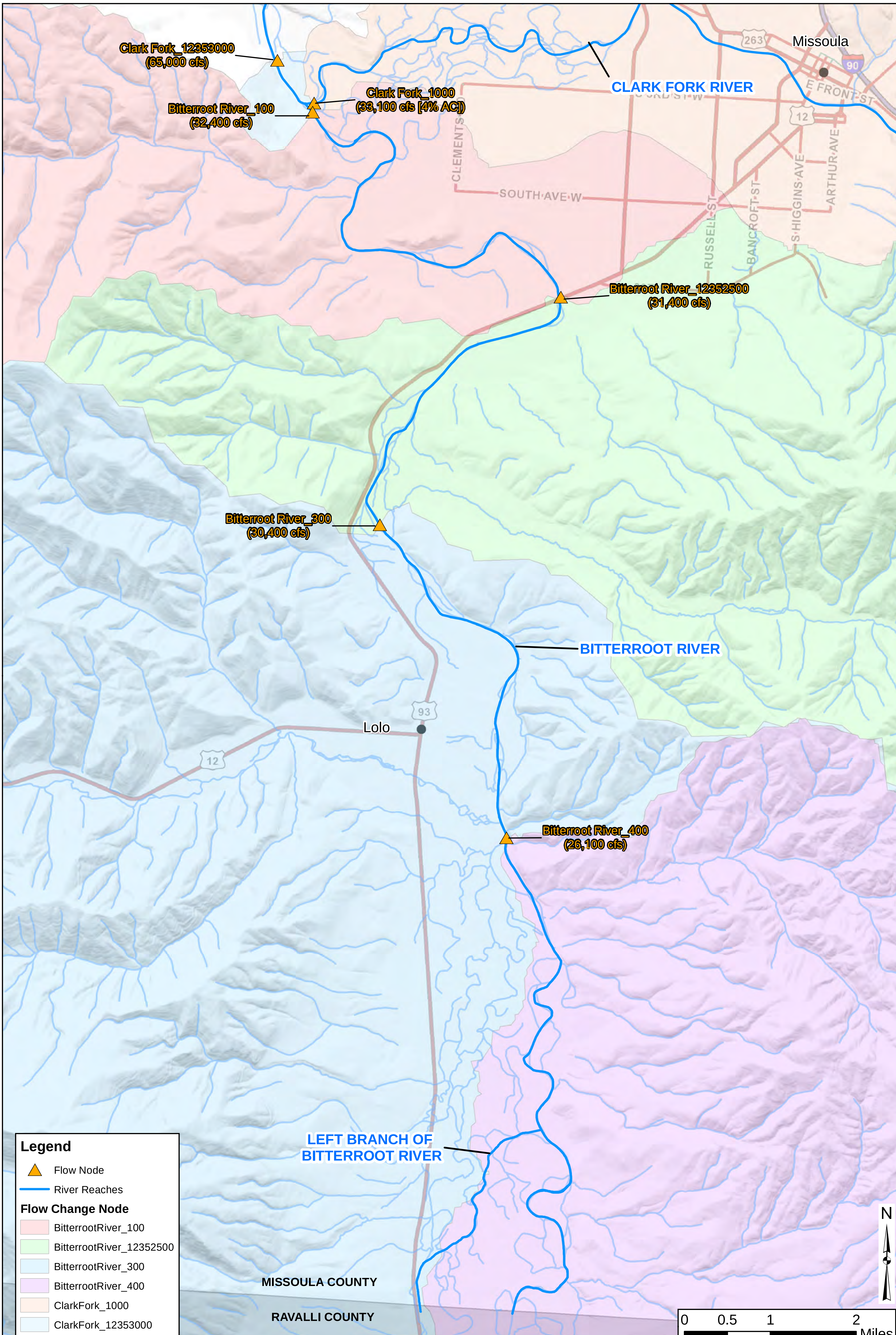

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Bitterroot River 1% AEP Discharges

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Figure 3

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3.1.6 Bitterroot River and Clark Fork River Coincidence

FEMA guidance documents (FEMA, 2016b) provide the following criteria for evaluating potential flow coincidence between flooding sources:

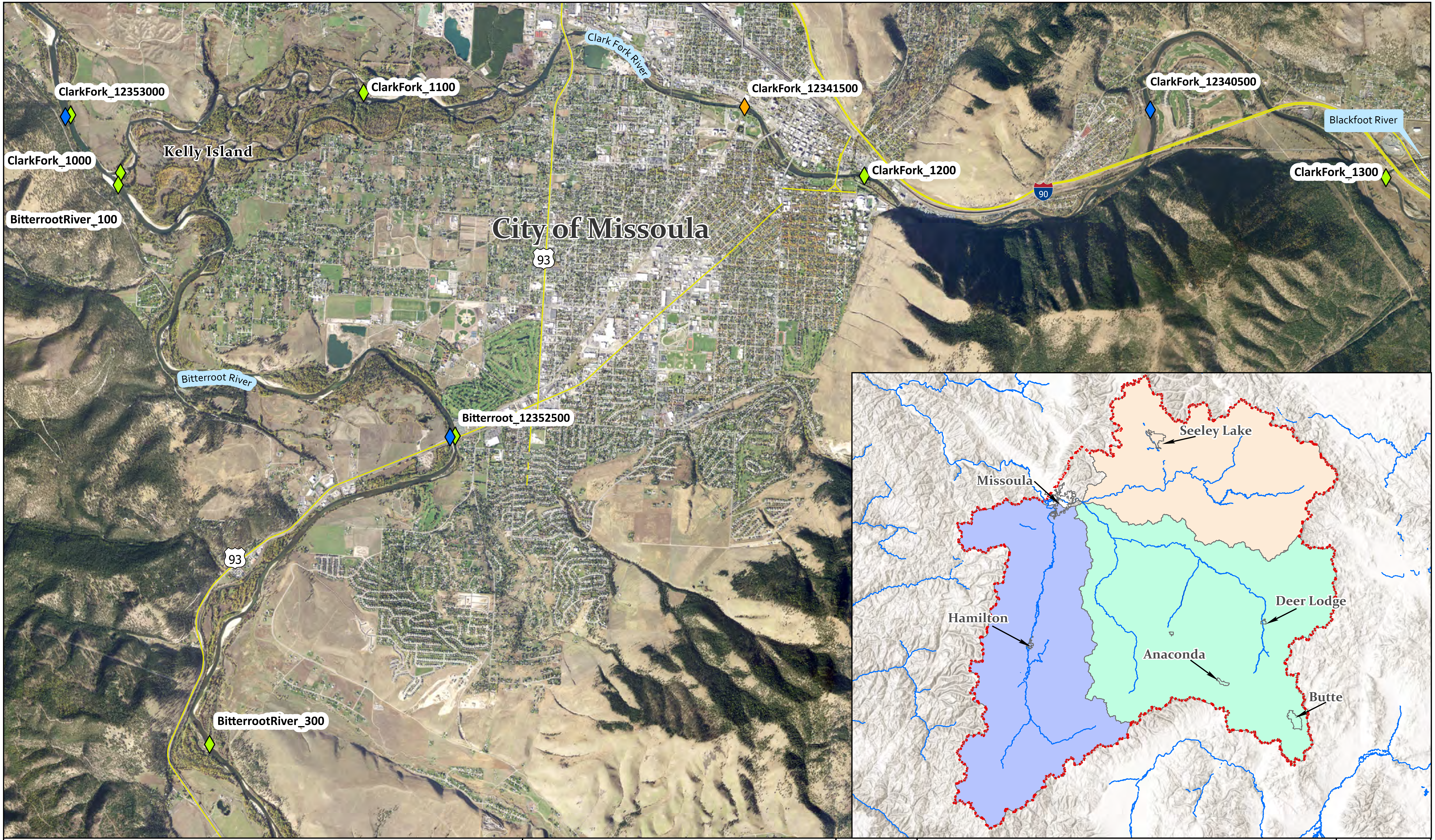
1. The ratio of the drainage areas lies between 0.6 and 1.4.
2. The arrival times of flood peaks are similar for the two combining watersheds.
3. The likelihood of both watersheds being covered by the storm being modeled is high.

Pioneer investigated the potential for coincidence and observed that at the confluence of the two rivers, the Bitterroot River watershed area of 2,857 square miles yields a ratio of 0.46 with the Clark Fork River watershed area of 6,149 square miles (Pioneer 2020a). Since the watershed drainage area ratio fell outside the FEMA guidance for coincidence, no additional investigation of the potential for coincident peaks as a boundary condition was taken during the hydrology investigation.

During development of the 2D hydraulic model for the Bitterroot River flood study reach, Morrison-Maierle observed appreciable potential flood risk variation on the Bitterroot River upstream of the confluence for coincident peak flow boundary conditions, including appreciable flood risk change between a 50% AC flow on the Clark Fork River and the 1% AC flow on the Bitterroot River. Consequently, a discussion was initiated with flood study stakeholders, including Montana DNRC and Compass as FEMA's technical support consultant. As a result, a more complete evaluation of the potential for and appropriate selection of peak flow coincidence for a boundary condition for hydraulic modeling was completed. The evaluation included review of stream gage records bounding the confluence area for historic coincident relationships.

Initial evaluation of the potential for coincident peaks completed by Compass included review of stream gage information and reference to Hydrologic Engineering Circular No. 22, Third Edition (HEC-22) Section 7.1.5, specifically Table 7-3. This reference provides additional potential coincidence relationships based on watershed drainage areas. Application of the HEC-22 approach indicated a fill 1:1 coincident peak flow relationship may be appropriate as the boundary condition for the Bitterroot River hydraulic analysis.

Stream gage information was investigated to understand what coincident peak relationship may have occurred in the past. USGS stream gage data for Bitterroot River 12352500 station at US Highway 93 and Clark Fork River (CFR) 12340500 station near the confluence of the Blackfoot River (Figure 4) for water years 1990 to 2019 was reviewed. The stream gage data indicated that the peaks occurred on the same day for 15 of the 30 water years (Figure 5). Including Bitterroot River peaks occurring 1 day on either side of the CFR peaks added 5 more years of coincidence (20 years out of 30 years); indicating a strong trend of coincidental peak flow occurrence at the Bitterroot River CFR confluence.



Legend
- INACTIVE USGS STREAM GAGE
- ACTIVE USGS STREAM GAGE
- FLOW NODES

WBDHU8 WATERSHEDS
- Bitterroot
- Blackfoot
- Clark Fork Above Blackfoot Confluence
- Clark Fork Below Bitterroot Confluence

N

0 3,000 6,000 Feet

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Bitterroot River and Clark Fork River Coincidence

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FIGURE NO.
FIG. 4

Historically occurring annual peak flow coincidence was evaluated for water years 1990 to 2019 for the Bitterroot and CFR stream gages 12352500 and 12340500, respectively. The highest available flows for the gage data were evaluated to understand the correlation of the peak flow rates at the CFR stream gage 12353000 on the same day (Figure 5).

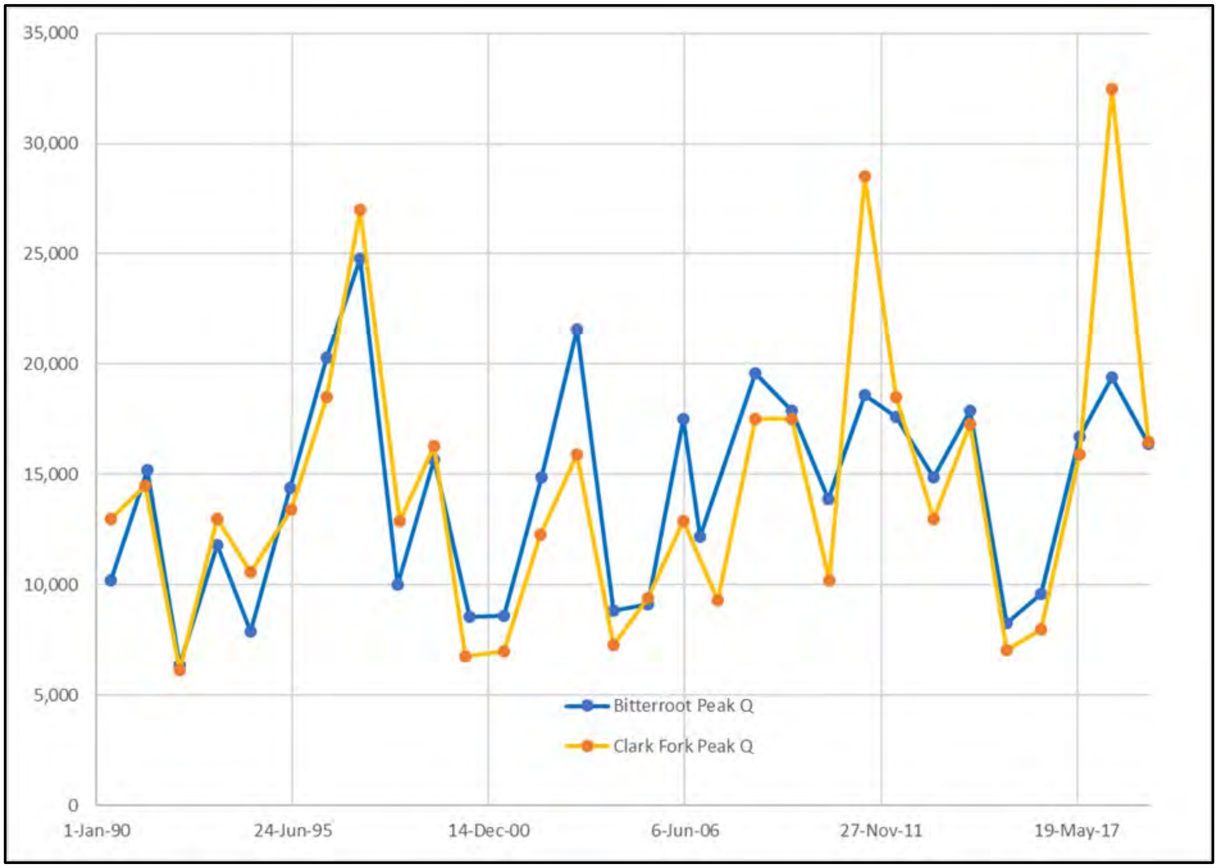


Figure 5. Bitterroot River 12352500 and Clark Fork River 12340500 Annual Peak Stream Gage Data Comparison

This evaluation included three flow events close to the flow rate for the 50% AC flood profile, two between the 50% and 10%, and one close to the 10% AC flood profile. The summed flows from the upstream gages were similar to the measured flow at CFR stream gage 12353000 with differences ranging from -2.1% to 5.4% (Table 7). Stream flow data to support similar evaluation for less frequent flooding events (4%, 2%, 1% AC profiles) was not available. However, the coincidence trend was strong for the six dates evaluated.

