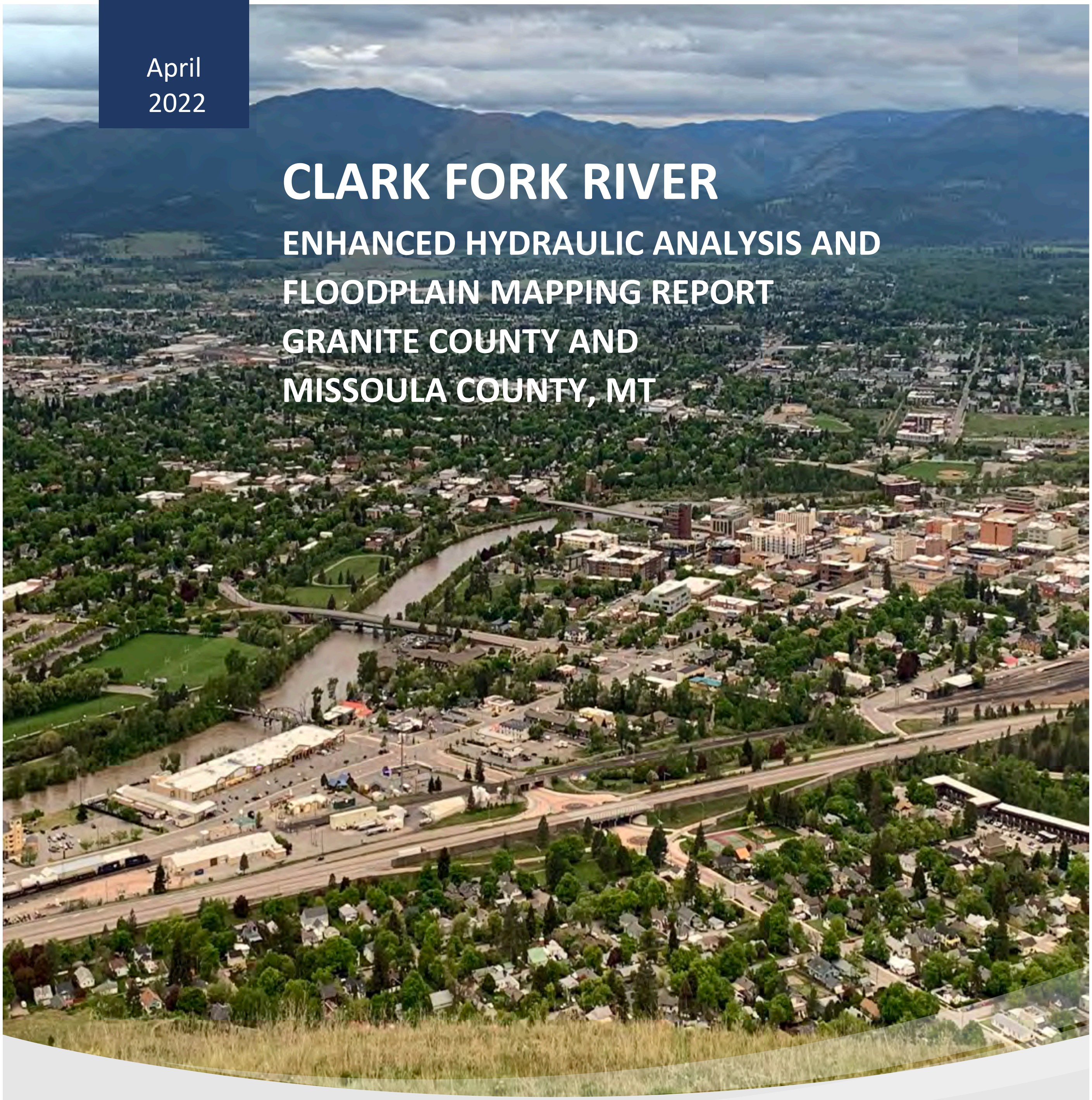
April
2022

CLARK FORK RIVER

ENHANCED HYDRAULIC ANALYSIS AND FLOODPLAIN MAPPING REPORT GRANITE COUNTY AND MISSOULA COUNTY, MT



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THE SEAL OF GRANITE COUNTY STATE OF MONTANA

PROJECT #19-128

Clark Fork River
Enhanced Hydraulic Analysis and Floodplain Mapping Report
Granite County and Missoula County, Montana

Contract No.: WO-AESI-199
Mapping Activity Statement No.: 2019-02 (Missoula-Granite PMR)
FEMA Case No.: 20-08-0033S

April 2022

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1 Introduction & Background

Allied Engineering Services, Inc. (AESI) completed detailed hydraulic analyses of the Clark Fork River and associated split flows in Granite County and Missoula County, Montana. Additional analysis was completed for the Lower Grant Creek near Missoula, MT to facilitate a floodplain mapping connection for a gap created by this study. Work was completed under a contract with the Montana Department of Natural Resources and Conservation (DNRC) associated with Mapping Activity Statement 2019-02 (Missoula-Granite PMR) and Federal Emergency Management (FEMA) Mapping Information Platform case 20-08-0033S. This report documents the hydraulic analyses and provides data for ensuing floodplain mapping efforts. Results of the analyses will be incorporated into both the Granite County and Missoula County, Montana, and Incorporated Areas Digital Flood Insurance Rate Map (DFIRM) and Flood Insurance Study (FIS). A Certification of Compliance was completed that confirms the study was completed using sound and accepted engineering practices and complies with all contract documents. FEMA guidelines and standards have been used to comply with the National Flood Insurance Program (NFIP).

The mapping for the existing Flood Insurance Study (FIS) in both counties is largely based on data and flood study work from the 1960s and 1970s. The purpose of this study is to provide updated Zone AE and Floodway mapping for the entire reach of both Granite County and Missoula County. Table 1-1 provides a list of primary flooding sources included in this hydraulic study, and Figure 1-1 in **Appendix A** shows the location of the flooding sources. The studies are classified as Enhanced with Floodway and utilize Hydraulic Analysis Option E as described in Table 1-2.

Table 1-1. Flooding Sources Studied

Flooding Source	Study Type	Upstream Limit	Downstream Limit	Primary Reach Length (miles)
Clark Fork River and Splits	Enhanced with Floodway - Option E (FEMA Guidance Document 52)	Boundary of Granite County and Powell County	Boundary of Mineral County and Missoula County	112.3
Lower Grant Creek	Enhanced without Floodway – Option E	845 ft Upstream of Miller Crossing	2996 ft Downstream of Miller Crossing	1

Table 1-2. Description of Hydraulic Analysis Options

Option	Cross Sections	Flow Paths (Left, Right, and Channel)	Manning's n Values	Structures	Flood Zone
E	Each section reviewed by engineers; channel bathymetry included in sections	Reach lengths adjusted based on draft floodplain	Overbanks from LULC data, channel value estimated separately and calibrated where possible	Included; structure data from as-builts, design plans, "measured" in the field, or other community datasets with opening information	AE

The hydraulic analysis was completed using peak discharges for the 10-, 4-, 2-, 1-, and 0.2-percent-annual-chance (10-, 25-, 50-, 100-, and 500-year) flood events. In this report, 1% Annual Chance (AC) event will be used synonymously with one-percent-annual-chance flood event, and the same applies to all other events. The hydraulic analysis also includes the 1-percent-plus-annual-chance flood event. The hydraulic work maps in **Appendix A** include the floodplain mapping for the 1- and 0.2-percent-annual-chance flood events along with floodway mapping.

The hydraulic analyses and floodplain mapping completed for this project relies upon data provided by several contractors. DOWL completed the bathymetric field surveying task, including bathymetric cross-section survey data (1) (2). Pioneer Technical Services, Inc. completed the hydraulic structure survey (3). Quantum Spatial provided the topographic LiDAR data (4). Pioneer Technical Services, Inc. completed the hydrologic analysis (5). Information related to the data provided by these contractors is included in the appropriate sections of this report.

1.1 Community Description

1.1.1 General Overview

The flooding sources studied are in the southern half of Missoula County and in the northern half of Granite County. The Clark Fork River flows through the City of Missoula and the Town of Drummond, the only incorporated city and town directly affected by these flooding sources.

Missoula and Granite County have experienced moderate population increases in the past 18 years, while the City of Missoula and the Town of Drummond have experienced more significant increases.

Table 1-3 summarizes the Census population data (6). Table 1-4 shows the Census housing unit estimates. With the continued development near these flooding sources, updated mapping of these flooding sources is needed. This study will help the communities understand the risks of living and working near these flooding sources.

Table 1-3. Census Population Estimates

Community	2000 Population	2010 Population	% Change from 2000 to 2010	2018 Population Estimate	% Change from 2010 to 2018
Granite County	2,830	3,079	8.8%	3,378	9.7%
Drummond	318	309	-2.8%	349	12.9%
Missoula County	95,802	109,299	14.1%	118,791	8.7%
Missoula	57,053	66,788	17.1%	74,428	11.4%

Table 1-4. Census Housing Units Estimates

Community	2000 Housing Units	2010 Housing Units	% Change from 2000 to 2010	2017 Housing Units	% Change from 2010 to 2017
Granite County	2,074	2,822	36.0%	2,835	0.4%
Drummond	140	143	2.1%	215	50.3%
Missoula County	41,319	50,106	21.3%	52,559	4.9%
Missoula	25,225	30,682	21.6%	32,755	6.8%

1.1.2 Historical Flooding

Several notable flooding events have occurred on the Clark Fork River throughout its observed history. The largest known flood event in Missoula County occurred in May and June of 1908 after continuous rains in the preceding days saturated the ground, and several inches of snow fell on June 6th. Warmer temps caused the snow to melt, and coupled with the saturated soils, runoff overwhelmed the Clark Fork River corridor.

Flooding generally occurs in the spring and early summer from snowmelt and/or rainfall runoff. Other notable flooding events include 1948, 1997, 2011, and 2018 with Clark Fork River gages recording several events over the 10-percent exceedance annual event. In addition to the gage measurements, the 1997, 2011, and 2018 events were recorded by aerial photography. Both high water marks and flooding extent boundaries were also recorded for the 2018 event. Key peak flood events along with the approximate return frequency as measured at the United States Geological Survey (USGS) gage on the Clark Fork above Missoula, Montana, include:

- 1908 48,000 cfs, 445 years (0.22%);
- 1948 31,500 cfs, 23 years (4.3%);
- 1997 27,000 cfs, 10 years (10%);
- 2011 28,500 cfs, 13 years (7.7%) ; and,
- 2018 32,500 cfs, 27 years (3.7%).

In reviewing the approximate return interval for the key flood events, it is important to note that more recent events (e.g. 1997, 2011, and 2018), where aerial photos were available showing extents of flooding, only represent the 10 to 27 year return frequency. Therefore, aerial photos used in this study unfortunately did not capture anything close to the 1-percent exceedance annual event.

In 2008, the Milltown Dam downstream of the Blackfoot River and Clark Fork River's confluence was removed affecting downstream flooding. A Letter of Map Revision (LOMR) was created in 2012 by River Design Group, Inc. to determine changes to flooding downstream of the site and is described in detail in the hydrology report (5 p. 21).

Refer to the hydrology report (5) for a detailed summary of historical records for the USGS stream gages in the study area.

1.2 Basin Description

The basin description text shown below for the Clark Fork River was taken directly from the Pioneer Technical Services hydrology report (5 p. 4).