Table 7. Historic Stream Gage Coincidence at Bitterroot and CFR Gage Stations

Date	Annual Chance Flood Profile	Bitterroot Gage 12352500 (cfs)	CFR Gage 12340500 (cfs)	CFR Gage 13253000 (cfs)	1:1 Coincidence (12352500 + 12340500) (cfs)	Δ between CFR node 1325300 & Summed Coincidence (%)
06-07-1991	50%	15,200	12,000	25,800	27,200	5.4
06-04-1999	50%	15,700	14,000	29,500	29,700	0.7
05-15-2013	50%	14,900	12,000	25,600	26,900	5.1
06-10-1996	50%<AC<10%	20,300	18,500	37,600	38,800	3.2
06-01-2003	50%<AC<10%	21,600	15,900	38,300	37,500	-2.1
05-18-1997	10%	24,800	27,000	aa51,600	51,800	0.4

A driving cause for coincidence is the watershed similarities between the Bitterroot and Blackfoot Rivers, which are significant tributaries of the Clark Fork River below and above Missoula, respectively. The confluence of the Clark Fork and Blackfoot Rivers is geographically close (Figure 4) to the confluence of the Bitterroot and Clark Fork Rivers.

The available peak stream flow data for flow events exceeding the 50% AC event indicates a potential trend toward less frequent (higher risk) peak flows on the Bitterroot River correlating with more frequent (lower risk) peak flows on the Clark Fork River. Because coincidence of flows is strongly indicated, combining peak flow rates for each flood event was evaluated for Bitterroot node 100 and CFR node 1000 for each annual chance flood profile. The flood flows as recommended in the Hydrology Report (Pioneer, 2020a) at the flow nodes bounding the Bitterroot and CFR confluence are provided in Table 8.

Table 8. Bitterroot and Clark Fork River Peak Flows from Hydrology Report at Confluence Area Flow Nodes

Annual Chance (%)	Bitterroot River Node 100 (cfs)	CFR Flow Node1000 (cfs)	CFR Flow Node 12353000 (cfs)
50	15,200	15,600	29,300
10	23,500	27,500	47,200
4	27,300	33,100	54,900
2	29,800	37,100	60,200
1	32,400	41,000	65,000
1%+	37,800	47,800	73,500
0.2	38,000	49,600	75,200

Coincidence combinations of Bitterroot node 100 and CFR node 1000 were evaluated to understand how potential coincidence relationships compared to the recommended peak flow rate at CFR node 12353000 from the Hydrology Report (Pioneer 2020a). Potential coincidence combinations are summarized in Table 9. Applying a 1:1 coincidence relationship between these two flow nodes would result in a flow value markedly greater than the peak flood flows recommended in the Hydrology Report (Pioneer, 2020a) at CFR flow node 12353000 starting with the 4% AC flood flow. Therefore, the 1:1 coincident peak flow relationship initially considered after review of the HEC-22 approach and the stream gage data investigation was discarded as unreasonably conservative.

Table 9. Potential Peak Flow Coincidence of the Bitterroot and Clark Fork Rivers for the Hydraulic Boundary Condition for the Bitterroot River Flood Study

Annual Chance (%)	Bitterroot with CFR 50% AC (cfs)	Bitterroot with CFR 10% AC (cfs)	Bitterroot with CFR 4% AC (cfs)	Bitterroot with CFR 2% AC (cfs)	Recommended CFR Coincidence (%)
50	30,800	42,700	48,300	52,300	50
10	39,100	51,000	56,600	60,600	10
4	42,900	54,800	60,400	64,400	10
2	45,400	57,300	62,900	66,900	4
1	48,000	59,900	65,500	69,500	4
1%+	53,400	65,300	70,900	74,900	2
0.2	53,600	65,500	71,100	75,100	2

CFR Annual Chance Event Coincidence Recommend for the Bitterroot Flood Study

Based on the comparative analyses, the coincidence relationships for the 50%, 10%, 4%, 2%, 1%, 1%+, and 0.2% annual chance flood profiles shown with blue highlight in Table 9 were selected for the Bitterroot River confluence with the Clark Fork River. The recommended flow relationships are summarized and compared to the recommended hydrologic peak flood flows for the Clark Fork River immediately downstream of the confluence at CFR 12353000. The recommended coincidence relationships have a difference ranging from -0.2% to 8.1% between CFR node 12353000 and the summed flows from Bitterroot node 100 and CFR node 1000 (Table 10).

Table 10. Recommended Coincident Peak Boundary Condition Flows

Bitterroot River AC (%)	CFR AC (%)	Bitterroot River Flow (cfs)	CFR Flow (cfs)	Σ Bitterroot River & CFR Flow (cfs)	CFR 12353000 Flow (cfs)	Percent Difference (%)
50	50	15,200	15,600	30,800	29,300	5.1
10	10	23,500	27,500	51,000	47,200	8.1
4	10	27,300	27,500	54,800	54,900	-0.2
2	4	29,800	33,100	62,900	60,200	4.5
1	4	32,400	33,100	65,500	65,000	0.8
1%+	2	37,800	37,100	74,900	73,500	1.9
0.2	2	38,000	37,100	75,100	75,200	-0.1

* The full Bitterroot River flooding source regulatory flow rate is conveyed by the combination of Bitterroot and Clark Fork River cross sections for the first five cross sections upstream of the confluence junction in the 1D hydraulic model.

The average of the difference across the six FEMA modeled profiles is 2.5% for the recommended coincidence relationships. These coincidence relationships yield reasonable representation of actual flood risk for the Bitterroot River hydraulic modeling boundary condition at its confluence with the Clark Fork River.

4.0 Hydraulics

The methods and techniques used to complete the hydraulic analysis for Bitterroot River within Missoula County, Montana are presented in the following sections. The analysis utilized the LiDAR mapping and field hydraulic structure survey to develop the Enhanced Level Option E with Floodway, 1% AC Zone AE and 0.2% AC Zone X mapping with floodway.

4.1 Hydraulic Analysis

This flood study covers Bitterroot River within Missoula County, MT. The Bitterroot River study area, as shown on Figure 1 begins at the confluence with the Clark Fork River and goes upstream to the Missoula-Ravalli County boundary. The studied length of each reach is summarized in Table 1.

Standard engineering practice, HEC-RAS modeling guidance, and FEMA Guidance were followed for the hydraulic model development. FEMA Guidance documents specifically pertinent to hydraulic modeling development include *General Hydraulic Considerations* (FEMA 2016b), *Hydraulics: One-Dimensional Analysis* (FEMA 2016c), and *Hydraulics: Two-Dimensional Analysis* (FEMA 2016d). The water surface elevations (WSEL's) were calculated with HEC-RAS, Version 5.0.7 hydraulic modeling software (Brunner 2019a). HEC-RAS provides the steady-flow analysis using the standard step energy balance calculation between cross sections starting at the most downstream cross section and moving upstream for subcritical analysis.

Cross sections were placed with the GeoHECRAS hydraulic computer modeling software (CivilGEO 2020) at flow distances or reach lengths generally ranging from approximately 15 to 500 feet and at structures located within the floodplain study reach. One cross section has a downstream channel length that is slightly greater than 500 feet in Bitterroot Reach 2 (River Station (RS) 107412), because the cross section is on a meander bend and most of the overbank reach length is much less than 500 feet. In the following subsections, is a summary description for the key hydraulic features associated with each reach studied. The Bitterroot River was broken up into two models, Bitterroot River Reach 1 and Bitterroot River Reach 2 to improve model performance and efficiency.

The Bitterroot River tie in with the Clark Fork River will be completed when the Clark Fork River hydraulics has been approved. The mapping of the Clark Fork River in the Bitterroot hydraulic analysis was provided as part of the analysis of coincident peaks with Clark Fork River. Map tie-in for the Bitterroot River at the Ravalli-Missoula County boundary is at cross section 111,207. This cross section was aligned with cross section A from the Ravalli County floodplain data set downloaded from the National Flood Hazard Layer (NFHL). The modeled water surface elevation for the current study is 3,193.7 feet and the Ravalli County effective water surface elevation at cross section A is 3,193.7 feet. A detailed description of the Ravalli County tie-in is included in Section 4.8 and Section 5.2. The effective mapping for Lolo Creek is a Zone AE with floodway and ties into the Bitterroot River at RS 70,559. The Miller Creek effective mapping is a Zone AE flood zone and ties into the Bitterroot River at RS 42,646.

4.1.1 Bitterroot River Reach 1

The Bitterroot River Reach 1 one-dimensional (1D) hydraulic model includes the confluence with the Clark Fork River and extends upstream to the south for approximately 11.9 river-miles near the town of Lolo. The reach 1 model cross sections overlap with reach 2 cross sections from station 62,902 to 65,150. Reach 1 includes 3 modeled hydraulic structure crossings. Additional minor structures within the flood fringe were determined to be insignificant and were not modeled; these are discussed in more detail in section 4.4 below.

Reach 1 boundary condition is a known water surface elevation from the 2D model based the coincident peak flow relationship between the Bitterroot and Clark Fork Rivers. The 2D model assumes normal depth slope of 0.00088 on the Clark Fork River below the Bitterroot River and Clark Fork River confluence and a 50% annual-chance event flow rate on the Clark Fork River upstream of the confluence. The hydraulic analysis on the Clark Fork River does not represent regulatory flood risk for the Clark Fork River flooding source. More in-depth discussions of the Bitterroot River and Clark Fork River coincidence are provided in the hydrology section 3.1.6 and in the 2D Model Development section 4.7.

The River Pines Road (Maclay Bridge) is overtopped by relatively minor lateral flows. The flow loss from the main stem was assigned to the 1D model based on the 2D model results and full flood source peak flows were reassigned to the first cross section (station 3,818) spanning the floodplain north of River Pines Road.

4.1.2 Bitterroot River Reach 2

The Bitterroot River Reach 2 one-dimensional (1D) hydraulic model begins near the town of Lolo and extends upstream to the south for approximately 9.7 river-miles to the Missoula-Ravalli County boundary. The reach 1 model cross sections overlap with reach 2 cross sections from station 62,902 to 65,150. Reach 2 boundary condition is a known water surface elevation from cross section 62,902 on reach 1.

Reach 2 includes a split flow path on the west side of the Bitterroot Valley beginning at the Missoula/Ravalli County boundary and running downstream approximately 2.7 miles to the confluence with the mainstem of the Bitterroot River. This split flow condition was recognized during the 2D model development and is described in section 4.7.2. Flow values for the split flow reach were informed by the 2D model. Flow sharing between the mainstem of the Bitterroot River and the Left Branch of Bitterroot River path occurs between north end of Carlton Creek Road and the convergence of Left Branch of Bitterroot River flow. Section 4.12 contains a detailed description of the split flow modeling.

Reach 2 includes 4 modeled hydraulic structure crossings, one structure on the Bitterroot River mainstem and three structures on the Left Branch of Bitterroot River. Additional minor structures within the flood fringe were determined to be insignificant and were not modeled, these are discussed in more detail in section 4.4 below.

4.2 Topographic Data Acquisition

The Montana Department of Natural Resource Conservation (DNRC) contracted with Quantum Spatial, Inc. (QSI) to acquire topographic Light Detection and Ranging (LiDAR) data for the project area. QSI performed a topographic LiDAR survey on the Bitterroot River within Missoula County for the DNRC between May 23, 2019 and June 16, 2019. The LiDAR survey included near-infrared wavelength for terrestrial topography for the Bitterroot River. The specifications for the LiDAR DEM required digital elevation data with a root mean square error (RMSE) less than or equal to 10 centimeters (approximately 4 inches), (QSI 2019). To verify the LiDAR Digital Elevation Model (DEM) data met the vertical accuracy criteria, QSI compared ground measured check points with the LiDAR DEM data at vegetated, non-vegetated and control point locations. The LiDAR DEM data met the relative vertical accuracy statistics reported in Missoula County LiDAR Technical Data Report as summarized in Table 11 (QSI 2019).

Table 11. QSI 2019 LiDAR Relative Vertical Accuracy

Parameter	Result
Sample	180 flight line surfaces
Average	0.105 feet
Median	0.112 feet
RMSE	0.114 feet
Standard Deviation	0.023 feet
95% Confidence (1.96*RMSE)	0.044 feet

The LiDAR deliverables included 1-foot grid bare earth digital elevation models (DEM) for the entire length of the Bitterroot River corridor (QSI 2019).

As discussed in section 4.7, the 2019 LiDAR data collected for the Missoula-Granite PMR project was supplemented with LiDAR data collected in 2008 in Ravalli County (Watershed Sciences 2008). The additional topographic information was needed to extend the 2D hydraulic model south into Ravalli County to upstream of the natural topography creating a split flow floodplain at the Missoula County southern border.

The LiDAR data was collected by Watershed Sciences between June 1-3 and June 5-6 in 2008. The specifications for the LiDAR DEM required digital elevation data with a RMSE less than or equal to 18.5 centimeters (approximately 7 inches).To verify the LiDAR DEM data met vertical accuracy requirements, Watershed Sciences compared ground measured check points with the LiDAR DEM data for various land covers within the collection area. The LiDAR DEM data met the relative vertical accuracy requirements for the topographic data collection. The relative vertical accuracy of the data set as reported in the LiDAR collection report is summarized in Table 12 (Watershed Sciences 2008).

Table 12. Watershed Sciences 2008 LiDAR Relative Vertical Accuracy

Parameter	Result
Sample	Multiple flight line surfaces
Average	0.131 feet
Median	0.131 feet
1-sigma relative deviation	0.131 feet
2-sigma relative deviation	0.164 feet
RMSE (absolute)	0.066 feet
Data Resolution	≥ 0.56 points / square feet

4.3 Bathymetric Survey

A bathymetric survey of the Bitterroot River was performed by DOWL (DOWL 2019) August and October of 2019. DOWL surveyed cross-sections approximately every 2,500 feet with four additional cross-sections at each of the mainstem bridges. The Highway 12/93 bridge and the railroad bridge were combined as one structure for the bathymetric survey. The bathymetric survey was used to build a low-flow channel into the DEM surface and to enhance the channel within structures.

4.4 Field Structure Survey

A field survey of the hydraulic structures for the Bitterroot River study was performed by Pioneer Technical Services, Inc. between October 2019 and May 2020 (Pioneer 2020b). A total of 21 structures were scoped to be surveyed on the Bitterroot River, however two structures were not found, and access permission for the survey of structure 136 was denied. Consequently, estimates from the aerial imagery were used to model the span and width of the structure. Eleven structures were determined to be insignificant because they were too small to influence flood flows. In general, these structures were culverts less than 3 feet in diameter or small bridges that were not within the main flow path. Structures included in the hydraulic modeling on the Bitterroot River and Left Branch of Bitterroot River flow reaches are summarized in Table 13.

Table 13. Structure Survey

ID No.	Structure Type	River Reach	Roadway	River Station (feet)
S120	Bridge	Bitterroot River	River Pines Road	4,000
S121	Bridge	Bitterroot River	Highway 12/93	26,780
S122	Bridge	Bitterroot River	MRL Railroad	26,890
S129	Bridge	Bitterroot River	Maclay Ranch Road	78,702
S135	Culvert	Left Branch of Bitterroot River	E Carlton Creek Rd	9,000
S136	Bridge	Left Branch of Bitterroot River	Private Bridge	12,330
S137	Culvert	Left Branch of Bitterroot River	Chief Looking Glass Road	14,019

4.5 Profile Baseline

The alignment of the Bitterroot River water line was prepared by Pioneer during the hydrologic analysis for study streams (Pioneer 2018a). The water line alignment was generally used to prepare profile baselines for the 1D modeling with adjustments as required to prepare the hydraulic model geometry. The profile baseline for the Bitterroot River aligns with the topographic data for the main channel at the time of topographic data collection. The Bitterroot River is well-known for channel migration. Therefore, the profile baseline alignment may not agree with some existing aerial imagery sources and more divergence is anticipated throughout the effective life of the floodplain study due to natural river migration.