> *The Clark Fork River is a major tributary to the Pend Oreille River and upper headwaters of the Columbia River located west of the continental divide in western Montana. The river is formed by the confluence of Silver Bow Creek and Warm Springs Creek. The river tributaries originate in the Deerlodge National Forest near the Continental Divide. The watershed is formed by the Bitterroot Mountains to the west, Deer Lodge Mountains to the east, and the Pintler and Highland Ranges to the south. The mainstem Clark Fork River begins at Warm Springs, Montana, and flows north for approximately 20 miles through the Deer Lodge Valley before tuning west. The Blackfoot and Bitterroot Rivers join the Clark Fork River near Missoula. Approximately 213 miles downstream of Missoula, the Clark Fork River terminates at Lake Pend Oreille. The entire Clark Fork River watershed encompasses approximately 22,905 square miles.*
>
> *The Clark Fork River basin elevations within the study area range from 10,463 feet in the Pintler Mountains to approximately 2,600 feet at Alberton. The overall basin elevations range from over 10,000 feet in the Pintler Mountains to 2,060 feet near the confluence with Pend Oreille Lake. The terrain varies from a high alpine environment in its headwaters to a heavily cultivated landscape in the Deer Lodge valley with expansive irrigated pasture lands, bracketed by rolling foothills. The majority of peak flows along the Clark Fork River gages occurred in May, June, or July, suggesting the hydrology of the basin is primarily snowmelt driven.*
>
> *Land use in the Clark Fork River basin is primarily agricultural with irrigated farming and ranching operations. Most of the intensely farmed land is located in the Deer Lodge Valley within the Clark Fork River floodplain. Missoula is the primary community in the Clark Fork River study area.*

Within the study area, the Clark Fork River channel spans a length of roughly 112 miles, cutting through a floodplain that is roughly 92 miles in valley distance. Of the total stream length of Clark Fork River in the study, the most downstream 2.7 miles of it was previously studied during the Mineral County Study (7). The river varies in slope through the study area. General slopes were calculated using the profile baseline for length and the bathymetric data for elevation. The generalized slope (S) of the river from upstream to downstream is as follows:

S = 0.0018 ft/ft Granite/Powell County border to 8,000 ft upstream of Main Street in Drummond.

S = 0.0024 ft/ft	8,000 ft upstream of Main Street in Drummond to the I-90 crossing downstream of Drummond.
S = 0.0020 ft/ft	I-90 crossing downstream of Drummond to I-90 Frontage Road Bridge.
S = 0.0024 ft/ft	I-90 Frontage Road Bridge to Granite/Missoula County border.
S = 0.0029 ft/ft	Granite/Missoula County border to Schwartz Creek Road bridge.
S = 0.0035 ft/ft	Schwartz Creek Road bridge to adjacent to Donovan Creek Road upstream of Turah.
S = 0.0033 ft/ft	Adjacent to Donovan Creek Road to RR bridge downstream of Blackfoot River.
S = 0.0017 ft/ft	RR bridge downstream of Blackfoot River to downstream of Bitterroot River.
S = 0.0011 ft/ft	Downstream of Bitterroot River to Frenchtown.
S = 0.0008 ft/ft	Frenchtown to Mineral/Missoula County border.

The general slope of Lower Grant Creek in the area of interest is:

S = 0.0043 ft/ft   RS 3840.4 to RS 367.8.

1.3 Previous Studies

The entire Clark Fork River in Missoula and Granite County was studied in the effective FEMA FIS. The FIS for Missoula County was revised March 7, 2019 (8) while the Granite County FIS has an effective date of April 19, 2016 (9). The Lower Grant Creek was studied as part of a Letter of Map Revision (LOMR) application in 2011 (10) (11). Special Flood Hazard Area (SFHA) zone designations are shown on the effective panels, Zone AE, A, and Zone X. The Zone AE designation is described on the panel as "*Special Flood Hazard Areas Inundated by 100-Year Flood; Base flood elevations determined.*" Zone AE refers to detailed study areas. Zone A designation is described on the panel as "*Special Flood Hazard Areas Inundated by 100-Year Flood; No base flood elevations determined*." Zone A refers to approximate study areas. The Zone X designation is described on the panel as "*Areas of 500-year flood; areas of 100-year flood with average depths of less than 1 foot or with drainage areas less than 1 square mile; and areas protected by levees from 100-year flood.*" Zone X is also defined as "*Areas determined to be outside 500-year flood plain*."

In addition to the SFHA zones a floodway is shown. FEMA's definition of a "Regulatory Floodway" means the channel of a river or other watercourse and the adjacent land areas that must be reserved in order to discharge the base flood without cumulatively increasing the water surface elevation more than a designated height. Communities must regulate development in these floodways to ensure that there are no increases in upstream flood elevations (12).

The Clark Fork River through Granite County is mapped as Zone A with the following exceptions which are mapped as Zone AE

- 0.9 miles at the downstream end of Granite County. The Clark Fork River weaves in and out of Missoula County in this area.
- 11.6 miles mapped as Zone AE with floodway near the Town of Drummond

The Clark Fork River through Missoula County is mapped as Zone AE with floodway with the exception of about 2.8 miles at the downstream end of Missoula County which is mapped as Zone A. Table 1-5 and Table 1-6 are taken from the hydrology report and show a summary of Clark Fork River floodplain mapping in Granite County and Missoula County.

Table 1-5. Clark Fork River Effective Floodplain Mapping Summary

County	Community	Map Panel Summary # of FIRM Panels	# of FBFM Panels	FIRM Panel Eff. Date	FIS Date
Missoula	Missoula Co. Unincorporated Areas, City of Missoula	66	24	07/06/2015	03/07/2019
Granite	Granite Co. Unincorporated Areas, City of Drummond	52	7	04/19/2016	04/19/2016

Table 1-6. Clark Fork River Effective Study Details

County	Stream	Study Details Approx (mi)	Detailed (mi)	Total (mi)
Missoula	Clark Fork	0	69.6	69.6
Missoula	Lower Grant Creek	0	1	1
Granite	Clark Fork	27.4	14.2*	41.6
*Detailed length is shown as 12.5 miles in spatial data the 14.2 is from the original Hydrology Report.				

2 Hydrologic Analysis

Pioneer Technical Services completed the hydrologic analyses for the Clark Fork River in July of 2020. Discharges for the 10-, 4-, 2-, 1-, 0.2, and 1-plus-percent-annual-chance flood events were estimated for use in the hydraulic analysis (5). The report provided a recommendation for the annual exceedance probability discharges to use in the hydraulic analysis. A summary of discharges from the hydrology report is provided in Table 2-1.

Table 2-1. Discharges Recommended from Hydrologic Analyses

Node/ USGS Station ID	Flooding Source and Location	Peak Discharges (cfs) 10%	4%	2%	1%	0.2%	1% +
2700[1]	Perkins Creek	6,410	8,540	10,200	12,000	16,400	18,200
2600[1]	Lower Flint Creek	6,450	8,610	10,300	12,200	16,700	18,500
12331600[1]	**Clark Fork at Drummond, MT**	**7,220**	**9,880**	**12,100**	**14,600**	**21,300**	**24,400**
2400[1]	Rattler Gulch	7,300	10,000	12,200	14,800	21,800	25,100
2300[1]	Mulkey Gulch	7,330	10,100	12,300	14,900	22,000	25,400
12331800[2]	**Clark Fork near Drummond, MT**	**7,420**	**10,200**	**12,500**	**15,200**	**22,600**	**26,100**

Node/ USGS Station ID	Flooding Source and Location	Peak Discharges (cfs) 10%	4%	2%	1%	0.2%	1% +
2100[1]	Harvey Creek	7,510	10,300	12,600	15,300	22,700	26,200
2000[1]	Tyler Creek	7,710	10,500	12,800	15,600	22,900	26,300
1900[1]	Dry Gulch	7,780	10,600	12,900	15,600	23,000	26,300
12331900[1]	**Clark Fork near Clinton, MT**	**7,930**	**10,800**	**13,100**	**15,800**	**23,200**	**26,400**
1700[1]	Rock Creek-Kitchen Gulch	8,060	10,900	13,300	16,000	23,300	26,500
1600[1]	Schwartz Creek	11,700	14,800	17,300	20,000	26,700	28,400
1500[1]	Wallace Creek	11,900	15,100	17,600	20,300	26,900	28,400
12334550[2]	**Clark Fork at Turah Bridge near Bonner, MT**	**12,000**	**15,200**	**17,700**	**20,400**	**27,000**	**28,500**
1300[1]	Clark Fork upstream of Blackfoot River	12,200	15,400	17,900	20,600	27,300	28,700
12340500*	Clark Fork above Missoula, MT	26,600	32,100	36,100	39,900	48,400	46,600
1200[1]	Lower Rattlesnake Creek	26,600	32,100	36,100	39,900	48,400	46,600
1100[1]	Grant Creek	27,100	32,600	36,700	40,500	49,000	47,200
1000[1]	Clark Fork upstream of Bitterroot River	27,500	33,100	37,100	41,000	49,600	47,800
12353000[2]	**Clark Fork below Missoula, MT**	**47,200**	**54,900**	**60,200**	**65,000**	**75,200**	**73,500**
800[1]	Deep Creek	47,500	55,200	60,600	65,400	75,600	73,900
700[1]	Rock Creek	48,000	55,800	61,200	66,000	76,300	74,600
600[1]	Mill Creek	48,300	56,100	61,500	66,400	76,700	75,000
500[1]	Roman Creek	48,600	56,500	61,900	66,800	77,200	75,400
400[1]	Sixmile Creek	48,800	56,700	62,100	67,000	77,400	75,700
300[1]	Ninemile Creek	49,000	56,900	62,400	67,300	77,700	76,000
200[1]	Petty Creek	50,300	58,400	64,000	69,000	79,600	77,900
100[1]	Missoula-Mineral County Boundary	50,900	59,100	64,700	69,800	80,400	78,700

[1]Analyzed with USGS two-site logarithmic interpolation method.
[2]Analyzed with USGS MOVE.3 extended record analysis.
*Gage not used as flow node in Hydrology Report or this study. Gage used for calibration only.

While these flows provided the basis for hydraulic analysis, the occurrence of split flows can result in different flow values at flow change locations. None occurred in this study. For more information on split flows and how they impact peak discharges, refer to **Section 3.5.7**.

The Clark Fork River splits into two channels around Kelly Island in the confluence area with the Bitterroot River. In the Hydrology study, flow node 1000 was placed at the confluence of the Bitterroot River with the northern channel of the Clark Fork River. The Bitterroot River enters the Clark Fork River floodplain at the confluence with the south channel of the Clark Fork River. The 1000 flow node was eliminated and instead the Node 12353000 flow was applied near the confluence of the Bitterroot with the Clark Fork River. The location of this flow change was at RS 174837. This cross section layout was shared with the same cross section in Morrison Maierle's Bitterroot River Floodplain Study, which is also being completed under the Missoula-Granite PMR project.

Discharges for Lower Grant Creek were taken from the current Missoula County FIS (8 p. 29) and are summarized below.

Table 2-2. Lower Grant Creek Discharges used in Analysis

Location	Flooding Source and Location	Peak Discharges (cfs)					
		10%	4%	2%	1%	0.2%	1% +
RS 22698	Lower Grant Creek	170	*	358	629	864	*
RS 4600	Bypass	3	*	111	286	451	*
RS 4541.7	Lower Grant Creek	167	*	247	343	413	*
***Not calculated for this Flood Risk Project.**							

3 Hydraulic Analysis

3.1 Methodology and Hydraulic Model Setup

One-dimensional (1D) hydraulic models were created for regulatory purposes. Select reaches of the 1D models are informed by detailed two-dimensional (2D) hydraulic models. Preliminary or "rough" 2D hydraulic models of a less comprehensive nature were also used to inform cross section layout in the other reaches of the 1D models. This section describes setup of the regulatory 1D models. A description of the detailed 2D models is provided in **Section 3.3**. See Figures 3-1 through 3-3 in **Appendix A** for model boundaries.