To appropriately model stream reaches, the locations of major tributary confluences and other flow change locations were identified as noted in hydrology section of this report. A profile baseline for the Left Branch of Bitterroot River was defined following the general location of the Squaw Creek main channel until just above E Carlton Creek Rd, where the majority of the flow follows the low-lying area flowing north-east to the convergence with the Bitterroot River main stem. Once the profile baseline for Left Branch of Bitterroot River diverges from the channel of Squaw Creek, the profile baseline does not follow a defined channel but instead is generalized following the majority of the flow. The flow change locations (flow nodes) of the Bitterroot River and Left Branch of Bitterroot River were set at river station locations as summarized in Tables 5 and 14. The profile baselines were also used to locate cross sections and key features along the streams.

Profile baselines were added during the hydraulic analysis to the Bitterroot River models to include flow reaches as required to appropriately account for hydraulic flow distribution and to prepare the preliminary floodplain mapping.

Table 14. Profile Baseline Key Features

Reach	River Station (feet)	Type	Description
Bitterroot River	32	Confluence	Confluence with Clark Fork River
Bitterroot River	4,000	Structure Crossing	River Pines Road (Maclay Bridge)
Bitterroot River	26,592	Flow Change	Bitterroot_100
Bitterroot River	26,780	Structure Crossing	Highway 12/93
Bitterroot River	26,890	Structure Crossing	Active Railroad Crossing
Bitterroot River	47,149	Flow Change	Bitterroot_12352500
Bitterroot River	62,461	Town	Unincorporated town of Lolo
Bitterroot River	71,002	Flow Change	Bitterroot_300
Bitterroot River	78,702	Structure Crossing	Maclay Ranch Road
Left Branch of Bitterroot River	0	Convergence	Left Branch of Bitterroot River Convergence with Bitterroot River
Left Branch of Bitterroot River	9,000	Structure Crossing	E Carlton Creek Rd

Table 14. Profile Baseline Key Features (cont.)

Reach	River Station (feet)	Type	Description
Left Branch of Bitterroot River	12,330	Structure Crossing	Private Bridge
Left Branch of Bitterroot River	14, 019	Structure Crossing	Chief Looking Glass Road
Left Branch of Bitterroot River	14, 019	Boundary/Flow Change	Limit of Study at Ravalli County Boundary & Bitterroot_400
Bitterroot River	111,207	Boundary/Flow Change	Limit of Study at Ravalli County Boundary & Bitterroot_400

4.6 Boundary Conditions

In accordance with the coincident discussion in section 3.1.6 above, the downstream boundary condition for the Bitterroot River flood study is dependent on a peak flow coincidence relationship between the Bitterroot and Clark Fork Rivers. Sensitivity analysis of the coincident boundary indicated flood risk on the Bitterroot River would be appreciably higher up to a mile upstream of the anticipated Clark Fork River floodplain extents. Therefore, both the 2D and 1D hydraulic models were extended upstream and downstream of the confluence between the Bitterroot and Clark Fork Rivers approximately two miles. Both the upstream and downstream extents of the modeling along the Clark Fork River were selected to ensure the boundary condition normal depth friction slope estimates for developing both the 2D and 1D models would not unreasonably affect model results.

To perform a hydraulic analysis in HEC-RAS, a boundary condition is specified at the downstream boundary of the 2D model or at the first downstream cross section of the 1D model reach. Per FEMA's One-Dimensional Hydraulics Guidance for Flood Risk Analysis and Mapping (FEMA 2016b), the downstream boundary condition of a hydraulic model should be taken from a previously established water surface elevation (WSEL), if available. Where a previously established WSEL is not available, a normal depth boundary condition should be selected. The normal depth slope is the slope of the Hydraulic Grade Line (HGL) which is calculated by iterative model runs resulting in convergence at the HGL slope. In most natural river systems, the HGL slope is equal, or nearly equal, to the mean channel bottom slope.

There is an effective floodplain with WSELs on the Clark Fork River. However, the Clark Fork River is also being studied as part of the larger Missoula-Granite PMR project, of which the Bitterroot River flood study is a part. Since the confluence area is being updated for both the Bitterroot and Clark Fork Rivers, a normal depth condition based on the high-quality topographic information collected for the project was selected for the downstream boundary condition for both 2D and 1D model development (Brunner 2016a; FEMA 2016d). Sensitivity analysis of the downstream boundary condition indicated the boundary condition was geographically far enough from the area of interest that both 2D and 1D model results were insensitive even to assignment of unreasonable boundary condition normal depth slopes.

As discussed above, hydraulic modeling of the confluence area along both the Bitterroot and Clark Fork Rivers was necessary to prepare appropriate representation of flood risk on the Bitterroot River near the confluence. For the 1D hydraulic model, the junction node was utilized for boundary condition for the Bitterroot River profile baseline. The 2D hydraulic model logic intrinsically routes flood flows in the confluence area and a unique boundary condition for the Bitterroot River was unnecessary. Similarly, for the Left Branch of Bitterroot River in the upper reach of the Bitterroot River floodplain, the junction node approach was utilized in the 1D hydraulic model and the 2D hydraulic model intrinsically routes flow.

The Bitterroot River flood study was broken into two separate 1D hydraulic models. The upper 1D hydraulic model was overlapped into the lower reach for several cross sections and known water surface elevations from the finalized lower hydraulic model were assigned as the downstream boundary condition. Computed water surface elevations at the most upstream overlapped cross section were compared between the two models to confirm the models appropriately tied with one another.

One-dimensional hydraulic models for floodplain studies typically prepared using sub-critical analysis methods and upstream boundary condition assignment is unnecessary. However, 2D hydraulic model logic requires an upstream boundary condition for inflow assignment. Upstream boundary conditions were established at the upstream model mesh limits for the Bitterroot River and the Clark Fork River flood sources. Flow aligning with the peak flow documented in the Hydrology Report (Pioneer 2020a) was assigned at the upstream boundary condition for all 2D hydraulic modelling plans.

Two-dimensional modeling is performed in an unsteady model which requires an inflow boundary condition for the inflow hydrograph. The inflow boundary condition also requires a friction slope entry to perform the model computations. The friction slope was estimated based on the natural ground slope at the boundary condition location (Brunner 2016a). The 2D hydraulic model was also extended upstream of the area of interest (Bitterroot/Clark Fork Confluence and Missoula County southern boundary) to ensure boundary condition value estimates would not unreasonably affect model results. The friction slope for internal 2D inflow boundary conditions were also estimated from the adjacent natural ground slope (Brunner 2016a). Sensitivity analyses indicated the model was insensitive to reasonable variation in friction slope estimates for inflow boundary conditions. For the internal inflow boundary conditions, the insensitivity was anticipated due to the small incremental flow increases relative to the full flood flows for each flood profile. Selected 2D boundary condition slopes are reported in section 4.7.3.

Downstream boundary conditions established for each model segment for the Bitterroot River floodplain study in Missoula County are summarized in Table 15.

Table 15. 1D Hydraulic Modeling Downstream Boundary Condition Summary

Stream Reach	Model Segment	Boundary Condition
Clark Fork River	Reach DS	Normal Depth Slope = 0.001412 ft/ft
	Reach US	Junction at Confluence with Bitterroot River
Bitterroot River	Reach 1	Junction at Confluence with Clark Fork River
	Reach 2, Seg. A	Known WSELs from Reach 1 at RS 62,902
	Reach 2, Seg. B	Junction at Convergence of Left Branch of Bitterroot River
	Left Branch of Bitterroot River	Junction at Convergence with Bitterroot River Reach 2, Segment B

4.7 Bitterroot River 2D Model Development

The purpose of the 2D hydraulic modeling along the Bitterroot River flooding source was to inform preparation of the 1D hydraulic model for regulatory floodplain development. Several sub-reaches of the Bitterroot River floodplain include a primary floodplain aligned with the main channel of the Bitterroot River and overbank flooding that is routed in historic river channels, oxbows, depressions of tributary streams, and man-made drainage features or irrigation canals. This is particularly applicable for the Bitterroot River reach upstream of Lolo, MT to the southern Missoula County boundary.

Development of 1D modeling to investigate and represent flooding along overbank channels can be very time consuming and can be influenced (both positively and negatively) by modeler assumptions of flow distribution among the overbank flood flow paths. Two-dimensional hydraulic modelling can be an invaluable tool for 1D hydraulic model development. When prepared appropriately, a 2D model can intrinsically demonstrate locations where floodplain flow paths diverge from the primary floodplain and improve certainty of estimated flood flow leaving the primary floodplain for all flood profiles. The 2D hydraulic modeling was completed with the USACE HEC-RAS v5.0.7 hydraulic modeling program.

4.7.1 Hydrology and Flow Changes

Hydrology data, including flowrates and flow change locations were taken from the Missoula-Granite PMR. MAS No. 2019-02; Hydrologic Analysis Report (Pioneer 2020a) prepared by Pioneer Technical Services and provided by DNRC. In a 2D hydraulic model, flow is “poured” into the model using an upstream boundary condition. The flow from the upstream boundary condition is routed throughout the model domain and released from the model domain at the downstream boundary condition. Flow changes within the model domain are additive to the original flow input. Flow changes were modeled at the locations noted for the 1D hydraulic model using an internal boundary condition. Flow file data for the 2D hydraulic modeling is summarized in Table 16.

Table 16. 2D Hydraulic Modeling Flow File Discharge Summary

	Bitterroot 50% AC - CFR 50% AC		Bitterroot 10% AC - CFR 10% AC		Bitterroot 4% AC - CFR 10% AC		Bitterroot 2% AC - CFR 4% AC		Bitterroot 1% AC - CFR 4% AC		Bitterroot 0.2% AC - CFR 2% AC		Bitterroot 1%+ AC - CFR 2% AC	
	Discharge		Discharge		Discharge		Discharge		Discharge		Discharge		Discharge	
Node Location	Flow File	Total	Flow File	Total	Flow File	Total	Flow File	Total	Flow File	Total	Flow File	Total	Flow File	Total
Bitterroot River Inflow[2]	14,200	14,200	18,500	18,500	21,000	21,000	23,900	23,900	26,100	26,100	32,800	32,800	33,100	33,100
400	400	14,600	3,400	21,900	4,300	25,300	4,000	27,900	4,300	30,400	3,300	36,100	2,800	35,900
300	100	14,700	800	22,700	1,100	26,400	1,000	28,900	1,000	31,400	800	36,900	700	36,600
USGS 12352500	500	15,200	800	23,500	900	27,300	900	29,800	1,000	32,400	1,100	38,000	1,200	37,800
Clark Fork River Inflow[3]	15,600	15,600	27,500	27,500	27,500	27,500	33,100	33,100	33,100	33,100	37,100	37,100	37,100	37,100
Clark Fork River Outflow[4]		30,800	-	51,000	-	54,800	-	62,900	-	65,500	-	75,100	-	74,900

1. No flow change node located at Bitterroot-CFR confluence.
2. Inflow located at upstream external boundary of 2D model area on Bitterroot River.
3. Inflow located at upstream external boundary of 2D model area on CFR and discharge based on Morrison-Maierle memo dated 8/18/2020.
4. Total discharge at 2D model external boundary condition line.

The inflow and outflow locations are based on the limits of the 2D model area for the Bitterroot River and Clark Fork River. As discussed in section 3.1.6 above, the inflow for the Clark Fork River was the 4% annual chance discharge rate corresponding with the 1% annual chance discharge in the Bitterroot River. Additional correlations for regulatory discharges are listed in Table 16. The three internal flow change locations are based on flow node locations documented in the hydrology task (Pioneer 2020a). The flow change locations in a 2D model require a polyline to apply additional discharge to the model, the polylines were drawn to intersect with the point flow node shapefiles included in the hydrology task. Internal boundary conditions were drawn internal to the 2D model area to apply the net discharge value. These internal boundary conditions are generally oriented perpendicular to the direction of flow and span the entire valley.

To simulate a 2D steady state model with the 2D unsteady state calculations in HEC-RAS, the flow file was developed with constant discharge values shown in Table 16 over the entire simulation time. A simulation time of 24 hours was used with a ramp up ratio of 0.1 to improve model stability. The measured flow rate at the outflow boundary condition, and internal model checks, indicate that the 2D model reaches steady state conditions approximately halfway through the 24-hour simulation time throughout the model domain.

4.7.2 Terrain and Structure Data

The foundation of the terrain for the 2D model is the digital elevation model (DEM) based on LiDAR data collected for the project by Quantum Spatial (QSI 2019). Several additional datasets were used to supplement and expand the DEM. The DEM prepared from topographic data collected using LiDAR methods which do not capture surface data beneath water surfaces or add structure data like piers. The recently collected LiDAR topographic data was limited to Missoula County.

Bathymetry data for this project was collected by DOWL along the primary channel of the Bitterroot and Clark Fork Rivers (DOWL 2019). The bathymetry data was used to stamp a low-flow channel into the DEM beneath the water surface. A multi-step process was used to approximate the river channel as closely as possible. To allow use of the LOFT tool in Autodesk Civil3D, each bathymetric cross section was reduced to 10 points within the river channel with the GeoHEC-RAS program. The point reduction tool performs point reduction while minimizing change in the flow area for each section. With an equal number of points at each cross section and the river baseline alignment, the LOFT tool was used to create a river bathymetry surface that transitions smoothly between each cross section along the river baseline. This approach allowed preparation of a low-flow channel that varied in width as indicated by aerial imagery and the LiDAR DEM, mitigating under-stamping and over-stamping of the low-flow channel between the bathymetric survey cross sections. This surface was exported from a TIN surface to a DEM for use in HEC-RAS and added to the LiDAR DEM.

Structure survey data for this project was collected by Pioneer Technical Services (Pioneer 2002b). The structure survey data was used to add pier and abutment topography for major structures on the Bitterroot River mainstem. Pier structure data on three bridges were included in the terrain to simulate the restricted conveyance. Maclay Bridge (S120), HWY93 South Bridge (S121) and MRL Railroad Bridge (S122) were each included in the terrain data. One additional bridge was also included at the Maclay Ranch Road Bridge (S129), but this bridge does not have piers, so only the abutments were added to the terrain. HEC-RAS is not capable of modeling a bridge deck in a 2D geometry. Since the modeled base flood elevation (BFE) at each structure listed is below the low chord of the bridge, no effect to the model would occur with inclusion of bridge deck information.

Initial model results indicated a split flow condition with natural high ground dividing flows at the Missoula/Ravalli County boundary. A split flow at an external boundary condition location is less desirable since the model input values could control the flow split versus the modeling calculations. To extend the model limits south into Ravalli County where a contiguous floodplain is located, additional terrain data was required. LiDAR topography (Watershed Sciences 2008) collected for Ravalli County was provided by DNRC thru the Montana State Library. The 2008 Ravalli County LiDAR was merged with the 2019 LiDAR DEM to extend the terrain limits to the south about 6,000 feet. The additional terrain included the natural topographic high ground causing the floodplain flow split observed at the Missoula County southern boundary. Low-flow bathymetric channel data in this reach was not available, so a constant trapezoidal channel shape was stamped into the extend LiDAR terrain following the profile of the terrain along the main channel. The trapezoidal channel dimensions were developed from the nearest few bathymetric survey cross sections in Missoula County. There were no structures located on this reach of the Bitterroot River.