HEC-RAS version 5.0.7 (13) was used to perform hydraulic modeling. Geometric data for the model was developed using RAS Mapper, AutoCAD Civil 3D, HEC-RAS, ArcGIS (14) and GeoHECRAS (15). ArcGIS software was used to create a mosaic surface raster which combined the LiDAR data for the overbank area and a custom channel surface created from the bathymetric survey points. The mosaic surface raster was imported into HEC-RAS's RAS Mapper to create a single terrain file for modeling. Hydraulic structures were modeled in accordance with HEC-RAS User's Manual, version 5.0 (16 pp. 5-1 to 5-33). Bathymetric sections were surveyed at all major structures for the study. Bridge cross sections 2 and 3 were placed on these bathymetric sections to best capture the channel bottom data. Structure sections 1 and 4 were placed in the best location possible to be outside the contraction and expansion zones of the bridge. Standards listed in FEMA Policy Standards for Flood Risk Analysis and Mapping (17) were also followed to ensure the study meets agency standards.

The Clark Fork River hydraulic modeling begins at the Granite/Powell County boundary and extends downstream to the Mineral/Missoula County boundary. The study was broken into several hydraulic models because of the length of the study. Five separate models were created for the project – three for the Clark Fork River in Missoula County and two for the Clark Fork River in Granite County.

Table 3-1 provides the model names and starting and ending stations for each model. The CFR_GC_Drum, CFR_MC_Msla, and the upstream portion of the CFR_MC_L models are informed by detailed 2D models. The 1D and detailed 2D model extents are coincident except where noted. Models are listed from upstream to downstream, and these locations are also depicted in **Appendix A**. In the table, CFR stands for Clark Fork River, LGC stands for Lower Grant Creek, GC stands for Granite County, and MC for Missoula County.

Table 3-1. Station Ranges for Regulatory 1D Hydraulic Model Reaches

Model Name	Description	Begin Station	End Station
CFR_GC_Drum (informed by detailed 2D model)	Starting at the I-90 crossing downstream of Drummond to the Granite and Powell County border	127625	228431
CFR_GC_L	Starting at Missoula and Granite County border to the I-90 crossing downstream of Drummond	0	127625
CFR_MC_U	Starting upstream of the Blackfoot River and Clark Fork River confluence to the Missoula and Granite County border	253970	364802
CFR_MC_Msla (informed by detailed 2D model)	Starting below the Bitterroot River and Clark Fork River confluence to upstream of the Blackfoot River and Clark Fork River confluence	162983	253790
CFR_MC_L (informed by detailed 2D model)	Starting from last cross section of Mineral County study.	14,775	162983
LGC_MC	Starting at first downstream cross section outside influence of historical Clark Fork River Mapping.	3840	368

Regulatory plans were created for each model. The regulatory plans apply the highest discharges from the split flow analysis, using flow change locations within the steady flow file. The regulatory plans were used for determination of water surface elevations for the 10-, 4-, 2-, 1-, and 0.2-percent-annual-chance events, as well as the 1-percent-plus simulation.

The floodway plans simulate the one-percent-annual-chance flood event with applied encroachments causing no more than 0.5-feet of rise in water surface elevations compared to base water surface elevations. Detailed information on floodway modeling can be found in **Section 3.5.10** of this report.

Split flow plans model the worst-case scenarios (WCS) for either the primary or secondary flooding sources and include a network of lateral weirs to compute split flow quantities. The lateral weirs are generally located on levee or non-levee features. The lateral weir structure is used so that a different water surface elevation can be computed at the location of a split from the main river, unlike a junction node. These lateral weirs can then be calibrated using the weir coefficient to match the 2D model split flows more closely. See

Table 3-2 for a list of the plans used in regulatory, calibration, and split flow models.

Table 3-2. Model Plans

Model	Plan	Description
CFR_GC_Drum	Drummond Split - Levee	Models regulatory flows with the abandoned railroad grade non-levee feature intact by assuming flow behind the non-levee feature is ineffective. Both lateral weirs and junctions are optimized to determine split flows.
CFR_GC_Drum	Drummond Split – No Levee	Models regulatory flows without the abandoned railroad grade non-levee feature intact by assuming flow behind the non-levee feature is effective. Both lateral weirs and junctions are optimized to determine split flows.
CFR_GC_Drum	Drummond Regulatory - Levee	Models worst case flows from the split flow models with the abandoned railroad grade non-levee feature intact. Flows are hardwired in.
CFR_GC_Drum	Drummond Regulatory – No Levee	Models worst case flows from the split flow models without the abandoned railroad grade non-levee feature intact. Flows are hardwired in.
CFR_GC_Drum	Drummond Floodway – No Levee	Models the 1% AC event with applied encroachment stations resulting in no more than 0.5 feet of rise compared to the 1% AC event without encroachment stations without the non-levee feature intact. The Drummond Regulatory – No Levee model was used as the basis for the floodway analysis. This plan was used to get the initial encroachment stations.
CFR_GC_Drum	Drummond Floodway – Levee	Models the 1% AC event with applied encroachment stations resulting in no more than 0.5 feet of rise compared to the 1% AC event without encroachment stations with the non-levee feature intact. The Drummond Regulatory – Levee model was used as the basis for the floodway analysis. This plan was used to get the surcharges using the encroachment stations from the Drummond Floodway – No Levee plan.
CFR_GC_L	Granite Lower - Regulatory	Models regulatory flows. Flows are hardwired in.
CFR_GC_L	Granite Lower - Floodway	Models the 1% AC event with applied encroachment stations resulting in no more than 0.5 feet of rise compared to the 1% AC event without encroachment stations. The Granite Lower -

Model	Plan	Description
		Regulatory plan was used as the basis for the floodway analysis.
CFR_MC_U	Missoula Upper - Regulatory	Models regulatory flows. Flows are hardwired in.
CFR_MC_U	Missoula Upper - Floodway	Models the 1% AC event with applied encroachment stations resulting in no more than 0.5 feet of rise compared to the 1% AC event without encroachment stations. The Missoula Upper - Regulatory plan was used as the basis for the floodway analysis.
CFR_MC_L	Lower Regulatory	Models regulatory flows. Flows are hardwired in.
CFR_MC_L	Lower Floodway	Models the 1% AC event with applied encroachment stations resulting in no more than 0.5 feet of rise compared to the 1% AC event without encroachment stations. Regulatory plan was used as the basis for the floodway analysis
CFR_MC_Msla	Monroc-Orchard Homes WCS	All levee and non-levee features are in-place except for the Monroc and Orchard Homes areas. This model is the WCS for flooding on the south side of the Clark Fork River. Monroc lateral structure is optimized to determine flows in Monroc split.
CFR_MC_Msla	Area 5 WCS	All levee and non-levee features are in-place except for the Levee 5 accredited levee. This model is the WCS for flooding behind the Area 5 Levee. Area 5 lateral structure is optimized to determine flow in Area 5 Split.
CFR_MC_Msla	Missoula Regulatory	Models regulatory flows. Flows are hardwired in from the two WCS's described above.
CFR_MC_Msla	Missoula Floodway	Models the 1% AC event with applied encroachment stations resulting in no more than 0.5 feet of rise compared to the 1% AC event without encroachment stations. Regulatory plan was used as the basis for the floodway analysis
LGC_MC	Regulatory	Regulatory flows hardwired from all lateral structures.

3.2 Field Survey and Topographic Information

The following subsections provide a description of the topographic data used for the hydraulic analysis. Field survey and LiDAR information was collected by other contractors using the methods and procedures outlined in FEMA's Guidelines and Specifications for Flood Risk Analysis and Mapping Data Capture Technical Reference (18), Guidance for Flood Risk Analysis and Mapping Data Capture – General (19), and Guidance for Flood Risk Analysis and Mapping Data Capture – Workflow Details (20).

3.2.1 LiDAR Collection

Terrain data was collected May 23 through June 16, 2019 in the form of LiDAR points by Quantum Spatial (4). They provided the following deliverables:

- Points
  - LAS v 1.4
    - Raw Calibrated Swaths
    - All Classified Returns
- Rasters
  - Hydroflattened Bare Earth Digital Elevation Model (DEM)
    - 3.0-Foot Pixel Resolution
    - GeoTIFF Format
    - ESRI File Geodatabase Raster Dataset Format (*.gdb)
    - Space delimited ASCII Files (*.asc)
- Vectors
  - Shapefiles (*.shp)
    - Site Boundary
    - Tile Index
    - Ground Survey Data
    - 1.0 Foot Contours
    - Total Area Flown
    - 3D Building Footprints
    - 3D Water's Edge Breaklines
  - ESRI Geodatabase (*.gdb)
    - 1.0-Foot Contours
    - 3D Water's Edge Breaklines
  - Space Delimited ASCII Text Files (*.txt)
    - 3D Water's Edge Breaklines

3.2.2 Field Survey Collection

Ground survey was collected for select riverine cross sections on the Clark Fork River in July, August, and October of 2019 by DOWL (1) (2). Ground survey was collected for hydraulic structures on the Clark Fork River from October 2019 to May 2020 by Pioneer Technical Services (3). Additional survey was collected by Pioneer Technical Services in the McCormick Park Area in June 2021 (21). Survey data was collected using GNSS RTK methods of survey. Trimble R8 Model-3 GNSS receivers were used, with Trimble TSC3 survey controllers and Trimble Access software. Table 3-3 lists the number of cross-section and hydraulic structure surveys that were completed within each county.

Table 3-3. Field Survey Collection Summary

Flooding Source and Reach	Number of Hydraulic Structures	Number of Cross Sections
Clark Fork River – Granite County	26	114
Clark Fork River – Missoula County	93	218

Cross section data was generally collected as follows:

- One cross section approximately every 2,500 feet
- Two cross sections upstream of hydraulic structures
- Two cross sections downstream of hydraulic structures

In July 2020, DOWL collected seven additional bathymetric cross-sections on side channels of the Clark Fork River in Missoula County (22). This survey was completed to supplement the bathymetric cross-sections completed in 2019.

The field survey data was presented in Montana State Plane Coordinate System, North American Datum of 1983 (NAD83-2011). Units are reported in International Feet. Elevations are referenced to the North American Vertical Datum of 1988 (NAVD88). Units are reported in U.S. Feet. GNSS-derived orthometric heights (elevations) were computed using Geoid 12B.

In addition to the above referenced data, photographs of each hydraulic structure were taken to assist with the creation of the hydraulic model bridge geometries. These photographs are included in **Appendix C** of this report.

The Area 3 Levee in Missoula contains approximately 900 feet of concrete flood wall. This flood wall was too thin to be captured by the LiDAR correctly. Morrison-Maierle, under contract with the City of Missoula, surveyed the top of the flood wall in October 2020 (23). Another area of interest, Area 5 Levee, was surveyed by Morrison-Maierle who surveyed the top of the earthen Levee in October 2021 (24).

3.3 Levees

The study area includes several levees and non-levee features (NLF). Table 3-4 below provides a summary of the levees and some of the more prominent non-levee features in the project area. The levees are listed from upstream to downstream. For those levees listed in the table with a System ID number, the National Levee Database provides information about these levees (25).

Table 3-4. Summary of Levees and Non-Levee Features in Study Area

Levee System Name	Non-Levee Feature Description	Levee System ID	Left or Right Bank	Current Status	Approx. Location of Upstream End	
					Latitude (WGS 84)	Longitude (WGS 84)
Drummond		5505000260	Right	Non-Accredited Levee	46.660833	-113.145556
NA	Abandoned railroad Grade in Drummond	NA	Right	Non-Levee Feature	46.648094	-113.123165
Turah		5505000288	Right	Non-Levee Feature	46.804444	-113.784444
Clark Fork River Area 3		5505000005	Right	Accredited Levee	46.867500	-113.987778
McCormick Park		5505000306	Left	Non-Levee Feature	46.868056	-113.994722
Clark Fork River Area 5		5505000004	Right	Accredited Levee	46.876111	-114.013333
Monroc		5505000181	Left	Non-Levee Feature	46.875000	-114.013889
Orchard Homes		5505000201	Left	Accredited Levee	46.875556	-114.043056
Orchard Homes Spur		380005000000	Left	Non-Levee Feature	46.869167	-114.057778
Stone Container		1805000049	Right	Non-Levee Feature	46.950724	-114.203150
NA	Abandoned railroad Grade in Frenchtown	NA	Right	Non-Levee Feature	46.993756	-114.219643

Refer to **Appendix C** for photos of some of these levees. Hydraulic modeling considerations for the levees is discussed in sections below, including the section on Worst Case Scenario Analyses and Floodway Analysis.

3.4 2D Hydraulic Modeling

Detailed and preliminary 2D hydraulic modeling was completed for select reaches of the Clark Fork River, using HEC-RAS 5.0.7. See Table 3-5 below for the extents of the 2D hydraulic model reaches as described, using the 1D cross sections stationing. As part of the scoping for this project, DNRC requested that 2D models be created for the areas with split flows, complicated features, and high population densities. Specifically, the City of Missoula area, Town of Drummond, and Frenchtown. These areas are referred to as detailed 2D models. Outside of these specific areas, preliminary or rough 2D models were created to aid in the creation of the

1D models. The preliminary 2D models are less comprehensive than the detailed models, and consequently, less time was spent refining these models. These models, however, still provided useful information to inform the 1D models and should prove useful to future studies that utilize 2D modeling.

The 2D model results were used to inform the 1D model for split flow locations, lateral structures, and cross section orientations. The water surface elevation (WSE) contours from the 2D models were used to orientate the 1D model cross sections, so the cross sections were generally placed on a constant water surface elevation. The following sections explain 2D modeling methodologies and decisions for the 2D hydraulic models.

Table 3-5. Station Ranges for 2D Hydraulic Model Reaches

General Location	Model Name	Downstream River Station	Upstream River Station	2D Model Type
Drummond	2D_CFR_GC_Drum	127377	228148	Detailed
Lower Granite County	2D_CFR_GC_L	0	129449	Preliminary/Rough
Upper Missoula County	2D_CFR_MC_U	250544	364802	Preliminary/Rough
City of Missoula	2D_CFR_MC_Msla	162590	250143	Detailed
Lower Missoula County	2D_CFR_MC_L	15018	168524	Detailed

3.4.1 Computational Boundary and Mesh

Computational boundaries were drawn to capture the flooding extents for the range of floods simulated. Upstream and downstream extents were drawn at locations where flow was better described by 1D modalities.

Hexagonal shaped mesh cells were selected for the detailed models since the hexagonal shape is better at modeling direction changes. The mesh size varied for the computational area. A sensitivity analysis was done for the detailed 2D model areas to determine cell sizing. This analysis started with smaller cell sizing and gradually increased the size of these cells. For some areas, a smaller cell size was appropriate like the smaller Granite County Clark Fork River stretches. The Missoula County areas favored a larger cell size, and this was proven by using the available gage data in these areas. Another factor when considering the most appropriate cell size is the computational run time associated with the cell sizing. A larger cell size results in a shorter run time. Since the primary use of the 2D models was to evaluate different levee and NLF scenarios, it was imperative that the model have a reasonable run time so that it could be easily revised and iterated.

Main conveyance paths, such as the main stem of the river, were given cell sizes that provided multiple cells across the flow path. Outside of the flow path, a larger cell size was used in areas that did not have any distinctive features or did not see flood flows. Breaklines were added to describe topographic features, such as certified and non-certified levee features, non-levee features, and channel extents. Cell size was reduced along these breaklines to prevent leakage across the high ground feature.

3.4.2 Boundary Conditions

Inflow and outflow boundary conditions were specified for each model. Inflow utilized the nearest downstream flow node flow rate. Most models used an outflow boundary condition of normal flow. The slope used for all flow changes was calculated from the LiDAR survey data. The most downstream 2D model for the Missoula County Lower was able to use the known WSE from the Mineral County 1D model. The City of Missoula model has an inflow boundary condition at the Bitterroot River to accurately model that confluence area. Care was taken to set inflow and outflow boundary conditions at locations that would not influence split flows.

Flow changes within the model were set in accordance with the flow nodes provided in the hydrology report. An internal boundary condition was used to apply the flow changes inside the 2D model computational mesh areas or on the outside for some cases where the flow change was from a tributary. Flow was added to the Bitterroot River channel near the confluence with the southern split of the Clark Fork River to simulate a more realistic situation. The flow added was simply the difference between the upstream and downstream flow nodes that span the confluence. The confluence area is complicated, and the large difference of flow change in this area is from the Bitterroot River. For the 2D model, using the only the flow nodes in this location would have not made modeling sense.

3.4.3 Manning's Roughness Coefficients

Manning's roughness coefficients (Manning's n values) were based on the 2017 National Agriculture Imagery Program (NAIP) aerial imagery, photographs provided by the field survey (1) (2) (3), and calibration at gages (see **Section 3.5.9.2**). Manning's n values were obtained by referencing information provided in "Open-Channel Hydraulics" (26 pp. 109-113), the Effective Flood Insurance Studies (9) (8), and "Roughness Characteristics of Natural Channels" (27 p. 26). A spatially varied shapefile was created in ArcGIS Pro to describe Manning's roughness values (also referred to Manning's n values) for the modeled areas. Buildings were modeled with a Manning's n value of 100 to simulate inundation without conveyance. Manning's roughness values used in report fell within the expected range from the cited sources above.

After observing model results and researching Manning's n values in 2D models, roughness values were uniformly lowered by 15% based on recommendations made by Andrew Friend, P.E. and Mark McBroom P.E. of Michael Baker International in their presentation *Smooth Transition: Adjusting Manning's n values for 2D modeling* (28). The lower Manning's n values resulted in simulations that more closely matched flooding extents observed on historical aerial photography, high water marks, and gage data.

Table 3-6 provides the Manning's roughness coefficients used for the 1D and 2D modeling.

Table 3-6. Applied Manning's roughness coefficients

Land Use and Description	Range of Manning's n Values for the 1D Model	Range of Manning's n Values for the 2D Model
Bare Earth	0.02	0.017
Channel	0.03 – 0.055	0.026 – 0.036
Cultivated	0.035	0.03
Dense Brush and Trees	0.1	0.085
Less Dense Brush and Trees	0.08	0.068
Light Brush	0.05	0.043
Light Commercial and Light Residential	0.06	0.051
Medium Brush	0.06	0.051
Medium Commercial and Medium Residential	0.08	0.068
Natural Field	0.04	0.034
Pond	0.03	0.026
Road	0.016	0.014
Short Grass	0.03	0.026

3.4.4 Development of a Channel Surface

To estimate the channel conveyance under the flattened water surface of the LiDAR data, an interpolated channel surface was created between surveyed channel cross sections and then merged with the LiDAR surface to create a continuous, composite surface. Both AutoCAD and ArcGIS grading and surface tools were used to create this surface. In general, AutoCAD feature lines were used to link the surveyed cross section together. These feature lines were drawn using the water boundary breaklines from the LiDAR data and NAIP 2017 Aerial imagery (29). The water boundary breaklines were created by the LiDAR supplier and were used to smooth the elevation data that was over open water. The feature lines create the channel bottom by interpolating a surface between them and a constant grade between survey cross sections. These feature lines included a channel thalweg and the right and left toe of slopes. Additional feature lines were added as needed for areas requiring greater accuracy (the City of Missoula vicinity) or for reaches where the three breaklines noticeably underestimated capacity in a larger river (the lower reaches in Missoula County). In a larger river, more feature lines can better map the conveyance area of the channel by giving the approximate surface a more natural shape.

This surface then had the survey points themselves added to it for additional detail. Top of bank breaklines were not used since they were close to the water boundary breaklines (LiDAR was collected during high water). This surface was then exported into the ArcGIS to be converted into a raster. When converting the Triangular Irregular Networks (TIN) surface into a gridded raster, some data was lost due to grid sizing and data size limits. For example, short steep banks are hard to capture with this technique. It was found that this small loss of data was worth the added detail on the channel bottom. The surface was then completed using ArcGIS since AutoCAD could not process the large amount of data associated with the edge of water breaklines. Using ArcGIS, the water surface breaklines (with z information drawn from the LiDAR dataset) were added to the channel surface, ensuring that the channel surface bottom daylighted to the full LiDAR surface.

This method works well for complex channel geometry and limited surveyed channel cross sections and has the benefit over a typified section in that it does not rely on accurate gage data during the time of flight. For the study area, active USGS gage data is limited geographically to the vicinity of the City of Missoula and a gage located about 10 miles west (downstream) of Drummond, and LiDAR (4) was collected over a range of dates, making it difficult to calibrate a typical cross section.

3.4.5 Hydraulic Structures

HEC-RAS does not currently have bridge modeling capabilities in 2D and can currently only model culverts (30 pp. 1-8). This limitation results in modeling bridge structures two ways: as box culverts or having the physical structure merged into terrain without a deck. The latter method is only valid if flood flows do not reach the low chord of the bridge. A small numerical study was done on the Higgins Avenue bridge to assess this approach for the structures throughout the study. Many of the structures on the Clark Fork River have low chords well above any flood heights, and only the piers and abutments interact with the flood events.

The South Higgins Avenue bridge has two sets of piers that are within the channel extents at all flows of interest. A truncated 2D model was used to determine if the piers have significant impact on the predicted flow depth or water surface elevation during the 1% probability flow event. The reach of the truncated model extends approximately 1,200 feet upstream of the bridge and 1,400 feet downstream of the bridge. The bridge spans about 971 feet. The upstream boundary condition is a typical inflow hydrograph, increasing from no flow to a steady value of 40,500 cfs (1% AC Event) (5). The downstream boundary condition is uniform flow with a slope of 0.001, representing the general bed slope in this region. During the 1% AC event, the predicted flow depth in the vicinity of the bridge piers ranges generally from 8 to 11 feet in this well-confined corridor, and the piers block less than 3% of the cross-sectional flow area. In the first model run, the piers were included and incorporated into the terrain. In the second model run, the piers were removed. During the 1% AC event, the water surface does not interact with the bridge deck for this structure. The difference between the resulting water surface elevations in the vicinity of the bridge for the two model runs was less than 0.1 feet throughout. Based on this analysis, the bridge piers can be removed in larger 2D models without detectable impact on water surface elevation predictions. This mechanism only affects 2D models as the 1D models have the bridge modelled as a detailed structure with piers intact.

3.4.6 Model Calibration

Historical information and gage measurements provide useful data to inform model parameters, test model sensitivity, and provide a sense of model accuracy. Several sources were investigated to assist with model calibration. Efforts were made to try and calibrate the 2D models to the 1D standard of 0.5 ft (31 p. 13). For the models with gage data, a similar process to the 1D model calibration was used by modeling select historical flooding events. For the other models without gage data, other methods were used to try and calibrate the models. To ensure that both models were hydraulicly similar, the 1% AC event WSE from both models were compared, using a raster difference in ArcMap. The results showed a mean difference of less than 0.3 feet for detailed 2D models and less than 0.7 feet for the preliminary or rough 2D models.