4.7.3 2D Model Geometry

Computation Grid

A single 2D flow area was used for the entire Bitterroot River study area. The model limits were drawn to extend well beyond the flooding limits of the discharges modeled. The limit of the 2D flow area was also extended about 2 miles up the Clark Fork River to a location with a reasonably contiguous flow area. The limit of the 2D flow area was extended south into Ravalli County (with the terrain discussed in the previous section) to capture a location with a contiguous flow area. This extension was needed to allow the model computations to determine the split flows that occur near the Missoula/Ravalli County line.

Regular computational grid spacings of 50 feet and 200 feet were evaluated with initial model runs to determine the effects on model results and run time. The 200 feet grid model ran in less than five minutes while the 50 feet grid took over 110 minutes. There were no noticeable differences in the resulting water surface elevations at the locations sampled throughout the model.

Using the regular grid spacing at 200 feet, additional breaklines were added to define the river channels and influential embankments such as roads, natural ridges, and ditches. Breaklines were also added at bridges with piers to ensure cell faces captured the piers represented in the terrain. Some of the breaklines added also used a shorter cell spacing to improve definition of the terrain feature.

Surface Roughness

The basis for the surface roughness Manning's n layer used in the 2D flow area is the National Land Cover Database (NLCD 2018). The database was clipped with ESRI ArcMap to the study area. A review of the NLCD and aerial imagery indicated the NLCD adequately captured land uses and land covers correlating to various Manning's n values.

However, the active river channels of the Bitterroot and Clark Fork Rivers as shown on the terrain were not consistently represented in NLCD. Particularly at bridge crossings. To ensure the active river channels could have a consistent Manning's n value, the NLCD raster and a raster generated from the limits of the bathymetric surface were merged in ArcMap. This combined raster was used to build the Manning's n layer in HEC-RAS. The NLCD raster value names and corresponding Manning's n values are shown in Table 17.

Table 17. Manning's n Roughness and 2016 NLCD for 2D Modeling

Raster Value Name	Manning's n
0 (open water)	0.02
open water	0.02
cultivated crops	0.03
pasture/hay	0.03
grassland/herbaceous	0.03
developed, open space	0.03
shrub/scrub	0.04
barren land rock/sand/clay	0.05
developed, medium intensity	0.06
developed, low intensity	0.06
emergent herbaceous wetlands	0.07
woody wetlands	0.10
developed, high intensity	0.07
evergreen forest	0.09
deciduous forest	0.09
mixed forest	0.09

Note there are two raster values (0 and open water) that were set equal and used in the model calibration by varying the Manning's value for the river channels. All Manning's values were determined with guidance from Chow's *Open-Channel Hydraulics* (Chow 1959), USGS/FHWA *Guide for Selecting Manning's Roughness Coefficients for Natural*

Channels and Floodplains (USGS 1989), and USGS *Determination of Roughness Coefficients for Streams Colorado* (USGS 1985). The roughness values selected reflect engineering judgement and experience for streams in Montana. The engineering judgement also includes the historic timing of Bitterroot River flooding, which occurs during snow-melt runoff in early to mid-spring; after leaf emergence, but before mature vegetation leaf out throughout the floodplain.

Boundary Conditions

The 2D flow area contains three external boundary condition lines and three internal boundary condition lines. The two external inflow boundary condition lines are located at the upstream limits of the 2D flow area on the Bitterroot and Clark Fork Rivers. The single external outflow boundary condition line was located at the downstream limit of the 2D flow area on the Clark Fork River. The three internal inflow boundary condition lines are located at the flow change nodes from the hydrology report. The inflow hydrographs are constant for each boundary condition and modeled discharge as shown in Table 15. The outflow boundary condition was set using normal depth. All boundary conditions in the model required a slope value. The slopes used were measured in HEC-RAS at the boundary condition locations and are shown in Table 18.

Table 18. 2D Modeling Boundary Conditions

Boundary Condition Name	Type	Slope
CFR-INFLOW	Flow Hydrograph	0.00109
BITT-INFLOW	Flow Hydrograph	0.00077
USGS-BITT	Flow Hydrograph	0.00146
FLOW-300	Flow Hydrograph	0.00093
FLOW-400	Flow Hydrograph	0.00013
CFR-OUTFLOW	Flow Hydrograph	0.00088

Structures

No structures were built into the model computations. The main stem Bitterroot bridge piers and abutments were built into the terrain and have computational grid faces bisecting them as described previously.

All other structures are minor in flow capacity in relation to the discharges modeled. Many already have inundation areas surrounding them and are not located in discrete split flow paths where they would control the discharge of conveyance paths.

Additionally, all structures other than the bridges are culverts with invert elevations below the adjacent terrain elevations. This relationship is not allowed in HEC-RAS 2D flow areas, additional data would be necessary to build these into a functional 2D model. Interpretation of the 2D modeling results, evaluation of the larger culverts at Chief Looking Glass Road and E Carlton Creek Rd in HY8 analysis software and the 1D hydraulic model confirmed even the relatively large culvert crossings cannot convey flood flows from the upstream flow split and have little to no impact on flood flow routing.

4.7.4 Sensitivity Analysis and Calibration

Diffusion Wave & Full Momentum

The 2D flow area was initially set up using diffusion wave equations. With several abrupt contractions and expansions in the conveyance area, the full momentum equations with an eddy viscosity coefficient of 0.5 resulted in noticeable improvement of the water surface elevation results for the 1% AC discharge. The full momentum equations were then used for the remaining discharges.

Computation Time Step and Courant Number

A 15 second time step provided Courant Numbers throughout the entire model less than 3.0 for the 1% AC discharge except for two cells located at the HWY93 South Bridge (S121), the Courant Number for both cells remained below 5.0. the time step was reduced to 10 seconds to compare the effects at this location with little change in Courant Number or water surface elevations. The model time step of 15 seconds was used for the remaining discharges. The model simulation time was set to run 24 hours so that steady state could be achieved throughout the 2D flow area and verified by plotting the flow time series.

Theta

Theta was set at 0.6 following HEC-RAS guidance to provide an explicit solution and no model instability was observed.

Initial Conditions Time and Ramp Up

To allow sufficient time to meet steady state results and reduce model instability with a rapid flow increase, the initial conditions time was set to 24 hours with 0.1 fraction of this time to ramp up from zero flow.

Calibration Data

There are two USGS gages located within the model 2D flow area with data on high-flow events and water surface elevations. The water surface elevations for these flow events at these gages were calculated by adding the gage height recorded to the gage datum provided in the survey reports by DOWL (DOWL 2019). Unique model plans were set up with the discharges recorded in the USGS data (flow file) and the Manning's n values revised (geometry file) to calibrate the river channel Manning's n. The results of the calibration effort are summarized in Table 19. Sensitivity analysis of Manning's n values revealed the model was relatively insensitive to roughness value changes for the floodplain overbanks but was sensitive to roughness value changes for the main channel.

Table 19. 2D Modeling Calibration Results

USGS Gage	Discharge (cfs)	River Channel Manning's n	Gage WSE (ft)	Model WSE (ft)	WSE ∆ (ft)
Bitterroot at Missoula 12353500	24,800	0.02	3,129.73	3,129.10	-0.63
	24,800	0.015	3,129.73	3,128.61	-1.12
	24,800	0.04	3,129.73	3,130.80	1.07
Clark Fork River below Missoula 12353000	55,100	0.02	3,099.54	3,099.64	0.10
	55,100	0.015	3,099.54	3,098.96	-0.58
	55,100	0.04	3,099.54	3,102.18	2.64

4.7.5 2D Modeling Results Summary

The 2D hydraulic model results provided key information at several locations in the Bitterroot Study area. As discussed above, the 2D modeling results indicated a flood flow split at the southern Missoula County boundary. Extending the 2D model to upstream of the natural high ground and allowing the model to calculate the flow split across the topography provided split flow data for 1D model development. The 2D modeling results were also used to determine lateral flows moving between the main stem of the Bitterroot River and the Left Branch of Bitterroot River reach north of the Missoula County boundary.

The 2D hydraulic model results also indicated that the Bitterroot River floodplain below the convergence of the Left Branch of Bitterroot River originating south of the county boundary does not have an important flow split. The portion of the Bitterroot River floodplain between the convergence of the Left Branch of Bitterroot River and Lolo, Montana is braided and comingled. Primary flood flow is provided by the floodplain aligned with the main channel and the multiple braids and other low areas do not provide consistent or continuous flood conveyance at a hydraulic profile differing from the mainstem water surface elevations and gradients.

The 2D hydraulic model results were also used to develop 1D hydraulic model geometry adjacent to the US 93 bridge and roadway embankment and adjacent to the Maclay Bridge/River Pines Road bridge crossings. At the Maclay Bridge/River Pines Road location flow overtopping the road embankment was extracted from the 2D model and assigned to the 1D geometry to better represent the flood risk upstream of the bridge and below the "shadow" of the road embankment. At the US 93 bridge and roadway embankment location, a worst-case scenario was performed with the highway and Montana Rail Link (MRL) railroad embankments removed from the terrain. The worst-case scenario for flooding across the inside of the meander bend informed 1D cross section development below the bridge to reasonably represent flood risk in the area immediately downstream of the non-levee embankments.

Finally, the 2D hydraulic model results were used to align cross sections with flood flow directions and a constant potentiometric surface. This was particularly important at the confluence with the Clark Fork River where the flood flow directions are driven by both the topography and the mass flow and momentum relationships of the Bitterroot and Clark Fork River floodplains. Flow change information was extracted from the 2D model results to adjust flow assignments to the Bitterroot River and Clark Fork River cross sections to better represent the flood risk in the confluence area.

4.8 Cross Section Development

The hydraulic model was predominately based on the terrain data provided by Quantum Spatial, Inc. (QSI). End points for all cross sections were established as required to capture the boundaries of the 0.2% annual-chance (500-year) floodplain. Cross sections were placed at key locations along the reach including breaks in channel slope, abrupt changes in floodplain width, and at bridge, culvert and diversion structure locations. Cross sections were filtered to less than 500 points per cross section as required by HEC-RAS.

One-dimensional hydraulic model cross section station elevation data was extracted from the terrain surface with a low-flow bathymetric channel developed for the 2D hydraulic modeling. Manual cross section elevation edits within the low-flow stream channels were also performed to better align with channel bathymetry at key locations bounding hydraulic structures and at USGS stream gages used for model calibration. Edits to cross section geometry were also made to address minor variations in the stamped bathymetric channel above the LiDAR water surface elevation to ensure final floodplain mapping geospatial locations and widths were consistent between the 1D hydraulic modeling and the floodplain mapping.

Manual edits were also made to cross sections immediately bounding modeled structures on the Left Branch of Bitterroot River stream reach. This was needed to allow modeling of structures and roadway elevations in accordance with survey data rather than the LiDAR topography on the small side channels where bathymetric data was not available. This type of edit was typically needed for narrow and shallow channels and depressions where the LiDAR DEM data set appeared to have simplified the ground topography as part of the raster elevation model development process or was influenced by water in the stream.

At the Missoula/Ravalli county line, the effective Ravalli County cross section was duplicated from the effective USGS WSPRO hydraulic model. Roughness values and other assigned variables for the duplicated section were retained from the effective Ravalli County hydraulic model and do not necessarily align with values or value ranges used for the new HEC-RAS v5.0.7 hydraulic modeling for the Bitterroot River in Missoula County.

One-dimensional model cross sections placement and orientation was informed by the results of the calibrated 2D model. Cross sections were generally placed perpendicular to flow paths and parallel with water surface contours from the 2D hydraulic modeling results. Therefore, the hydraulic model cross sections and related geometry are more complex than standard practice for traditional 1D hydraulic model geometry development. This approach provides continuity between the 2D hydraulic model results and the 1D hydraulic model assumption of a constant water surface elevation for each model cross section. Placement of cross sections parallel as informed by the 2D hydraulic model also allowed direct measurement of lateral flows from the 2D hydraulic model results to be used as a target value for the 1D hydraulic model where flow split or lateral flow sharing occurs between 1D hydraulic model nodes.

For both the confluence of the Bitterroot and Clark Fork Rivers and the convergence of the Bitterroot River mainstem with the Left Branch of Bitterroot River, cross sections end points were butted together at the merge point of the flooding sources. At the confluence, cross sections associated with the Bitterroot and Clark Fork River above the junction collectively represent the floodplain area for flood flow conveyance. Lateral weirs were inserted in the 1D hydraulic model to assist in tracking areas of flow change between the model reaches. However, the lateral weir features are not active in the 1D hydraulic model and flow changes between the two reaches were assigned to the 1D hydraulic model directly from flow data extracted from the 2D hydraulic model.

Upstream of the US 93 and MRL Railroad crossing of the Bitterroot River, the railroad and highway embankments are not overtopped by the flood flows. However, the embankments do obstruct natural floodplain overbank flow paths across the inside of the large meander bend of the Bitterroot River. Cross sections were prepared perpendicular to the road embankments for the portion of the stream alignment flowing east across the Bitterroot Valley above the bridge crossings. Below the bridge crossings, the cross sections were extended across the entire Bitterroot River and aligned with the results of a 2D model worst-case scenario where the embankments were removed from the ground topography. This allows the 1D model to reasonably represent flood risk for both the existing condition upstream of the embankments and for the potential condition of failure of the non-levee embankments and associated increased flood risk throughout the natural floodplain immediately downstream (north) of the highway and railroad bridge crossing.

4.9 Hydraulic Structures

The geometries of hydraulic structures were modeled based on data collected during the Structure Survey (Pioneer 2020b). The data package included GPS survey points for 18 hydraulic structures located within the study limits. Eleven of the structure were determined to be insignificant. Seven of the structures were included in the hydraulic model and are listed in Table 13. Each structure was assigned an identification code with an 'S' and a number generally corresponding to the order of the structures beginning at the downstream extent of the tributary stream study reach and progressing upstream. The structures crossing Bitterroot River include highway crossings, railroad track alignments, and roadway crossings along County, frontage or private roadways.

Expansion and contraction coefficient assignments at the two upstream and one downstream bridge cross sections were used to model bridge/culvert/diversion constrictions. The expansion and contraction coefficients were generally increased from the natural channel values of 0.1 and 0.3, to 0.3 and 0.5, respectively. This standard hydraulic modeling practice was employed to account for the increased head loss associated with the relatively abrupt transitions and increasing/decreasing velocities that accompany the expansion and contraction of flows at hydraulic conveyance structures. These values are recommended in the HEC-RAS model documentation and reference manuals.

The bridge modeling approach was set for both high and low-flow methods based on the bridge configuration. High flow methods were either the Energy (Standard Step) or Pressure/Weir flow. The Energy method (Standard Step) was utilized when there was freeboard to the bridge low-chord and/or when the road elevation approaching the bridge was lower than the crossing producing a bridge that was perched above the roadway elevation in the overbanks. Otherwise, the Pressure/Weir flow method was the high flow method used when flood waters would impact and/or overtop the bridge structure.

The low-flow methods include the Energy, Momentum or Yarnell methodologies. Only the Energy method was utilized for clear-span structure with no piers. The Momentum Balance and Yarnell equation methods were evaluated if the structure was constructed with mid-span piers. The Momentum and Yarnell methods are low-flow methods used to account for the hydraulic losses due to water moving around the piers. The momentum method required an input for the drag coefficient (C_D), and the Yarnell equation required a pier shape coefficient (K).