See Table 3-7 and 3-8 for computational parameters used for the detailed and preliminary 2D HEC-RAS models. Most parameters for the models were held constant. Parameters that are reliant on model geometry and cell layout, like eddy viscosity or computational interval (time step), are specific to each model. The computational interval is dependent on the Courant Number. It is suggested that the Courant number be kept below 3 and above 0.7. The Courant Number is dependent on cell size and flow velocity, so each model had to calculate the maximum Courant Number separately and adjust the computational interval accordingly.

Table 3-7. HEC-RAS Detailed 2D Model Computational Parameters

Computational Parameter	Model		
	CFR_GC_Drum_2D	CFR_MC_Msla_2D	CFR_MC_L_2D
Simulation Time (hrs)	76	24	24
Computational Interval (sec)	60	10-12	10-12
Output Interval (min)	60	60	60
Theta	.8	.8	.8
Theta Warmup	1	1	1
Water Surface Tolerance	.01	.01	.01
Volume Tolerance	.01	.01	.01
Maximum Iterations	20	20	20
Equation Set	Full Momentum	Full Momentum	Full Momentum
Initial Conditions Time (hrs)	24	24	24
Initial Conditions Ramp Up Factor (0-1)	0.5	0.5	0.5
Eddy Viscosity Transverse Missing Coefficient	-	0.3	0.3

Table 3-8. Preliminary 2D Model Computational Parameters

Computational Parameter	Model CFR_GC_L	CFR_MC_U
Simulation Time (hrs)	60	76
Computational Interval (sec)	15	15
Output Interval (min)	5	60
Theta	.8	.8
Theta Warmup	1	1
Water Surface Tolerance	.01	.01
Volume Tolerance	.01	.01
Maximum Iterations	20	20
Equation Set	Full Momentum	Full Momentum
Initial Conditions Time (hrs)	6	24
Initial Conditions Ramp Up Factor (0-1)	0.1	0.5
Eddy Viscosity Transverse Missing Coefficient	-	-

3.4.6.1 Historical Sources

The Montana Department of Transportation Air Photo Unit was visited by AESI staff on March 12, 2020 (Personal Communication T. Chingas, April 2, 2021) to search for aerial photographs and any other available historical flooding information. Photographs taken during flooding in 1975 and 1981 were found for the areas along the Clark Fork River. The 1975 flood was photographed in the City of Missoula area and at Turah, Beavertail Creek, and Bearmouth Creek. The 1981 flood was captured from Drummond to Deerlodge.

The Missoula County floodplain administrator provided several historical flooding information sources, including aerial photographs, highwater marks, and flood inundation extents for flooding that occurred in 1997, 2011, and 2018. The following table summarizes the received data.

Table 3-9. Summary of available historical flood data

Flooding Year	Available Data	Source
1975	Aerial photographs in the City of Missoula and at Turah, Beavertail Creek, and Bearmouth Creek vicinities	MDT
1981	Aerial photographs from Deerlodge to Drummond. Note, there is no USGS stream gage data in 1981 for the Drummond vicinity.	MDT
1997	Orthorectified aerial images and associated georeferencing files in the City of Missoula area, confluence of Clark Fork and Bitterroot to Frenchtown area, upstream of the Clark Fork and Bitterroot confluences, and Rock Creek Airport to East Missoula	Missoula County
2011	Aerial photographs (taken by hand from a plane) in the City of Missoula area and upstream to Turah.	Missoula County
2018	Orthorectified aerial images and associated georeferencing files in the Orchard Homes and City of Missoula vicinities, shapefiles of highwater marks and flood inundation boundaries	Missoula County

The received data was visually compared to simulated floods at the recorded peak flows on the day or time span that the data was recorded. Given channel morphology changes and some uncertainty regarding flows at the time aerial photography was taken, exact agreement between the model and the recorded data was not expected. However, simulated results generally show reasonable agreement with the aerial photography and provided shapefiles.

For the reaches without gage data, the aerial photography was used to increase confidence in model accuracy. These reaches included CFR_MC_L and CFR_GC_Drum. For CFR_MC_L, the 1997 event has the best data for this reach, so a plan was created to simulate the flow during the day of the flight over this area on May 19, 1997. For CFR_GC_Drum, the 1981 event has the best data for this reach, so a plan was created to simulate flow during the day of the flight over this area on May 23, 1981. Once the models were completed, the inundation extents were then compared to the aerial photographs. The older aerial photos are in black and white, so distinguishing inundation extents can be difficult, and also the river channel appears to have moved since the time of these photographs. With those limitations in mind, the flooding extents generally match.

Historical aerial photographs were not detailed enough to facilitate rigorous statistical comparisons to model output. Engineering judgment was used to determine that the coincidence between aerial photos, and model output increased the confidence in the appropriateness of the 2D models.

3.4.6.2 USGS Stream Gage Data

Several gages with flow and stage information exist along the reaches modeled. There are four active USGS stream gages along the studied reach of the Clark Fork River. DOWL surveyed elevation reference marks at these gages. Table 3-10 provides a summary of these four USGS stream gages. Two of these gages, Clark Fork above Missoula and Clark Fork below Missoula, are located in the Missoula County – Missoula detailed 2D hydraulic model. The other two gages are located in rough 2D models as noted in the table below.

Table 3-10. USGS Stream Gage Data Used in Model Calibration

River	Gage #	USGS Description	Model and RS
Clark Fork River	12331800	Clark Fork near Drummond	2D_CFR_GC_L, RS 91250*
Clark Fork River	12334550	Clark Fork at Turah Bridge near Bonner	2D_CFR_MC_U*, RS 277545
Clark Fork River	12340500	Clark Fork above Missoula	2D_CFR_MC_Msla, RS 233697
Clark Fork River	12353000	Clark Fork below Missoula	2D_CFR_MC_Msla, RS 167502

* Gages located in rough 2D model segments.

Calibration was completed at the Clark Fork above Missoula gage and the Clark Fork below Missoula gage by adjusting model parameters to better match the measured data. Measured and simulated water surface elevations within 0.5 feet (31 p. 13) were considered to be in good agreement. For the 2D models, this small difference between gage data and model data was not always possible. The main difference for this may be the higher reliance the 2D model has on the terrain and approximate channel bottom and land use layer. Engineering judgement was used to try and bring the difference in observed and modeled water surface level as close as possible. This included changing channel Manning's n values, modifying the channel bottom and calculation parameters. Lidar or surveyed topographies were not manipulated. Calibration using USGS stream gage data for the models is described in further detail below.

Granite County - Lower Model (CFR_GC_L) – Gage 12331800

The CFR_GC_L model calibrated well to USGS Gage 12331800. The gage height is recorded on the right downstream pier of the Bear Gulch Road bridge (S105). The channel Manning's n was adjusted to 0.036 to achieve calibration. WSEs calibrated within 0.25 and 0.78 feet of the observed events in 1996 and 1997 respectively. Therefore, the mean absolute error considering both calibration events is 0.52 feet which is just above the calibration goal.

Missoula County - Upper Model (CFR_MC_U) – Gage 12334550

The CFR_MC_U model calibrated well to USGS Gage 12334550. The gage height is recorded on the upstream side of the Turah Road bridge (S083). The channel Manning's n was adjusted to 0.036 to achieve calibration. WSEs calibrated within 0.18 and 0.51 feet of the observed events in 2011 and 1997, respectively. Therefore, the mean absolute error considering both calibration events is 0.35 feet which meets the calibration goal.

Missoula County - Missoula Model (CFR_MC_Msla) – Gage 12340500

The CFR_MC_Msla model calibrated well to USGS Gage 12340500. The gage height is recorded 25 feet downstream of the cableway that is used for discharge measurements. This location is about 1200 feet downstream of the Deer Creek Road bridge (S078). The channel Manning's n was adjusted to 0.026 to achieve calibration. WSEs calibrated within 0.53 and 0.59 feet of the observed events in 2018 and 1997 respectively. Therefore, the mean absolute error considering both calibration events is 0.56 feet which is just above the calibration goal.

Missoula County - Missoula Model (CFR_MC_Msla) – Gage 12353000

The CFR_MC_Msla model calibrated well to USGS Gage 12353000. The gage height is recorded 300 feet upstream of the cableway that is used for discharge measurements. This location is about 1.5 miles downstream of the confluence with the Bitterroot River and 2.6 miles upstream of the Kona Ranch Road bridge (S028). The channel Manning's n was adjusted to 0.026 to achieve calibration. WSEs calibrated to within -0.36 and -0.30 feet of the observed events in 1997 and 2018, respectively. Therefore, the mean absolute error considering both calibration events is 0.33 feet which meets the calibration goal.

3.4.7 Split Flow Analysis

Split flows were automatically simulated by the 2D models. Breaklines were included to ensure that high ground was accurately modeled and prevents flow from "leaking" through barriers. The breaklines place the edge of the cells on high ground, forcing the model to calculate the water surface elevation needed to overtop that high ground. This process is very useful to identify areas that would split from the main flow and how to address them in the 1D model. Both the preliminary and detailed models used breaklines on the highwater marks of the rivers. Generally, the water boundary breaklines from the LiDAR data set could be used for this purpose. Other items such as levees and non-levee features had breaklines placed on the crowns or highest points. The difference between the detailed and preliminary models is that breakline placement was refined with model iterations to best capture split flows. In turn, this creates a better computational mesh for subsequent analysis.

3.4.8 Multiple/Worst-Case Scenario Analysis

Worst-case scenario analyses (WCSA) were simulated to determine the most extensive flooding possible. WCSA focused on the presence or removal of non-levee features (NLF), levees, and non-accredited levees from the model. Non-levee features in low population areas were generally not addressed in the 2D model and are addressed using ineffective flow in the 1D model. Elsewhere, accredited and non-accredited levees, mostly occurring in the City of Missoula area, were modeled as in-place and as removed within the 2D simulation. This was completed by producing multiple surfaces that depicted the terrain with the feature in-place or with the natural ground approximated as the toe of the exiting feature. Complicating the analysis, the proximity of the levees meant that multiple combinations of levee and natural ground scenarios needed to be explored to ensure that flows were maximized in the main stem and in the splits. The following text describes specific WCSA performed. Setup of the WCSA for the regulatory 1D hydraulic model is discussed in **Section 3.5**.

<u>Drummond (CFR_GC_Drum model)</u>

The Clark Fork River flows in a northwesterly direction to the south of Drummond. In the area around Drummond, an abandoned railroad grade exists on the north side of the Clark Fork, extending 1.5 miles downstream and 1.9 miles upstream of State Highway 1. This railroad grade acts like a levee separating the flow on the north side from the flow in the main channel (refer to Figure 3-4.).

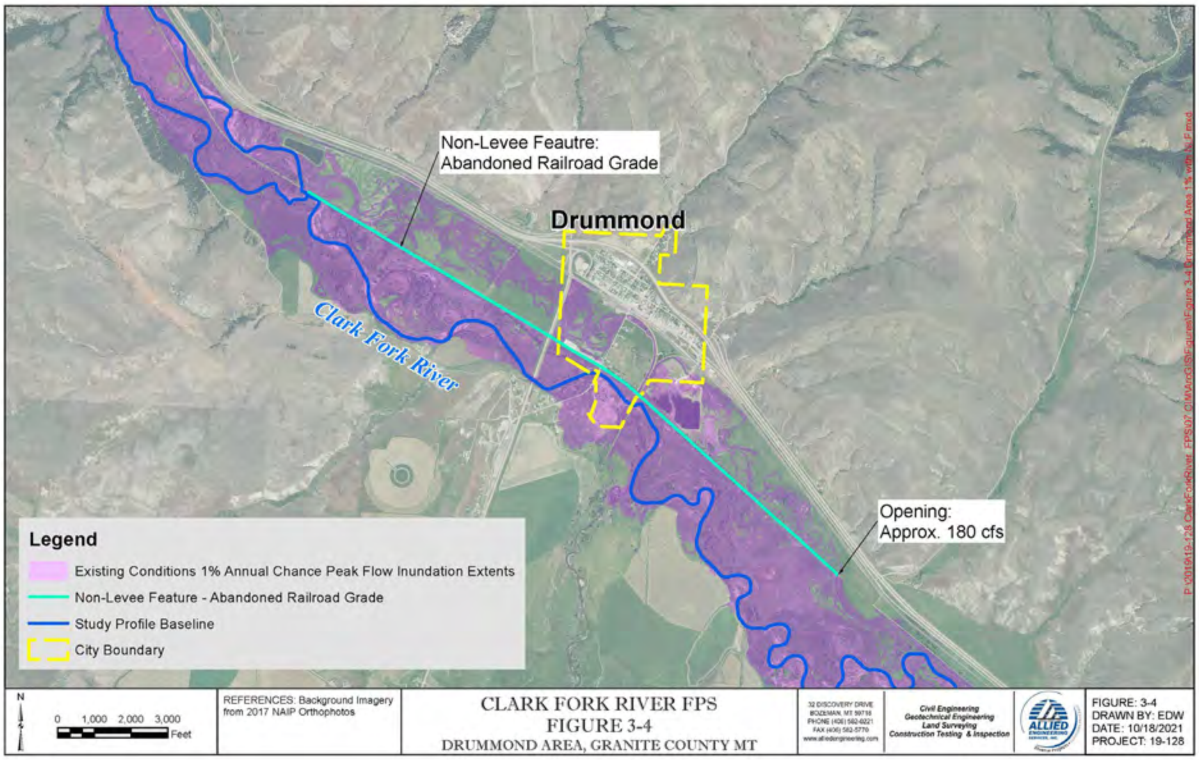

Figure 3-4. Drummond area existing conditions one-percent annual chance peak flow inundation extents.

Figure 3-4. shows the one-percent annual chance peak flow inundation extents from the existing conditions 2D hydraulic model for Drummond. An opening at the upstream end of the abandoned railroad grade allows a flow of approximately 180 cfs to enter the right side of the railroad grade and to flow northwest along Bergman Slough. Figure 3-5 shows the one-percent-annual-chance flood event inundation extents for the condition where the abandoned railroad grade is removed from the 2D hydraulic model.

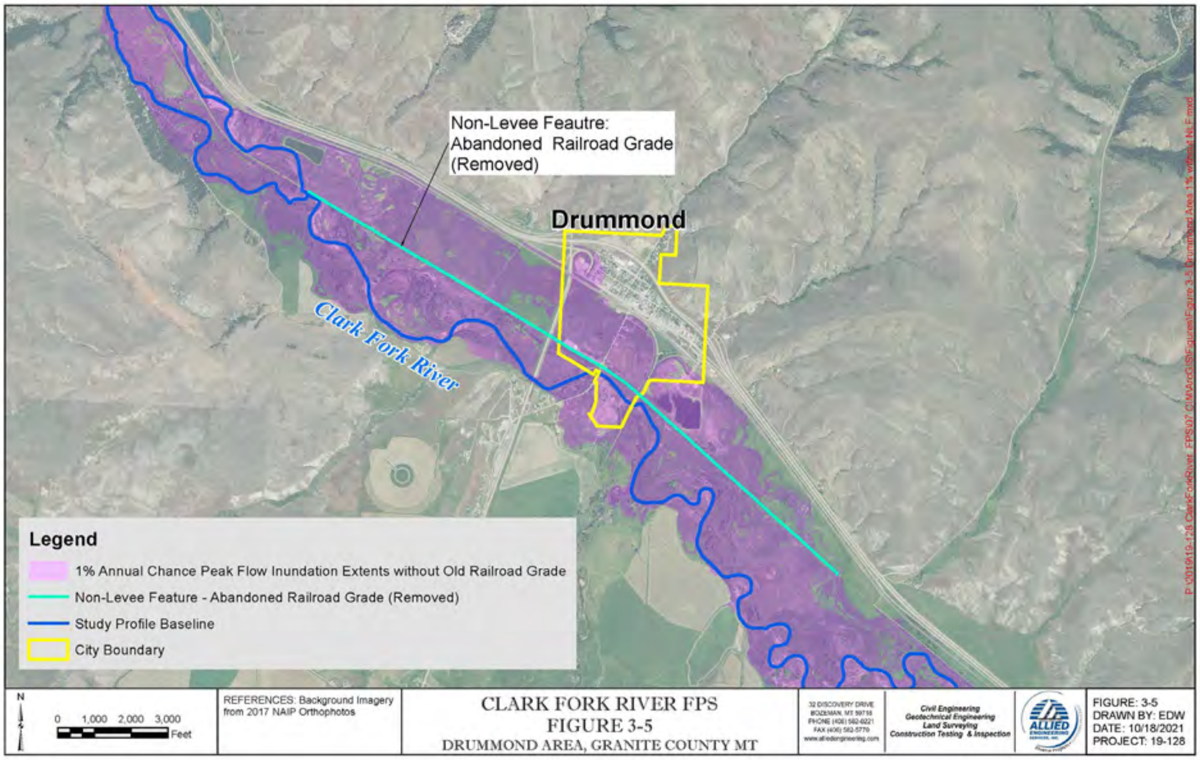

Figure 3-5. Drummond area one-percent annual chance peak flow inundation extents without abandoned railroad grade.

The worst-case scenario for flooding on the Clark Fork River side of the abandoned railroad grade is represented with the abandoned railroad grade in place (Figure 3-4.). The worst-case scenario for flooding on the landward side of the abandoned railroad grade is represented with removal of the abandoned railroad grade (Figure 3-5).

<u>Missoula (CFR_MC_Msla model)</u>

The WCSA for this model involves five different "levee" features. Table 3-11 below provides a summary of the worst-case scenarios simulated in the 2D City of Missoula model. The paragraphs below provide additional detail about these worst-case scenarios. The primary uses for these models are to facilitate calibration for lateral structures, to provide guidance for cross section and profile alignment in the 1D model, and to capture all split flows.

Table 3-11 Missoula Model WCS Summary

	Missoula Model Levees - In Place(X), Removed (Blank)					
WCS Name	**Area 3**	**Area 5**	**McCormick Park**	**Monroc**	**Orchard Homes**	**Orchard Homes Spur**
Existing Conditions	X	X	X	X	X	X
No Levees (Natural Valley)						
Area 5	X		X	X	X	X
Monroc and Orchard Homes	X	X	X			

Area 3 and Area 5 are both accredited levees on the right bank of the river. For both of these levees, the worst-case scenario is when they fail independently. The Area 3 levee does not convey flow away from the main river corridor and is not influenced by other downstream levees. No separate model was needed for this levee and instead flood behind Area 3 is depicted by the Natural Valley scenario. This was modeled with two separate 2D models.

On the left bank near these accredited levees are two non-levee features. The McCormick Park non-levee is overtopped in the 2D model. This flow then backs up behind the railroad before overtopping the openings in the railroad berm. The flow moves west and mingles with flow from the Clark Fork in the low area near the Russel Street bridge. The berm caused by the Russel Street bridge embankment forces all flow back into the Clark Fork River. For this area's 1D model results, see discussion below as the results are much different given the water surface elevation of the 1D model is lower.

The Monroc non-levee feature provides flood protection during the 1% AC event. When removed, flood water from the Clark Fork River flows out of the main channel through a relatively flat urban area before crossing North Reserve Street and flowing behind the Orchard Homes accredited levee. Some flow does leave the Monroc split just upstream of the Orchard Homes levee. Having the Orchard Homes levee in-place keeps a portion of the Monroc split flows from returning to the main flow until it is has flowed around the downstream end of the Orchard Homes levee. The Orchard Homes levee itself does prevent Clark Fork River flood water from overtopping during the 1% AC event. However, Clark Fork River flood water overtops natural ground on the left bank upstream of the levee. This location is downstream of North Reserve Street. Flood water overtopping natural ground at this location flows along the landward side of the levee before flowing back into the Clark Fork River. The WCS for the landward side of the Orchard Homes levee is when both the Monroc non-levee feature and the Orchard Homes levee are removed.

<u>Missoula County Downstream of Missoula (CFR_MC_L model)</u>

In this model, there are two areas with potential WCSA but were instead modeled using the existing conditions model. These areas are Stone Container NLF and the abandoned railroad grade NLF south of Frenchtown.

The Stone Container NLF is located on the right bank of the Clark Fork River (RS 111475 to RS 123236). When left in-place, this non-levee feature is not overtopped for any of the events modeled. The 2D model leaves the feature in-place to model water surface elevations similar to the 1D model. The 1D model utilizes ineffective flow on the landward side of the levee to show inundation but no conveyance behind the NLF.

The abandoned railroad grade NLF south of Frenchtown prevents a large portion of the floodplain from conveying flood flows but does have enough structures to allow for inundation from the Clark Fork River. In the 2D model, this area was modeled with openings placed into the railroad grade at existing hydraulic structures to allow for exchange of flood flows from riverward to the landward side of the feature. At each hydraulic structure in the railroad grade, a strip of the embankment was removed that was as wide as the existing structure or at least three feet to create an opening. This approach more closely matches the 1D model results that used ineffective flow in this area to model the resulting shallow flooding north of the railroad berm.

3.5 1D Hydraulic Modeling

The Clark Fork River in Missoula County was split into three 1D hydraulic models. In Granite County, two 1D models were developed. The extent of each of these models is also shown on Figures 3-1, 3-2, and 3-3 located in **Appendix A**. Lower Grant Creek was modeled from the original HEC-RAS model used in the approved 2011 LOMR application. The terrain used to plot the flooding extents was updated with the LiDAR data used for the Clark Fork River. Flows used in the original model were modified to match the existing Missoula County FIS discharge table.

3.5.1 Profile Baseline

The water line developed during the hydrologic analysis approximates the channel centerline and was used to establish the profile baselines. The water line was reviewed against the 2017 NAIP aerial photograph and the LiDAR terrain. Based on the review, minor adjustments were made to the water lines before using the linework as the final profile baseline.

River stationing for cross sections and other notable features references the stream distance as measured by the profile baseline and increases from downstream to upstream. Each modeled stream and its associated station reference are shown in Table 3-12. Profile Baseline Key Features Summary Tables along the Clark Fork River are located in **Appendix B**.

Table 3-12. Summary of Station References

Flooding Source	Station Reference
Clark Fork River – Missoula County	14,775 Feet upstream of Mineral/Missoula County Boundary
Area 5 Split	400 Feet upstream of Confluence with Clark Fork River
Monroc Split	1538 Feet upstream of Confluence with Clark Fork River
Clark Fork Divided Flow	262 Feet upstream of Confluence with Clark Fork River
Clark Fork River – Granite County	0.0 Feet upstream of Missoula/Granite County Boundary
Lower Grant Creek	367 ft upstream of confluence with Clark Fork Floodplain

3.5.2 Boundary Conditions

Known water surface elevations from downstream models were used as downstream boundary conditions for the Clark Fork River reaches. Split flow reaches used junctions with the Clark Fork River for the downstream boundary conditions. Table 3-13 summarizes the boundary conditions used in the analysis.