The pier shapes for the bridge structures consisted of square nose piers, circular piers and elongated piers with 90° angle triangular or semicircular nose and tail geometry. The C_D and K coefficients used for the different pier shapes are summarized in Table 20.

Table 20. Pier C_D and K Coefficients

Pier Shape	C_D	K
Triangular nose with 90° angle	1.6	0.9
Semicircular nose and tail	1.33	0.9
Square Piers	2.0	1.25

A summary of the bridge structure and hydraulic model settings for each structure are summarized in Tables 21 and 22, respectively.

Culvert crossings were modeled using survey measurements for the invert and crest of culvert provided by Pioneer. Overbank data was extracted from the LiDAR terrain data. In this study, culvert barrel inverts were commonly below the bounding channel elevations, due to LiDAR averaging in narrow streams or LIDAR influenced by water in the stream. Internal hydraulic structure cross sections were adjusted as needed to fit with survey data and field photograph interpretation. This approach more closely matched culvert invert depth below the roadway deck and provided reasonable backwater elevations controlled by the channel elevations bounding the structure. A summary of culvert structure hydraulic model settings is provided in Table 23.

The following sections describe the unique conditions for hydraulic structure crossings for Bitterroot River Reach 1 and Bitterroot River Reach 2. All other hydraulic structures were modeled using standard engineering and HEC-RAS practice.

4.9.1 Bitterroot River Reach 1

Bitterroot River Reach 1 has three modeled hydraulic structure crossings. Several small culverts were determined to be insignificant because the amount of flow that they could pass would not influence flood flows. The structure crossing River Pines Road at RS

4,000 is constructed with both triangle nose piers and square piers because HEC-RAS only allows one pier coefficient for piers, the pier coefficient was set for the triangle nose piers that are in the primary flow area. As mentioned above, the Maclay Bridge/River Pines Road location flow overtopping the road embankment was extracted from the 2D model and assigned to the 1D geometry to better represent the flood risk upstream of the bridge and below the "shadow" of the road embankment.

The structure crossing the MRL Railroad at RS 26,890 is also constructed with both triangle nose piers and square piers because HEC-RAS only allows one pier coefficient for piers the pier coefficient was set for the triangle nose pier that are in the primary flow area.

4.9.2 Bitterroot River Reach 2

Bitterroot River Reach 2 has one modeled hydraulic structure crossing the Bitterroot River and three modeled hydraulic structures crossing Left Branch of Bitterroot River. Several small culverts were determined to be insignificant because the amount of flow that they could pass would not influence flood flows or they were outside of the flow channels for the reach. The Bitterroot River structure crossing Maclay Ranch Road at RS 78,702 does not include a roadway embankment that encroaches on the floodplain; therefore, the cross-sections do not bound the roadway on the left and right overbanks.

As mentioned in the 2D model development, the E Carlton Creek Road and private bridge structures modeled along the Left Branch of Bitterroot River are not adequate to pass the full flow that is conveyed on the western side of the valley and majority of the flood flow overtops the roadways to the east of the structure, for this reason it was determined that the profile baseline would not pass through the structures.

The bridge and culvert crossing structure and modeling data are summarized in Tables 21, 22 and 23.

Table 21. Summary of Bridge Structures

ID No.	Roadway	Stream Reach	River Station (feet)	Spans	Total Span (feet)	Deck Width (feet)	Pier Widths (feet)	Appendix C Photo Page #
S120	River Pines Road	Bitterroot River	4,000	4	342.5	17.3	5.2**, 5.2**, & 2.5	1
S121	Highway 12/93	Bitterroot River	26,780	4	347.4	77.5	Three at 3.5	5
S122	MRL Railroad	Bitterroot River	26,890	4	410.7	10	1, 7.1, 9.7**, 9.7**, 6.8, & 1	10
S129	Maclay Ranch Road	Bitterroot River	78,702	1	203.6	10	-	16
S136	Private Bridge*	Left Branch of Bitterroot River	12,330	1	32	16.3	-	Not Available

* Bridge structure not surveyed; No Access granted
** Mean width reported

Table 22. Summary of Bridge Model Settings

ID No.	Roadway	Stream Reach	River Station (feet)	Contraction Coefficient	Expansion Coefficient	Low Flow Method	High Flow Method
S120	River Pines Road	Bitterroot River	4,000	0.3	0.5	Momentum	Energy Only
S121	Highway 12/93	Bitterroot River	26,780	0.3	0.5	Momentum	Energy Only
S122	MRL Railroad	Bitterroot River	26,890	0.3	0.5	Momentum	Energy Only
S129	Maclay Ranch Road	Bitterroot River	78,702	0.3	0.5	Energy	Energy Only
S136	Private Bridge	Left Branch of Bitterroot River	12,330	0.3	0.5	Energy	Energy Only

Table 23. Summary of Culvert Crossings

ID No.	Roadway	Stream Reach	River Station (feet)	Culvert Length (feet)	Culvert Type	Culvert Shape	Culvert Size (feet)	Appendix C Photo Page #
S137	E Carlton Creek Road	Left Branch of Bitterroot River	9,000	50	CSPA	Double Barrel Arch	5.4x7.6, 5.4x7.6	18
S137	Chief Looking Glass Road	Left Branch of Bitterroot River	14,019	57.4	RCP	Triple Barrel Circular	6.0, 6.0, 6.0	19

Culvert Types:
CSPA – Corrugated Steel Pipe Arch,
RCP – Reinforced Concrete Pipe,

Photographs 1 thru 5 illustrate the different types of roadway hydraulic conveyance structures that were modeled for the Bitterroot River Flood Risk Project. Photographs of all the modeled bridge, culvert, and diversion structures which were evaluated during the structure survey are provided in Appendix C.

Photograph 1: Bitterroot River – River Pines Road (S120)

Photograph 2: Bitterroot River – Highway 12/93 and Railroad (S121 & S122)

Photograph 3: Left Branch of Bitterroot River – E Carlton Creek Rd at RS 9,000 (S135)

Photograph 4: Bitterroot River – Maclay Ranch Road at RS 78,702 (S129)

Photograph 5: Left Branch of Bitterroot River – Chief Looking Glass Rd at RS 14,019 (S137)

4.10 Manning's 'n' Values

Manning's 'n' values are coefficients representing the frictional resistance (surface roughness) acting on water when flowing overland or through a channel. The coefficients are used in the calculations to determine water surface elevations. Fourteen land classes were developed for the study area based on the National Land Cover Database (NLCD 2018) to establish Manning's 'n' values based on ground and cover conditions. Manning's 'n' values assigned to the fourteen land classes with guidance from Chow's *Open-Channel Hydraulics* (Chow 1959), USGS publications, *Guide to Selecting Manning's Roughness Coefficients for Natural Channels and Flood Plains* (USGS 1989) and *Determination of Roughness Coefficients for Streams Colorado* (USGS 1985) were also referenced to confirm Manning's roughness value assignments and reasonable ranges for various landcover types. The roughness values selected reflect engineering judgement and experience for streams in Montana. The engineering judgement also includes the historic timing of Bitterroot River flooding, which occurs during snow-melt runoff in early to mid-spring; after leaf emergence, but before mature vegetation leaf out of throughout the floodplain.

The landcover data set from the 2D hydraulic model development was used to assign Manning's roughness values to 1D hydraulic model cross sections. The roughness layer is a conversion from the NLCD raster-based landcover dataset which has a resolution of 100 feet. HEC-RAS 1D hydraulic models are limited to 20 roughness changes throughout a cross section. Due to the width of the Bitterroot River floodplain and the raster resolution, there were many cross sections where the initial landcover data set developed for the 2D hydraulic model exceeded the allowed number of roughness changes. Therefore, the landcover dataset was edited to eliminate small areas of landcover within larger landcover categories to generalize the landcover data to a resolution suitable for the 1D hydraulic model limitations.

The potential range of Manning's 'n' values for each landcover class along with the values selected for 1D hydraulic modeling are summarized in **Error! Reference source not found.**24.

Table 24. Manning's n Roughness and 2016 NLCD for 1D Hydraulic Modeling

NLCD Value Name	Potential Manning's 'n' Value Range	Initial Value
Open Water	0.025 – 0.040*	0.028
Cultivated Crops	0.028 – 0.055	0.030
Pasture/Hay	0.028 – 0.055	0.030
Grassland/Herbaceous	0.028 – 0.055	0.030
Shrub/Scrub	0.035 – 0.060	0.040
Barren Land Rock/Sand/Clay	0.040 – 0.070	0.050
Emergent Herbaceous Wetlands	0.045 – 0.080	0.070
Woody Wetlands	0.055 – 0.120	0.100
Evergreen Forest	0.050 – 0.100	0.090
Deciduous Forest	0.050 – 0.100	0.090
Developed, Open Space	0.028 – 0.040	0.030
Developed, Low Intensity	0.050 – 0.070	0.060
Developed, Medium Intensity	0.050 – 0.090	0.060
Developed, High Intensity	0.060 – 0.100	0.070

* Channel value range was 0.025 to 0.040 other than transitioning to and duplicating Ravalli County cross section at the Missoula/Ravalli county line.

The location of the roughness values for the channel were manually adjusted from the initially extracted station locations to align with the final bank station assignments for the 1D hydraulic model. Manning's 'n' values for the channel were evaluated based on hydraulic modeling response. Adjustments, within the reasonable range, were made to sub-reaches of the hydraulic model to improve correlation between the 2D and 1D hydraulic model results and to yield reasonable profiles in the final model. Changes were not made to the overbank landcover roughness values.

Note that the roughness value for the mainstem river channel in the 1D modeling is higher than the value used for the 2D modeling. Due to the difference between 2D and 1D hydraulic model logic and computation methods, a shift in the assigned roughness values was necessary to calibrate each model type with the stream gage data. The 2D hydraulic model results generally correlate within one half foot of the 1D model results throughout the Bitterroot River study area. The average computed water surface elevation correlation between the two approaches is typically within a few tenths of a foot.

4.11 Areas of Non-Conveyance

As indicated on the Hydraulic work maps in Appendix A, there are reaches where no flow or backwater conditions exist. These conditions provide limited or no-conveyance in the downstream direction. For these areas, the ineffective flow area method was implemented to calculate the total effective conveyance for each cross section in the hydraulic simulation.

The areas of non-conveyance included the following:

- Backwater and ponded areas.
- Flow constriction or expansion.
- Areas isolated by non-accredited earthen berms or railroad and roadway embankments.
- Presence of high topography either upstream or downstream that eliminates flow in a topographically low area.
- Non-conveyance related to profiles exceeding the 1% AEP flow where needed to compute reasonable profiles.

The permanent option for ineffective areas was utilized occasionally throughout the hydraulic models. The permanent option was utilized as part of the suite of variable adjustments necessary to yield reasonable relationships between the profiles. When the permanent ineffective flow option was used, the water surface elevation for the 1% AEP profile was reviewed to ensure the permanent option did not appreciably alter the regulatory water surface elevation. Where ineffective areas have been set in the hydraulic models, a comment was included in the cross section description noting the reason the ineffective area was utilized. This method of documentation was selected to aid in both hydraulic model review for this flood study and to provide future model users with easy access to the purpose of the ineffective flow setting at each model node.

Review of the modeled cross sections in HEC-RAS identified connected backwater depression areas that are not hydraulically connected to the stream body. These areas were also classified as ineffective flow areas so that the model calculated the appropriate conveyance at the cross section. The river stations where connected backwater occurs are discussed in more detail in Section 5.1.

4.12 1D Hydraulic Modeling for Split Flow and Flow Change Informed by 2D Modeling

Flow change information was extracted from the 2D hydraulic model results at the confluence to assign comingling flood flows to the cross sections associated with the Bitterroot and Clark Fork Rivers. Flow change information was also extracted from the 2D hydraulic model and assigned to the 1D model to appropriately represent the overtopping of River Pines Road (Maclay Bridge) just upstream of the Bitterroot River and Clark Fork River confluence. As discussed in section 4.2 and section 4.7, the 2D hydraulic analysis indicated a split flow reach at the southern Missoula County boundary.

4.12.1 Flow Change – Confluence and River Pines Road/Maclay Bridge

One-dimensional hydraulic model logic is based on a profile baseline representing a stream reach. Confluence between stream reaches is typically modeled using a junction model node and cross sections are developed for each stream reach. Traditional 1D hydraulic model logic does not allow cross sections to cross multiple model river reach lines. The flow pattern indicated in the 2D model results indicates a small angle between the Bitterroot and Clark Fork River model reach lines. Development of cross sections meeting 1D hydraulic model logic was completed by aligning endpoints of the cross sections associated with both the Bitterroot and Clark Fork River reach lines. Collectively, the two cross sections represent the total conveyance of the floodplain through the confluence.

Due to the geometric relationship of the main stem channels at the confluence, the cross section width for cross sections associated with the Bitterroot River become narrower as the junction node is approached. Assigning the full Bitterroot River flood source flow to the first three cross sections on the Bitterroot River overestimated the water surface elevation on the Bitterroot River and the tie in with the Clark Fork River modeled water surface elevation for the 1% AC profile was poor. Flow conveyed by each of the downstream cross sections was extracted from the 2D hydraulic model results as a target for the 1D hydraulic model flow and stage results. The optimization tool in the 1D hydraulic model was utilized to automatically track flow sharing across the lateral area between model cross sections. With the automatic optimization routine, flow conservation is maintained in the model computations and flow at each cross section is automatically assigned by the software. Lateral structure variables were assigned to maintain alignment between the 2D and 1D hydraulic model results. This approach allowed reasonable representation of flood risk and computed 1D hydraulic model water surface elevations well within the typical one-half foot tie in between the Bitterroot and Clark Fork River cross sections. The flow change discharges are summarized in Table 25 and presented for the 1% AC profile on Figure 6.

The road embankment for River Pines Road west of the Maclay Bridge inhibits flood access to the valley floor on the inside of a large meander bend of the Bitterroot River. The road is generally aligned with the main stem channel of the Bitterroot River and perpendicularly to the natural overbank flood flow direction on the inside of the meander bend (Figure 6). The geometry of the road and bridge crossing do not align with ideal 1D hydraulic model geometry development or model logic. Additionally, the floodplain extents immediately downstream of the road embankment extend from the hillside forming the western side of the valley across the inside of the meander to the main channel. Topographic features between the confluence and River Pines Road do not indicate flood risk along a flood reach with dissimilar water surface elevations from the mainstem water surface elevations.

Therefore, lateral weirs were developed between the left end points of the cross sections perpendicular to River Pines Road upstream of the Maclay Bridge (Figure 6). These lateral weirs provide model structure to transfer flow overtopping River Pines road to the valley-wide cross section (RS 3818) immediately below River Pines Road. As noted above for the confluence area, the optimization functionality of HEC-RAS was used to compute and track flow leaving the upstream cross sections and entering cross section 3818. Flow results across River Pines Road were extracted from the 2D hydraulic model and used as targets for the 1D hydraulic model. Lateral structure variables were assigned to maintain alignment between the 2D and 1D hydraulic model results. Full flood flows for the Bitterroot River were assigned to cross section 3,818 below the bridge and the River Pines Road embankment to represent conveyance of all flooding by the valley-wide cross section. The flow change discharges are summarized in Table 25 and presented for the 1% AC profile on Figure 6.