Table 3-13. Boundary Conditions

Clark Fork Reach or Split	Boundary Condition
CFR_GC_Drum	Known Water Surface Elevation from CFR_GC_L Model
CFR_GC_L	Known Water Surface Elevation from CFR_MC_U Model
CFR_MC_U	Known Water Surface Elevation from CFR_MC_Msla Model
CFR_MC_Msla	Known Water Surface Elevation from CFR_MC_L Model
CFR_MC_L	Known Water Surface Elevation from Clark Fork River Mineral County Hydraulic Model
Area 5 Split	Junction (Energy) with main stem of the Clark Fork
Monroc Split	Junction (Energy) with main stem of the Clark Fork
Clark Fork Divided Flow	Junction (Energy) with main stem of the Clark Fork
Lower Grant Creek	Normal Depth using channel slope of 0.005 ft/ft

3.5.3 Manning's Roughness Coefficients

Refer to **Section 3.4.3** for a description of the Manning's roughness coefficients used for modeling. One difference between the 2D and 1D model roughness coefficients is how buildings were represented. For the 2D models, the building footprints were assigned a Manning's n of 100. In the 1D models, buildings that were in a cross section were assigned as blocked flow areas. The buildings were not inundated, and assuming that they were not swept away during high flows, they would essentially serve as obstructions, removing potential flow area from the cross section. **Section 3.5.9** discusses model calibration and the adjustment of Manning's roughness coefficients to best match measured and observed data.

3.5.4 Development of Cross-Sectional Geometries

Cross section locations were set using guidance provided in the HEC-RAS Hydraulic Reference Manual (16), as well as established floodplain modeling practice. Additionally, the 2019 LiDAR (4), 2D hydraulic models, and the 2019 bathymetric field survey by DOWL (1) (2) assisted with cross section placement. Per DNRC's guidance, cross sections were initially placed at an average spacing of approximately 500 feet with intermediate cross sections occasionally added where more detail was warranted (near structures or where cross section geometry was more variable). Occasionally, increased cross section spacing was necessary in areas where channel sinuosity or wide and complex floodplains prevented closer spacing.

All cross-sectional geometries sampled the composite surface formed between the 2019 LiDAR and the interpolated channel bottom surface described in **Section 3.3.4**. Cross sections coincident with surveyed bathymetric points directly utilized the surveyed points by superimposing the points to the cross section.

For cross sections on the secondary flooding sources without bathymetric survey data, cross-sectional geometries were determined using the LiDAR terrain data only. The split flows in the City of Missoula are urban, and the LiDAR accurately depicts the terrain without additional survey. In several other split flow locations, there was no surface water flow when the LiDAR was collected, so LiDAR surfaces could be used directly.

As recommended in the HEC-RAS Hydraulic Reference Manual (16), contraction and expansion coefficients were set as 0.1 and 0.3 in areas of gradual transition, and 0.3 and 0.5 at typical bridge sections 2, 3, and 4.

Bank stations were placed at the boundary between the stream channel and the overbank/floodplain area. Bank stations were generally placed at a topographic inflection point which provides a clear break between the stream and the overbank/floodplain. As a general criterion for choosing bank stations, grades steeper than 30% were categorized as part of the channel. Several cross sections have bank stations higher than the largest events modeled because of steeply eroded banks.

Cross section numbering in the model is based on the HEC-RAS river stations as determined by the length of the profile baseline from the county line in each model. Photographs of cross sections adjacent to hydraulic structures are provided in **Appendix C.**

3.5.5 Hydraulic Structures

Hydraulic structures were modeled in HEC-RAS using conventional engineering practice and guidance provided in the HEC-RAS Hydraulic Reference Manual (16). A total of 119 structures were surveyed in Missoula and Granite Counties for the Clark Fork River by Pioneer (3). Not all structures were used in the analysis. See Table 3-14 below for list of structures used. Several structures, including culverts, were determined to be insignificant because their conveyance capacity would not influence flood flows. Other structures were excluded because they are on irrigation ditches that follow the contour of the land and do not convey flow through the floodplain.

Table 3-14 Structures Included in Hydraulic Models

Model Name	Structures Included	Total Modeled Structures
CFR_MC_L_1D	S001, S002, S003, S004, S005, S0026	6
CFR_MC_Msla_1D	S033, S034, S035, S036, S037, S038, S039, S045, S052, S055, S065, S069, S074, S075, S076, S077, S078, S079, S080	18
CFR_MC_U_1D	S083, S087, S089, S090	4
LGC_MC	RS 2995.86, RS 4116, Bypass Culverts	3
Missoula County Total		31
GC_L	S091, S092, S094, S095, S096, S097, S098, S099, S100, S102, S105, S107, S108	13
GC_Drummond	S109, S110, S111, S112, S115, S116, S117, S118	7
Granite County Total		20

Hydraulic structures' dimensions were configured from the collected survey data and checked against the field sketches. Photographs were used to visually check the geometry of each individual hydraulic structure and verify pier shapes.

Guidance provided in the HEC-RAS Hydraulic Reference Manual was used to determine low flow and high flow hydraulic structure modeling approaches. For most of the structures in this study, the low chord and the abutments were not inundated during the 1% AC event. At these locations, the structures had very little influence on the floodplain.

The CFR_MC_L_1D model has two skewed bridges on Interstate 90. S002 and S003 are two bridges that are located close together. Since the two bridges have different locations for piers, the bridges were modeled separately. Both bridges are skewed 45 degrees from the main flow. This is the maximum allowed skew in HEC-RAS, the true skew angle is closer to 48 degrees. In this model, three bridges (S002, S003, and S005) used energy only for low flow calculations. This change was done to remove large changes in WSE caused by the structures. See additional discussion below.

In initial simulations, the CFR_MC_Msla_1D model indicated large drops in water surface elevation (up to 5 feet) just downstream of several of the bridges. In these models, the Momentum and Energy equations were selected, with HEC-RAS opting for the result having the highest energy. Not only were these drops in WSE troubling, comparisons between model output and the calibrating gage 12340500 indicated that the influence of the bridges was overestimated. These bridges tend to be in settings where there is little or no contraction/expansion in the bridge cross sections, and in all cases, there was no interaction between the water surface and the deck. Changing the bridge model at these structures from Momentum/Energy to Energy Only achieved a more typical WSE profile through the bridge sections and made model predictions more consistent with gage information. As a result, structures S052, S076, and S077 had only the Energy equation activated for low flow during the simulation. This process was also used in the downstream study of Mineral County (7 p. 22) for the Clark Fork River.

Other atypical structures in the model include the pile weir S033 downstream of Missoula and the MRL Railroad Embankment (S049, S050, and S501). S033 is an irrigation diversion weir that spans the main channel only. This structure was modeled by modified channel bottom geometry to include the apex of the weir. The channel bottom was raised to the top of the steel piles in the weir. This process was used because the Clark Fork River has a large floodplain in this area with multiple flow paths, so a traditional in-line structure would be inappropriate. The model achieved a critical depth prediction over the weir itself which is as expected. The MRL Railroad embankment was not modeled as a hydraulic structure, and instead the area was left as ineffective flow as none of the flood profiles overtop the embankment.

The unnamed bridge and abandoned piers and abutments (S034, S035, and S036) located at RS 196063 were modeled as a structure by creating a synthetic bridge deck over the abandoned piers. No profiles came close to overtopping the bridge decks or piers, so this method was used to simplify structure geometry modeling at this location.

Two Interstate 90 crossings in the model had double bridges. Both S077 and S079 are constructed of identical bridges placed parallel to each other. These structures were modeled as one large bridge at each double bridge crossing. The piers of the structures were constructed in a straight line to the flow, so the structure was shown as a wide bridge in HEC-RAS. This method is acceptable for structures like this where the flow does not have enough time to fully expand or contract before passing under the next structure (32 pp. 5-30).

The CFR_GC_L 1D model also had pile weir diversion structure (S094) that spanned the entire channel. This structure was modeled the same way as S033, using a modified channel bottom geometry to include the apex of the weir. The channel bottom was raised to the top of the piles in the weir. The model achieved a critical depth prediction over the weir itself which is as expected.

There were several bridge structures with no deck and only abutments and piers remaining in the channel and along the banks. These structures were modeled by assigning the area of the piers and abutments perpendicular to flow as blocked obstructions.

The CFR_GC_Drum 1D model “No Levee” plans had three separate multiple crossing locations where the Clark Fork River flows under MT Highway 1 (S110, S111, S112, S113), Main St (S115, S116) and the MRL Railroad (S117, S118). The “Levee” plans have the area to the right of the abandoned railroad grade as ineffective, so the structures that were not spanning the Clark Fork River’s main channel were removed from that geometry. The structure spanning the main channel (S113) at MT Highway 1 was modeled as a regular bridge structure. The culvert (S111) where Bergman Slough flows under MT Highway 1 was modeled as a regular culvert. The two other bridge structures (S110 and S112) at MT Highway 1 were modeled using blocked obstructions to represent their piers. This method was used because very little flow was being directed through these openings, and it simplified the multiple opening analysis. The other two multiple opening analysis locations only consisted of two bridge structures, and both were modeled.

For the Lower Grant Creek model three structures were included to finalize the flow optimization of the model stretch needed for floodplain modeling. The three structures are two bridges and one culvert bypass. The bypass flow is fed by a lateral structure at river station 4600. Flow entering the bypass then flows into three 5-ft diameter culverts that carry flow out of the Lower Grant Creek Floodplain into the Clark Fork River Floodplain. Optimization was re-run for this lateral structure because it determines the discharge rates for the needed mapping in Lower Grant Creek.

3.5.6 Non-Conveyance/Blocked Obstruction Areas

Ineffective areas and blocked obstructions were applied at cross sections to accurately depict areas conveying flood flows. Ineffective flow areas were used in the models for the following hydraulic scenarios:

- Ineffective flow areas are used in the cross sections adjacent to hydraulic structures to represent the physical obstruction of the structure and represent the expansion or contraction flow path either to or from the structure. Hydraulic structure modeling guidance provided in the HEC-RAS Hydraulic Reference Manual (16) was used to place these ineffective flow areas.
- Ineffective areas were added to the models in areas assessed to be hydraulically disconnected since flow would not be conveyed downstream in these areas.
- Areas of backwater were modeled as ineffective flow.
- Areas where the flow would not be in the primary direction of flow were modeled as ineffective flow areas. An example would be where an old meander comes into the river laterally at a cross section.
- Areas near buildings (or in the hydraulic “shadow” of buildings) were occasionally modeled as ineffective areas. This was done to account for areas of flow that would not be active behind buildings.
- Areas that cross lakes, ponds, and all other localized depressions.

Blocked obstructions were also used in the model as follows:

- Blocked obstructions were placed to represent buildings or other physical obstructions in a cross section.

Ineffective flow areas and blocked obstructions were placed in accordance with engineering judgment and guidance from the HEC-RAS Hydraulic Reference Manual.

3.5.7 Split Flow Analysis

Split flows, including locations and magnitudes, were determined from the 2D model. Split flows with a significant amount of flow, depth (average depth greater than 0.5 feet), and length were modeled.

Table 3-15 lists each of these split flows, the flooding source, the split type, and the length of the split flow reach. In total, over 5.3 miles of secondary flooding sources were modeled. Split flow names matched official geographic names where possible, and generic split names were applied elsewhere. In the City of Missoula model, the split flows are named after the levee or NLF that created the split.

Non-levee features are structures that cannot be accredited in accordance with the Code of Federal Regulations, Title 44, Chapter 1, Section 59.1 (33). Since non-levee features cannot be considered permanent structures, WCSA were performed where necessary to determine the highest possible flows on primary or secondary flooding sources. The highest computed flow was then applied to the final regulatory model.