Table 25. River Pines Road/Maclay Bridge Flow Data Summary

Bitterroot River Reach 1 - River Pines Road/Maclay Bridge Flow Data Summary

Plan: Bitterroot River R1 MultipleProfile

Recurrance Interval		Bitterroot River River Station														
		65150	47149	26592	6023[1]	5610[1]	5196[1]	4719[1]	4244[1]	4044[1]	3818	1454[2]	1168[2]	876[2]	520[2]	32[2]
Flow Rate (cfs)	10% AC	21,900	22,700	23,500	23,500	23,500	23,500	23,500	23,500	23,500	23,500	24,303	24,407	24,347	21,184	22,599
	4% AC	25,300	26,400	27,300	27,300	27,300	27,294	27,246	27,246	27,246	27,300	27,405	27,065	26,406	22,589	24,105
	2% AC	27,900	28,900	29,800	29,774	29,682	29,537	29,085	29,062	29,062	29,800	30,214	29,833	29,044	24,848	26,314
	1% AC	30,400	31,400	32,400	32,295	31,929	31,486	30,500	30,363	30,363	32,400	31,999	31,490	30,516	26,005	27,517
	1%+ AC	35,900	36,600	37,800	37,257	36,164	35,042	32,957	32,199	32,183	37,802	36,629	35,946	34,698	29,550	31,093
	0.2% AC	36,100	36,900	38,000	37,438	36,316	35,167	33,039	32,249	32,231	37,998	36,763	36,063	34,790	29,652	31,260

Note 1: Bitterroot River flows adjacent to US side of River Pines Rd reduced from source flood flow by amount overtopping road. Full flood source flow resumes at Bitterroot River RS 3818

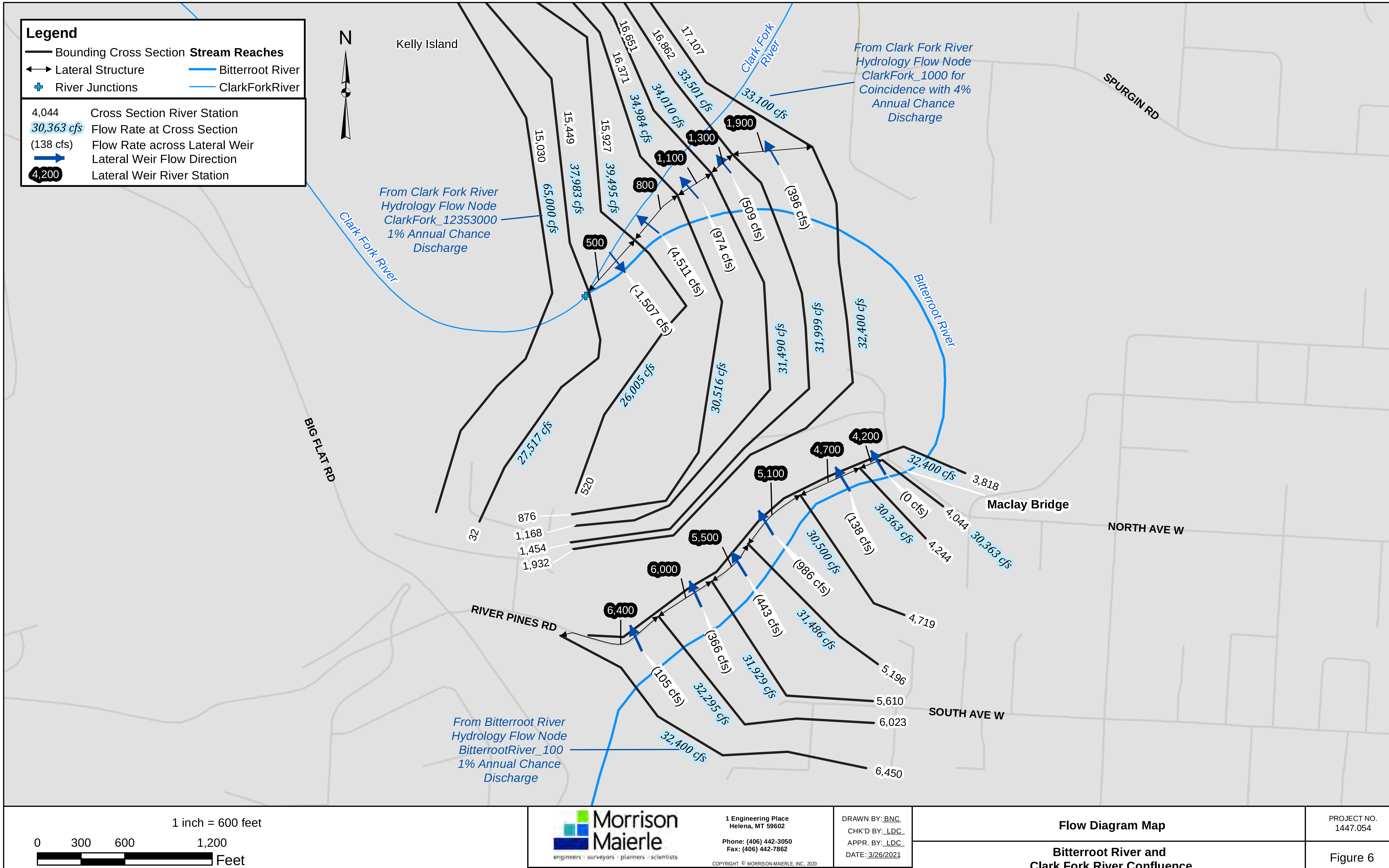
Note 2: Bitterroot River Clark Fork River flow exchanges in confluence area

Recurrance Interval		Clark Fork River River Station					
		23768	16862	16651	16371	15927	15449
Flow Rate (cfs)	10% AC	27,500	26,697	26,593	26,653	29,816	28,401
	4% AC	27,500	27,395	27,735	28,394	32,211	30,695
	2% AC	33,100	32,686	33,067	33,856	38,052	36,586
	1% AC	33,100	33,501	34,010	34,984	39,495	37,983
	0.2% AC	37,100	38,271	38,954	40,202	45,350	43,807
	1%+ AC	37,100	38,337	39,037	40,310	45,448	43,840

Lateral Weir Flow Data Summary Table

Recurrance Interval		Bitterroot River - Reach 1						Clark Fork River - US				
		6400	6000	5500	5100	4700	4200	1900	1300	1100	800	500
Flow Rate (cfs)	10% AC	0	0	0	0	0	0	-803	-103	60	3166	-1411
	4% AC	0	0	6	48	0	0	-105	340	660	3818	-1513
	2% AC	26	92	145	452	24	0	-399	383	791	4202	-1464
	1% AC	105	366	443	986	138	0	396	509	974	4511	-1507
	1%+ AC	541	1093	1122	2085	762	16	1171	682	1247	5146	-1545
	0.2% AC	562	1122	1149	2126	791	17	1252	701	1272	5129	-1609

Note: Conservation of flow was confirmed at the downstream boundary of all Lateral Weir nodes where cross section end points align between reaches.



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APPR. BY: LDC
DATE: 3/26/2021

Flow Diagram Map

Bitterroot River and Clark Fork River Confluence

PROJECT NO. 1447.054

Figure 6

4.12.2 Flow Split at Missoula County Boundary – 1D Model Development

As mentioned in Section 4.7 above, the purpose of the 2D model is to provide clarity on the split flow flood flow rates and to demonstrate flood flow patterns. These two inputs allow efficient development of 1D modeling since flood flow rates can be directly assigned in the model. Additionally, 1D model cross sections can be constructed that are perpendicular to the flood flows and confirm that the 1D constraint of a single flood elevation across a cross section is appropriate by orienting cross sections parallel to 2D model water surface elevation contours.

The 2D model results indicated that there is a split flow that occurs upstream of the Ravalli/Missoula County boundary routing flood flows through the Left Branch of Bitterroot River drainage area on the west side of the valley. The 1D model included this as a split flow reach because output from the 2D model indicated that water surface elevations from on west side of the valley were significantly different which makes development of valley wide cross sections difficult. As described in Section 4.8 Cross Section Development, cross sections for the 1D hydraulic model were aligned perpendicularly to the general flood flow direction indicated by the 2D modeling. At the convergence of the Bitterroot River mainstem with the Left Branch of Bitterroot River, cross sections end points were butted together at the merge point of the flooding sources with lateral weirs set in between to allow for flow sharing.

As described above, flow conveyed by each of the lateral weirs was extracted from the 2D hydraulic model results as a target for the 1D hydraulic model flow and stage results. The optimization tool in the 1D hydraulic model was utilized to automatically track flow sharing across the lateral area between model cross sections. With the automatic optimization routine, flow conservation is maintained in the model computations and flow at each cross section is automatically assigned by the software. Lateral structure variables were assigned to maintain alignment between the 2D and 1D hydraulic model results. This approach allowed reasonable representation of flood risk and computed 1D hydraulic model water surface elevations. The water budget for the split flow is provided in Table 26 for all profiles. The split flow relationships are illustrated for the 1% AEP profile in the flow diagram shown on Figure 7. Flow rates for the split flow flooding within the Left Branch of Bitterroot River reach were extracted from the 2D model using profile lines. The profile lines were aligned with 1D lateral weirs. The flow logic included measurement of flood flow rates at the lateral weir associated with the split flow path. The flood flow in the Left Branch of Bitterroot River flow path was subtracted from the associated cross section in the Bitterroot reach to ensure conservation of flow throughout the model domain.

Hydraulic structures were modeled as described in Section 4.7 above. Lateral weirs were inserted in the 1D hydraulic model at the lateral flow divergence and convergence locations for the 1% AEP profile. Lateral weirs were also placed at locations where cross section end points were insufficient to contain the 0.2% AEP flood profile to meet FEMA modeling requirements and standard engineering practice. The 1D hydraulic model does not actively optimize the flow rate across the lateral weirs separating the split flow reaches.

A Junction node was utilized at convergence of the Left Branch of Bitterroot River flow reach with Bitterroot River. Flow lengths across the junction were adjusted to represent the centerline flow path of flood flows rather than the profile baseline alignment distance as appropriate. The Energy Equation was selected as the junction computation mode.

Table 26. Bitterroot River- Left Branch of Bitterroot River Flow Data Summary

Missoula-Granite PMR (Bitterroot River)
Mapping Activity Statement: No. 2019-02
Bitterroot River Reach 2 - Split Flow Data Summary
Plan: Bitterroot River R2 MultipleProfile

Recurrance Interval		Bitterroot River Reach 2 River Station															
		Segment B														Segment A	
		111207	107412*	105623*	104913*	104731*	102284*	100861*	99624*	97648*	96905*	96545*	95383*	94425*	93931*	93200	71002
Flow Rate (cfs)	10% AC	18,363	18,226	18,226	18,226	18,065	18,073	18,073	18,067	18,055	18,055	18,055	18,055	18,055	18,055	18,500	21,900
	4% AC	20,646	20,471	20,471	20,471	20,185	20,198	20,198	20,189	20,167	20,163	20,161	20,152	20,152	20,152	21,000	25,300
	2% AC	23,025	22,809	22,753	22,753	22,294	22,314	22,314	22,321	22,285	22,263	22,258	22,228	22,228	22,228	23,900	27,900
	1% AC	24,402	24,160	24,038	24,038	23,470	23,496	23,500	23,559	23,514	23,461	23,452	23,504	23,504	23,504	26,100	30,400
	1%+ AC	27,984	27,662	27,282	27,277	26,392	26,440	26,534	27,112	27,037	26,807	26,764	27,240	27,252	27,266	33,100	35,900
	0.2% AC	27,854	27,535	27,161	27,157	26,284	26,331	26,418	26,943	26,870	26,650	26,609	27,068	27,079	27,092	32,800	36,100

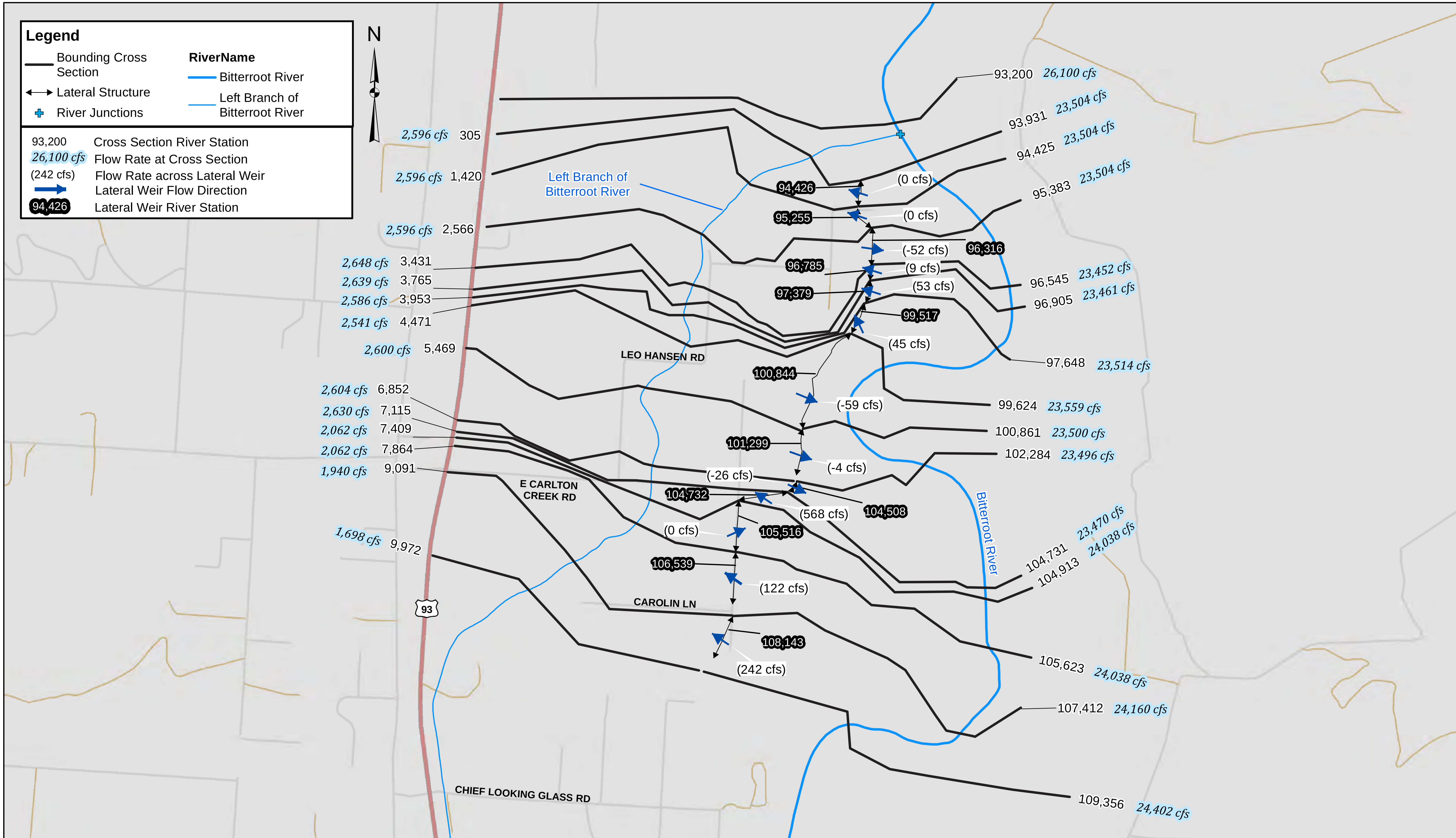
*Bitterroot River flows reduced by flow into Left Branch of Bitterroot River as indicated by 2D model. Full flood source flow resumes at Bitterroot River RS 93,200.

Recurrance Interval		Left Branch of Bitterroot River Station													
		14432	9091	7864	7409	7115	6852	5469	4471	3953	3765	3431	2566	1420	305
Flow Rate (cfs)	10% AC	137	274	274	274	435	427	427	433	445	445	445	445	445	445
	4% AC	354	529	529	529	815	802	802	811	833	837	839	848	848	848
	2% AC	875	1,091	1,147	1,147	1,606	1,586	1,586	1,579	1,615	1,637	1,642	1,672	1,672	1,672
	1% AC	1,698	1,940	2,062	2,062	2,630	2,604	2,600	2,541	2,586	2,639	2,648	2,596	2,596	2,596
	1%+ AC	5,116	5,438	5,818	5,823	6,708	6,660	6,566	5,988	6,063	6,293	6,336	5,860	5,848	5,834
	0.2% AC	4,946	5,265	5,639	5,643	6,516	6,469	6,382	5,857	5,930	6,150	6,191	5,732	5,721	5,708

Lateral Weir Flow Data Summary Table

Recurrance Interval		Bitterroot River - Reach 2												
		108143	106539	105516	104732	104508	101299	100844	99517	97379	96785	96316	95255	94426
Flow Rate (cfs)	10% AC	137	0	0	161	-8	0	6	12	0	0	0	0	0
	4% AC	175	0	0	286	-13	0	9	22	4	2	9	0	0
	2% AC	216	56	0	459	-20	0	-7	36	22	5	30	0	0
	1% AC	242	122	0	568	-26	-4	-59	45	53	9	-52	0	0
	1%+ AC	322	380	5	885	-48	-94	-578	75	230	43	-476	-12	-14
	0.2% AC	319	374	4	873	-47	-87	-525	73	220	41	-459	-11	-13

Note: Conservation of flow was confirmed at the downstream boundary of all Lateral Weir nodes where cross section end points aligned between reaches.



1 inch = 1,500 feet

0 750 1,500 3,000 Feet

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CHK'D BY: KKM
APPR. BY: LDC
DATE: 3/26/2021

Flow Diagram Map

Bitterroot River and Left Branch of Bitterroot River Confluence

PROJECT NO. 1447.054

Figure 7

4.13 Critical Depth & Profile Smoothing

Critical depths have been allowed to remain in the model at locations where a critical or supercritical flow regime is hydraulically reasonable and follows the research results that the United States Forest Service (USFS) has published for moderately steep and steep streams (USFS 2014). Generally, these critical depths are at locations where the channel profile drops at a significant gradient or where a flow regime change could occur. As this model has been completed using sub-critical calculation routines in HEC-RAS, a super-critical profile is not provided in the model.

Profile smoothing is required where minor modeling numerical idiosyncrasy or, structural effects result in a water surface elevation higher than the upstream calculation node. As this type of hydraulic jump is less conservative than a water surface profile that is flat or increases upstream, the numerical model is checked and adjusted to remove the drawdown. In some cases, especially around structures, a hydraulic jump downstream may reasonably occur; in these cases, the flood profile is smoothed to present reasonable water surface elevations. Smoothing was completed in accordance with FEMA Guidance *Flood Profiles* (FEMA 2016a). The hydraulic model is adjusted for the 1% AC flood profile. Other profiles were smoothed at locations where model inputs resulted in a drawdown for the non-regulatory flood profile.

4.14 Model Calibration

As discussed in section 3.1.6, the flood flow modeled on the Clark Fork River below the confluence with the Bitterroot River is the recommended peak flood flows for each regulatory profile. The flood flows for the downstream reach of the Clark Fork River are from the gage analysis of USGS gage 12353000, Clark Fork River below Missoula MT. The Bitterroot River reach includes USGS gage 12352500 Bitterroot River near Missoula MT, which is just downstream of the US 93 crossing of the Bitterroot River. Both of these gages are active and have a long period of record. Historic peak flow data was extracted from the gage records for use in model calibration and results verification. Calibration of the 1D model was developed primarily by adjusting the channel Manning's roughness. The 1D hydraulic model was sensitive to global changes in channel roughness and relatively insensitive to changes in overbank roughness. Therefore, calibration of the 1D model was completed by varying the global channel roughness with no changes to the overbank roughness values.

Reference marks for the USGS gages were surveyed in fall 2019 by DOWL (DOWL 2019b & DOWL 2019c). Water surface elevations were calculated for the highest available flow records based on the USGS gage height records and the 2019 DOWL survey in NAVD88 datum. For the Clark Fork River Gage, there were five separate historic flood events within +/- 10% the 4% AC flood profile peak flow. These were the largest available flow records in the stream gage data. The stage and discharge for the five events were plotted and a parabolic regression was prepared to allow calculation of the expected gage elevation for the 4% AC flood profile. The purpose of the regression was to prepare a single calibration comparison value that reasonably represented the scatter of historic stage discharge relationships at the gage. The modeled water surface of the Clark Fork River was within a tenth of a foot for the 4% AC profile peak flow rate of

54,900 cfs (Figure 8). This calibration result is well within the four tenths of a foot stage scatter in the gage record (see 1972 & 2018 records). The 1D hydraulic modeling results for Clark Fork River below the confluence are reasonably calibrated for the purposes of a floodplain study.

DOWL Survey of Gage Height (NAVD88)

DOWL Missoula County Clark Fork River USGS Stream Gage Report dated October 2019

USGS Gage 12353000 - Clark Fork River below Missoula MT

Peak Flow Data within +\- 10% of Q25

Date	Gage Height (ft)	Stream Flow (cfs)	WSEL NAVD88 (feet)
5/18/1997	12.18	55,100	3099.54
5/23/1948	12.08	52,800	3099.44
6/3/1972	11.71	52,200	3099.07
5/11/2018	12.14	52,200	3099.50
6/10/1964	11.45	50,100	3098.8

Gage Datum 3087.36 NAVD88

Calculated Gage Height from Flow Curve

	Stream Flow (cfs)	WSEL (ft NAVD88)
≈ CFR RS 7,870 Q_{25}	54,900	3,099.6
Model CFR RS 7,643	**54,900**	**3,099.5**
Model CFR RS 8,076	**54,900**	**3,099.8**

Note: 1997 Data is nearly identical to Flood Study Q25

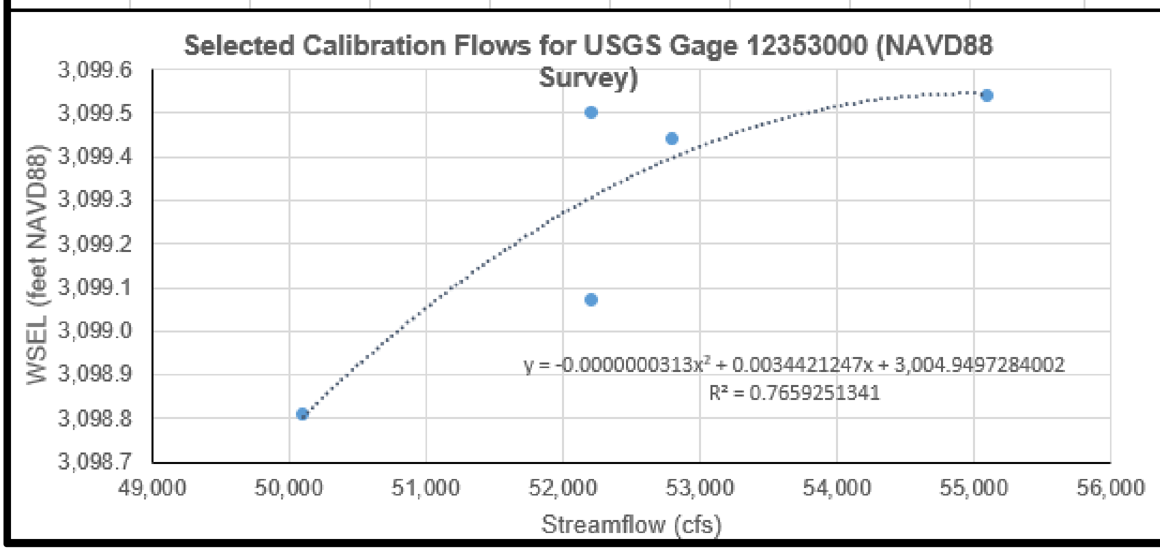

Figure 8. 1D Hydraulic Model Calibration to Clark Fork River Stream Gage 12353000

For the Bitterroot River Gage, there were six separate historic flood events within +/- 20% the 10% AC flood profile peak flow. Of those historic events, one was within 10% of the 4% AC flood profile. These were the largest available flow records in the stream gage data. The stage and discharge for the six events were plotted and a parabolic regression was prepared to allow calculation of the expected gage elevation for the 10% and 4% AC flood profiles. The purpose of the regression was to prepare a single calibration comparison values that reasonably represented the scatter of historic stage discharge relationships at the gage. The modeled water surface of the Bitterroot River was within four tenths of a foot for the 10% AC profile peak flow rate of 22,700 cfs and within one tenth of a foot for the 4% AC profile peak flow rate of 26,400 cfs (Figure 9).

This calibration result is well within the four tenths of a foot stage scatter in the gage record (see 1996, 2008 & 2018 records). The modeling results for Bitterroot River in the vicinity of the US 93 bridge crossing are reasonably calibrated for the purposes of a floodplain study.

DOWL Survey of Gage Height (NAVD88)

DOWL Missoula County Bitterroot River USGS Stream Gage Report dated October 2019

USGS Gage 12352500 - Bitterroot River near Missoula MT

Recent Peak Flow Records (post 1990)

Date	Gage Height (ft)	Stream Flow (cfs)	WSEL NAVD88 (feet)
5/18/1997	13.11	24,800	3129.73
6/1/2003	12.65	21,600	3129.27
6/10/1996	11.83	20,300	3128.45
5/21/2008	11.97	19,600	3128.59
5/11/2018	12.23	19,400	3128.85
6/9/2011	11.37	18,600	3128.0

Gage Datum 3116.62 NAVD88

Calculated Gage Height from Flow Curve

	Stream Flow (cfs)	WSEL (ft NAVD88)
Q_{10}	22,700	3,129.5
Q_{25}	26,400	3,129.8
Model Btrrt RS 26,707 Q_{10}	**22,700**	**3,129.2**
Model Btrrt RS 26,707 Q_{25}	**26,400**	**3,129.9**

Note: 1899 peak flow data is nearly identical to Flood Study Q_{500}. However, reported gage height in 1899 is inconsistent with gage heights reported for much lower flows over the past 30 years.

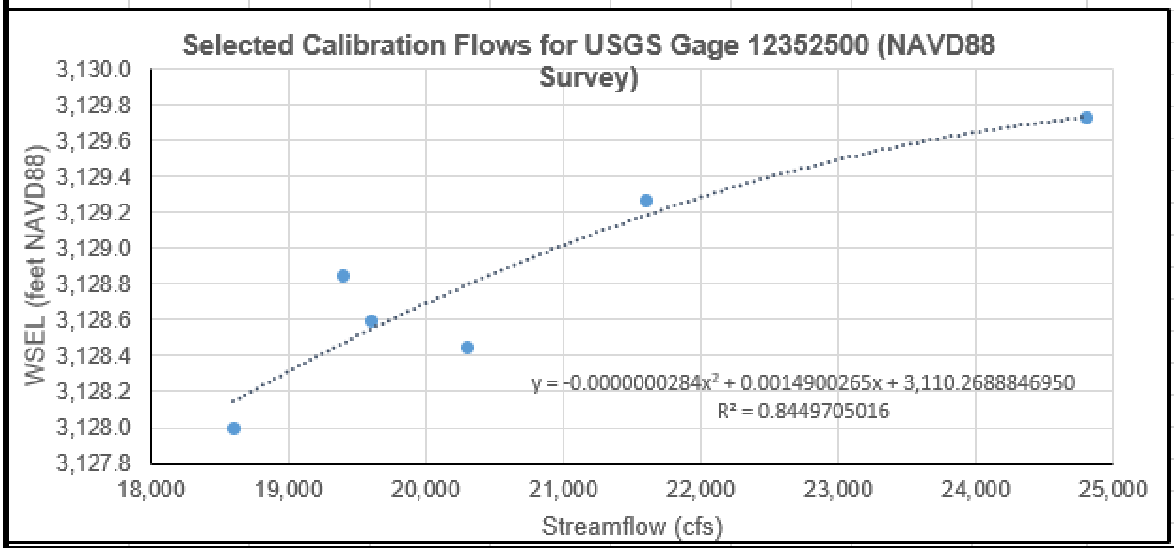

Figure 9. 1D Hydraulic Model Calibration to Bitterroot River Stream Gage 12352500

Aerial flood imagery was provided by the Montana DNRC and Missoula County from the 1997 flood on the Bitterroot River. The 1997 flood was between the 10% AC and 4% AC profiles peak flow rates for the flood study. Qualitative comparison of the hydraulic model results and associated floodplain mapping are generally consistent with the imagery and terrain floodplain interpretation.

4.15 Floodways

Floodway encroachments were computed for the Bitterroot River at each cross section. Between cross sections, the floodway boundaries were interpolated. In accordance with FEMA Guidance (FEMA 2019), the floodway encroachments were developed using HEC-RAS Method 4 with the equal reduction of conveyance option. As recommended in HEC-RAS application references (Brunner 2016c), the initial automated runs were converted to HEC-RAS Method 1 through the process of fine-tuning the automated floodway surcharge results to ensure maximum surcharge limits were not exceeded and final floodway boundary represented reasonable hydraulic transitions throughout the study reach. The results of the floodway computations are tabulated for lettered cross sections and are presented in the Floodway Data Tables in Appendix D. The work maps show only the floodway boundary in cases where the floodway and 1% AC floodplain are either close together or collinear.

In Montana, the designated floodway is developed using a 0.5-foot surcharge instead of the Federal maximum of 1.0-foot (DNRC 2014). The state criteria takes precedence over the minimum federal criteria for purposes of regulating development in the floodplain, as set forth in the Code of Federal Regulations, 44 CFR, 60.3cd (2).

Development of the full 0.5-feet of surcharge allowance is not always possible at all cross sections. The 0.5-foot allowance is a maximum limit that cannot be exceeded at any cross section throughout the study reach. The floodway modeling may produce a surcharge at an upstream cross section that exceeds the 0.5-foot maximum limit. Therefore, some cross sections, as shown in the Floodway Data Table, have surcharges of less than the 0.5-foot allowable maximum because of the effect that a greater encroachment at these locations would have on adjacent cross sections. The floodway encroachments were also set outside of ineffective flow areas and must include the bank stations of each cross section as stated in State of Montana and FEMA guidelines.

Floodway encroachments were developed for the Clark Fork River profile baseline to provide a reasonable boundary condition for floodway water surface elevations on the Bitterroot River at the confluence of the two rivers. The floodway encroachments on the Clark Fork River are not regulatory encroachments and were prepared only to satisfy boundary condition development for the Bitterroot River.

A worst-case analysis was performed on the Bitterroot River to determine if it was necessary to map a floodway on the Left Branch of Bitterroot River reach. In this simulation plan all of the flow is placed on the Bitterroot River mainstem. If the increase water surface elevations for the one-percent annual chance are less than or equal to 0.5-foot, only the Bitterroot River requires a floodway. If the increase in water surface elevations are greater than 0.5-foot, then the split flow reach must have a floodway as well. The result of the worst-case analysis was that the increase in elevations were less than or equal to 0.5-foot for all cross-sections and no floodway is required on Left Branch of Bitterroot River. Since the Left Branch of Bitterroot River is part of the hydraulic model geometry, it is included in the floodway plan. However, there is no regulatory floodway along the Left Branch of Bitterroot River flood flow path.

4.16 Flood Profiles

Flood profile panels were developed in accordance with FEMA Guidance and Standards. Horizontal and vertical scales were selected at 1 IN:200 FT and 1 IN:5 FT respectively. The horizontal and vertical scales were selected to provide profile panels where all six profiles could be distinguished in most locations. The selected scale and panel layout were chosen to provide easily interpretable flood profiles for public review and community floodplain administration.

Following standard practice, drawdowns and crossing profiles within the structures were smoothed on the profile. There is one crossing profile between the 0.2% annual-chance profile and the 1%+ annual-chance profile that is a result of the hydrology discussed in Section 3.1.5. This crossing profile occurs between RS 74,137 and RS 74,597 on the Bitterroot River. The hydraulic modeling is tuned to reasonably represent the regulatory (1% AC) profile. Drawdowns in non-regulatory profiles occur occasionally in the hydraulic modeling. The drawdowns were smoothed in the flood profile products to present reasonable hydraulic relationships in accordance with FEMA guidance and engineering standard practice. Flood profiles for both Bitterroot River and Left Branch of Bitterroot River are provided in Appendix B.

4.17 Quality Control and cHECk-RAS

An internal quality control evaluation is completed for each submitted reach this includes checks on the simulation model, profile, work map, and floodway data table. This evaluation checks to make sure FEMA guidelines and Standards are being met and that standard practice is being used in modeling. The completed checklists are included in Appendix F.

FEMA's automated review software cHECk-RAS, Version 2.0.1 (FEMA 2013) was utilized to verify the acceptability of the hydraulic analyses described above. Files from the HEC-RAS version 5.0.7 analyses were uploaded into cHECk-RAS. Several messages in cHECk-RAS are incorrect and appear to be related to the loss of output reading functionality when the current version of cHECk-RAS reads HEC-RAS 5.0.7 data. These messages were checked to verify that a cHECk-RAS read error exists and are noted on the cHECk-RAS report.

cHECk-RAS evaluates the following five categories of the hydraulic modeling:

- NT (Manning's roughness coefficients and transition loss coefficients)
- XS (Cross sections)
- Floodways
- Structures
- Profiles

The cHECk-RAS output messages for the Bitterroot River Reach 1 and Reach 2 models were reviewed and each issue was either resolved or investigated to confirm that the modeling was correct and that the cHECk-RAS message was not applicable. Appendix E includes the list of cHECk-RAS messages and responses to each message for each modeled stream reach.

5.0 Floodplain Mapping

Floodplain mapping was prepared using GeoHECRAS (CivilGEO 2020 mapping tools and ESRI ArcMap 10.7 (ESRI 2019). The GeoHECRAS application generates the raw floodplain delineation by intersecting the LiDAR Digital Elevation Model (DEM) with a separate DEM representing the water surface elevations of the 1% and 0.2% annual-chance events. The results of the hydraulic modelling and topographic data are used to create products for end users that are described in the following sections.

5.1 Hydraulic Work Maps

The resulting floodplains from the 1% and 0.2% AC flood events are displayed on the hydraulic work maps provided in Appendix A. The base map used for the hydraulic work map is the 2017 National Agriculture Imagery Program (NAIP) aerial imagery. Along with the flooding extents, stream profile baselines along with the cross sections utilized during the hydraulic analysis are displayed on the work maps. The layout of the cross sections and structures representing existing conditions are presented on the work maps. At some locations, modeled cross sections have been removed from the work maps for clarity due to the dense placement required for the numerical model. Node names have been recorded in the model to assist the user when reviewing the model and the work maps. Lettered cross sections are named with the appropriate letter label, mapped non-lettered cross sections are noted as NL-not labeled and non-mapped cross sections are noted as NL/NM-for not labeled and not-mapped. Zone AE symbolized polygons are the floodplain delineated for the regulatory floodplain. Floodway symbolized polygons are the regulatory floodway associated with the regulatory floodplain

Typically, islands that were marginally higher than the adjacent 1% annual-chance water surface profile and less than one-half acre in size were not delineated. Large backwater areas that extended through multiple cross sections were also modified to represent the elevation associated with the location where the backwater initiates from the main channel. These two adjustments provide a slight variance in the mapped widths versus the top widths described by the HEC-RAS model at selected locations. A table of the 1% AC flood event backwater elevations and the corresponding profile baseline station is included in Table 27.

Table 27. Backwater Elevation Summary

Tributary Reach	River Station (feet)	1% AC (WSE)
Bitterroot River	79,053	3,165
Bitterroot River	92,702	3,176
Left Branch of Bitterroot River	2,566	3178
Left Branch of Bitterroot River	9,972	3188

Morrison Maierle

5.2 Map Tie-in Locations

The Bitterroot River floodplain study originates at its confluence with the Clark Fork River. As discussed in section 4.6, the boundary condition of the Bitterroot River flood study is a coincident relationship with the Clark Fork River flood source. The hydraulic modeling between the Bitterroot and Clark Fork River reaches tie within one-half foot where cross sections collectively convey the combined flood flows, as required in FEMA guidance. A new floodplain study for the Clark Fork River through the confluence area is part of the Missoula-Granite PMR and Allied Engineering was assigned the Clark Fork River floodplain study by the Montana DNRC. In the final mapping for Missoula County, a Zone Break Line will be included on the FIRM maps indicating the equal flood risk match line between the Bitterroot River and Clark Fork River flooding sources. Preliminary coordination during floodplain study development with Allied Engineering has indicated the flooding sources will tie within FEMA requirements for elevation and will also meet current FEMA Database Verification Tool (DVT) check logic for preparing FIRM panels during the Preliminary Mapping task.

Main stem Bitterroot River cross section 111,207 is a duplication of cross section A from the effective Ravalli County spatial data set downloaded from the NFHL and from the effective Ravalli County USGS WSPRO hydraulic model. Montana DNRC prefers floodplain mapping tie-in at jurisdictional boundaries to be “snapped” to the adjacent effective floodplain mapping. The effective floodplain mapping in Ravalli County was delineated based on LiDAR contour mapping circa 2009. Montana DNRC also prefers hydraulic tie-in at the jurisdiction boundary to align to the tenth of a foot. Hydraulic modeling variables were transitioned from the typical initial values for the Missoula County HEC-RAS v5.0.7 assignments starting several cross sections downstream of the county line to more closely align with the values used in the effective Ravalli County hydraulic modeling. The resulting water surface elevations for both 1% AC flood and the floodway matched the effective Ravalli County floodplain information to the tenth as preferred.

The recently collected LiDAR terrain for Missoula County aligns reasonably well with the 2009 LiDAR terrain data for Ravalli County. Since the modeled elevations were similar, floodplain mapping for Missoula County was prepared to “snap” to the effective mapping in Ravalli County on the main stem of the Bitterroot River, which meets the preference of Montana DNRC. The floodway boundary was prepared to conform with FEMA requirements for map tie-in with the effective floodway mapping for Ravalli County on the Bitterroot River main stem reach.

The modeling and mapping do not tie-in vertically or seamlessly horizontally for the Left Branch of Bitterroot River. The tie-in issue appears to be driven by flooding source flow variance between the effective Ravalli County FIS and this flood study update for Missoula County (Table 28).

Table 28. Bitterroot River Flooding Source 1% AC Flood Flow Comparison for Missoula and Ravalli Counties

Reach	Ravalli FIS Discharges (cfs)	Missoula County Discharges (cfs)	Ravalli Co. Flow as % of Missoula Co. Flow
Bitterroot River	27,400	24,402	112%
Left Branch of Bitterroot River	9,000	1,698	530%
Total Bitterroot River Flooding Source	36,400	26,100	140%

The mainstem Bitterroot River flow rate was not reduced to maintain conservation of flow and it is unclear how the reported Ravalli County FIS flood flow for Left Branch of Bitterroot River was developed. Investigation of the effective hydraulic modeling for Ravalli County revealed the mapped floodway and floodplain for Left Branch of Bitterroot River in Ravalli County is apparently not supported as split flow in the hydraulic modeling. Flood elevations are constant on the Ravalli side of the county boundary for both the Left Branch of Bitterroot River and main stem Bitterroot River.

The floodplain analysis for the Missoula County is backed by hydraulic modeling of the flow split (see sections 4.7.2 and 4.12.2) and the combined flow rate for Left Branch of Bitterroot River and the Bitterroot River main stem maintain conservation of flow from the Bitterroot River flooding source. As noted above, the proposed flood elevations tie well on the main stem of the Bitterroot River at the county line. However, the flood elevations do not tie well on the Left Branch of Bitterroot River at the county line, likely due to the large variance in flood flow and the difference in hydraulic modeling and mapping approach.

The 1% AC floodplain mapping for Left Branch of Bitterroot River has been prepared to “snap” to the effective Ravalli County floodplain. As discussed in section 4.15, a floodway was not required on the Left Branch of Bitterroot River in Missoula County. The effective Ravalli County flood risk mapping includes a floodway along the Left Branch of Bitterroot River Split flow path. The effective Ravalli County and proposed Missoula County floodplain analysis and mapping approach are not aligned, and floodway regulation is not recommended for the Left Branch of Bitterroot River in Missoula County. The final mapping of the 0.2% AC floodplain does not “snap” at the Ravalli/Missoula county line. The effective FIS Report for Ravalli County does not have a published flow value for 0.2% AC on Left Branch of Bitterroot River however, the same order of magnitude difference for the 0.2% AC profile as for the 1% AC profile (Table 28) is assumed. It is unreasonable to “snap” the proposed Missoula County 0.2% AC floodplain to the effective Ravalli County 0.2% AC floodplain. FEMA Region 8 approval was obtained for this tie-in variance. Approval documentation is included in the Correspondence folder of digital Floodplain Mapping task dataset.

5.3 Floodplain Boundary Smoothing

Floodplain Boundary Smoothing was completed in compliance with the May 2018 FEMA FIRM Database Schema and FEMA Database Verification Tool parameters applicable at the time this project contract was signed in September of 2019. Floodplain smoothing was conducted using several automated processing tools and manually corrected after processing to ensure floodplain widths, fringe widths, polygon gaps, and polygon overlaps all met FEMA criteria and standard engineering practices.

Due to the narrow topography of many of the overbank low areas, final regulatory mapped widths may be expanded to a minimum of 25 or 50 feet (5% of the FIRM panel scale). Narrow 0.2% AC floodplain fringes along the regulatory floodplain was removed from the final mapping. This was necessary to provide mapping visible at the FIRM panel scale of 1:1000.

The Quality Control process for floodplain boundary preparation was documented in review checklists as part of the Floodplain Mapping task scope of work.

5.4 Floodplain Islands and Disconnected Ponding

Floodplain islands are occasionally included in the floodplain mapping. Typically, these areas were relatively large, blocky areas of natural high ground that was elevated above the computed flood water surface elevation by more than one foot. Small, narrow, or minor elevation (<1 foot) areas above the rough floodplain mapping were included within the mapped floodplain area. Since the Bitterroot River hydraulic model was a 1D model informed by a 2D model, the proposed islands were compared to the 2D model results as well to ensure that both models showed the island as out of the floodplain.

Generally, disconnected ponding across anthropogenic high ground (e.g. dikes, berms, old road grades or embankments) was shown as connected to the floodplain with a continuous floodplain map boundary. Where disconnected ponding occurred across an active roadway, the ponding was shown as a separate polygon to provide map users with information on what routes are expected to remain traversable during a flood event.

5.5 Changes Since Last FIRM Mapping

Changes Since Last FIRM (CSLF) mapping products assist public entities and landowners in interpreting the changes to the floodplain mapping proposed for the new study compared to the effective mapping being replaced. CLSF mapping was completed during the Floodplain Mapping task as requested by the Montana DNRC. CSLF spatial files are provided in the Supplemental Data folder of the digital submission of the Floodplain Mapping task upon approval of the mapping task, CSLF work maps will be submitted to Montana DNRC as part of the Community Format Submittal.

5.6 Letters of Map Change

A review was made of the Letters of Map Change (LOMC) and Letters of Map Amendment (LOMA) along the Bitterroot River study area to identify locations where previously issued LOMC/LOMA may need to be considered in the context of the changes proposed by this updated study. Twenty-nine LOMC\LOMAs were identified along the Bitterroot River study reaches were found in a search of FEMA records (Table 29).

Table 29. FEMA Records for Bitterroot River Study Reach LOMC/LOMA Case Numbers

LOMC/LOMA ID		
02-08-236A	09-08-0635A	16-08-1349A
03-08-0577A	10-08-0532A	17-08-0930A
04-08-0278A	11-08-0563A	18-05-0583A
04-08-0668A	11-08-0619A	18-08-0252A
05-08-0097A	12-08-0478A	18-08-0658A
05-08-0123A	13-08-0650A	18-08-0964A
05-08-0241A	14-08-0436A	20-08-0379A
05-08-0432A	15-08-1374A	97-08-355A
05-08-0535A	16-08-0394A	99-08-057A
07-08-0825A	16-08-0769A	-

5.7 Floodplain Boundary Standard Audit

A Floodplain Boundary Standard (FBS) Audit was completed as part of the Floodplain Mapping Task scope of work. The FBS Audit is a standardized self-review of the regulatory floodplain boundary to be carried into final mapping products. This project was within risk class C, which requires at least 85% of the test points to be within +/- 1 foot of the ground elevation. Test points were deleted from the floodplain boundary at study termination where the boundary is perpendicular to the flood flow direction. When an initial FBS Audit results in a pass rate greater than the required 85% threshold, the 38-foot radius horizontal tolerance additional check is not required. FBS Audit summary reports are included in Appendices and test point shapefiles are included in the Supplemental Data folder of the digital submission as part of the Floodplain Mapping Task scope of work.

5.8 Depth & WSE Grids

Depth and WSE Grids were prepared for each profile included in the hydraulic model (10%, 4% 2%, 1%, 1%+, & 0.2% AC) as part of the Floodplain Mapping Task. The grid data are raw depth grids ready for further processing in accordance with the FEMA Guidance Flood Depth and Analysis Grids once the final mapping products have been approved. These grid data products are included in the Supplemental Data folder of the digital submission as part of the Floodplain Mapping Task scope of work.

6.0 Flood Insurance Study Products

Digital profiles for the 10%, 4%, 2%, 1%, 1%+, and 0.2% annual-chance water surface elevations were created using FEMA's RASPLOT software (FEMA 2015). Additional information, edits and formatting were made using the dxf editing tools within RASPLOT for this Hydraulics Task submittal. Final profiles were converted to AutoCAD dwg files for final flood risk product delivery through the project review and approval progression. Profiles were developed using the guidance found in FEMA Guidance for Flood Risk Analysis and Mapping: Flood Profiles (FEMA 2016a). The water surface profiles illustrating the results of the study are provided in Appendix B and in the FIS Report folder under the Bitterroot River folder of the digital submission.

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APPENDICES