Table 3-15. Split Flow Descriptions

Split Flow Name	Flooding Source	Split Type (LS, Junction, Gate)	Stream Length (miles)
Clark Fork Divided Flow	Clark Fork River	Junction Clark Fork Reach 4	2.1
Area 5 Split	Clark Fork River	LS 207404	1.4
Monroc Split	Clark Fork River	LS 206287	1.8

3.5.8 Multiple/Worst Case Scenario Analysis

WCSA modeled with the 1D hydraulic models are informed by the WCSA completed with the 2D hydraulic models. The following text describes the WCSA performed for the models:

<u>Drummond (CFR_GC_Drum model)</u>

The WSCAs for the Drummond area includes the following modeling approach:

- Worst case for Clark Fork River side of the NLF (abandoned railroad grade) – valley wide cross-sections are used with the area to right of the abandoned railroad grade designated as ineffective flow. The 2D hydraulic model shows a small amount of flow (~180 cfs) to the right of the NLF. For the WCSA, this flow is assumed to be on the Clark Fork River side of the NLF.
- Worst case for the area landward of the NLF – valley wide cross-sections are used with the area to the right of the NLF designated as effective flow.

Refer to Figure 3-6 for a schematic depiction of the 1D model setup for the Drummond WCSA. This modeling approach affected the split flow quantities for the Clark Fork Divided Flow split. The WSCA for the Clark Fork River side resulted in more flow in the Clark Fork Divided Flow split compared to the WSCA for the landward side of the NLF.

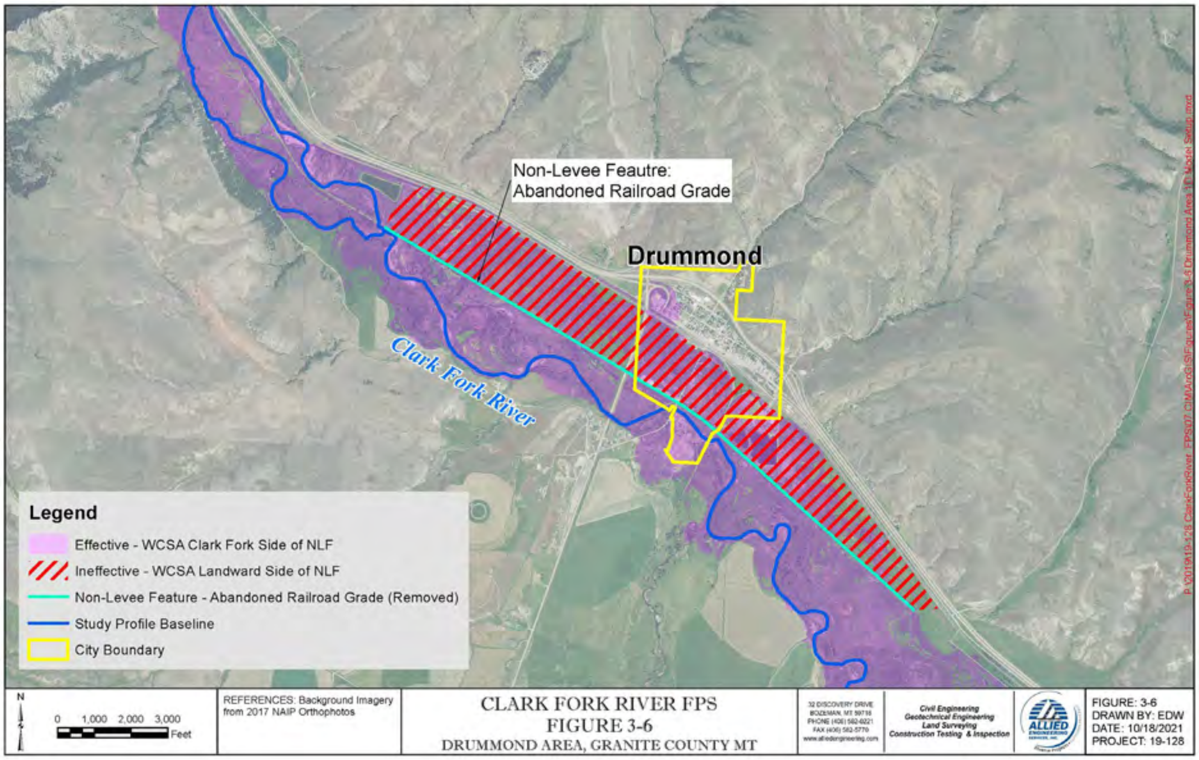

Figure 3-6. Drummond area worst case scenario analysis 1D model setup.

<u>City of Missoula (CFR_MC_Msla model)</u>

The WSCAs for the City of Missoula area include the following modeling approach for the both the Area 5 WCS and Monroc-Orchard Homes WCS plans. As mentioned earlier, the 2D model was used to estimate flows into this split. This flow estimate was then used to calibrate the weir coefficient used on the lateral structures to achieve flow splits similar to the 2D model flow. This approach was used for all lateral structures in the model.

Area 5 WCS

Worst Case for Area 5 removes the accredited levee and replaces it with natural ground. A lateral structure (LS 207404) is placed in its location to allow flow overtopping this area to flow into the Area 5 Split reach. In this model, all other levees or NLF are left in place to give the highest possible Clark Fork River WSE.

Flow that enters the Area 5 Split then flows southeast, eventually spilling back into the Clark Fork River along its right bank though multiple lateral structures. Three lateral structures utilize Area 5 Split as the WSE source to determine flow lost back into the Clark Fork River. These lateral structures are LS 4452, LS 3846, and LS 2714. Please note that the Area 5 Levee is accredited, and the modeled flooding will be mapped as Zone X.

Monroc-Orchard Homes WCS

Worst Case for the Monroc and Orchard Homes levee areas removes the Monroc NLF and leaves all other levees and NLF in place. At Monroc, the LS 206287 was placed along the NLF's original centerline to allow flow into the Monroc Split. This flow then travels west into an urban area before returning to the Clark Fork River just upstream of the Orchard Homes Levee.

Both the Orchard Homes levee and spur are left in place, but long cross sections are used to calculate conveyance and mapping on its landward side. The Monroc NLF and Orchard Homes were done in tandem because they do interact as shown in the 2D model. A small amount of flow from the Monroc Split will find its way behind the Orchard Homes Levee. This is represented in the 1D model by combining the Monroc Split flows back into the Clark Fork River before the Orchard Homes levee and spur NLF area. The average hydraulic depth for the Monroc Split was found to be below 0.5 feet, making it likely that the split will be mapped as Zone X.

McCormick Park Area

The McCormick NLF does provide flood protection, and the WCS is for it to be removed in the 1D model. Flow from the Clark Fork River enters the McCormick park area then pools in the McCormick Park area as ineffective flow. This backwatering is caused by the elevated MRL railroad that cuts across the floodplain in this area. The elevated railroad creates a spill elevation that the water must reach before spilling to the west. None of the flood profiles reach the spill elevation. Given the area's non-conveyance, this area is modeled using extended cross-sections from the Clark Fork River. Flooding downstream of the railroad berm has been revised during mapping to show only backwater from the overtopping off the left bank of the Clark Fork upstream of the Russel Street bridge.

An existing ditch flows from the McCormick Park area that has several culvert crossings on it. (S048, S047, S044, S043, S042, S041, S040). As stated above, culverts and ditches are generally not considered adequate flood control structures due to low capacities and a tendency to become blocked with flood debris.

<u>Missoula County Downstream of Missoula (CFR_MC_L model)</u>

At Frenchtown, the Clark Fork River flow direction changes from flowing north to flowing west. Adjacent to Frenchtown, there is a large floodplain on the right overbank of the Clark Fork River that contains historical channels of the river. The middle of this floodplain is transected by an abandoned railroad grade. This NLF is not overtopped by the 1% AC event or 0.2% AC event. Conveyance through the abandoned railroad grade is limited by relatively small hydraulic structures. To be conservative, the area to the right of the abandoned railroad grade was designated as ineffective flow. This same approach was then used for the Stone Container NLF to give a conservative WSE for the Clark Fork River but show mapping through the NLF.

Table 3-16. Locations of Worst Case Scenario Analyses.

Split Structure	Source River	Split(s)	Structure Type	WCSA Main River	WCSA Split
McCormick NLF	Clark Fork River	NA	Non-Levee Structure	In Place	NLF Removed
Area 5 Levee LS 207404	Clark Fork River	Area 5 Split	Accredited Levee	Levee In Place	Levee Removed
Monroc NLF LS 206287	Clark Fork River	Monroc Split	Non-Levee Structure	NLF In Place	NLF Removed

3.5.9 Model Calibration

As discussed in **Section 3.4.6**, several sources were investigated to assist with model calibration and check the accuracy of the 1D model.

3.5.9.1 Historical Sources

Refer to **Section 3.4.6.1** for a description of historical sources used to assist with model calibration. The 1997 and 1981 aerial imagery was used to attempt to calibrate the MC_L and GC_Drum model, respectively. These models have no active gages on them. As mentioned earlier, this imagery is older and not of high quality.

3.5.9.2 USGS Stream Gage Data

Table 3-17 provides a summary of the four active USGS stream gages used to calibrate the 1D hydraulic models.

Table 3-17. USGS Stream Gage Data Used in Model Calibration

River	Gage #	USGS Description	Model and RS
Clark Fork River	12331800	Clark Fork near Drummond	1D_CFR_GC_L, RS 91250
Clark Fork River	12334550	Clark Fork at Turah Bridge near Bonner	1D_CFR_MC_U, RS 277545
Clark Fork River	12340500	Clark Fork above Missoula	1D_CFR_MC_Msla, RS 233697
Clark Fork River	12353000	Clark Fork below Missoula	1D_CFR_MC_Msla, RS 167502

Calibration was completed at the gages shown in Table 3-17 by adjusting model parameters to better match the measured data. Measured and simulated water surface elevations within 0.5-feet (31 p. 13) were considered to be in good agreement. Calibration for the models is described in further detail below.

Granite County – Lower Model (CFR_GC_L) – Gage 12331800

The CFR_GC_L model calibrated well to USGS Gage 12331800. The channel Manning's n was adjusted to 0.042 to achieve calibration.

Table 3-18. Gage 12331800 Historical Flooding

Calibration Event	Peak Flow	Approximate Annual Chance Flood Event	WSE Difference
(Year)	(cfs)	(% AC)	(ft)
1996	9800	5%	-0.18
2011	8220	8%	0.03
2018	6260	21%	0.24
2017	5900	25%	0.29
1997	5000	33%	0.37

WSEs calibrated in the range of -0.18 to 0.37 feet of the observed events with a median value of 0.24 feet. The mean absolute error is 0.19 feet which meets the calibration goal.

Missoula County – Upper Model (CFR_MC_U) – Gage 12334550

The CFR_MC_U model calibrated well to USGS Gage 12334550. The channel Manning's n was adjusted to 0.042 to achieve calibration.

Table 3-19. Gage 12334550 Historical Flooding

Calibration Event	Peak Flow	Approximate Annual Chance Flood Event	WSE Difference
(Year)	(cfs)	(% AC)	(ft)
2011	13300	8%	-0.18
1996	12400	9%	-0.06
2018	12300	9%	-0.04
2017	9950	24%	0.17
1997	9870	25%	0.18

WSEs calibrated in the range of -0.18 to 0.18 feet of the observed events with a median value of -0.04 feet. The mean absolute error is 0.13 feet which meets the calibration goal.

Missoula County – Missoula Model (CFR_MC_Msla) – Gage 12340500

The CFR_MC_Msla model calibrated well to USGS Gage 12340500. The channel Manning's n was adjusted to 0.03 to achieve calibration.

Table 3-20. Gage 12340500 Historical Flooding

Calibration Event	Peak Flow	Approximate Annual Chance Flood Event	WSE Difference
(Year)	(cfs)	(% AC)	(ft)
2018	32,500	9%	-0.15
1975	32,300	10%	-0.15
1964	31,700	13%	-0.14
1948	31,500	14%	-0.14
1981	29,500	29%	-0.12
1997	27,000	47%	-0.09

WSEs calibrated with a median value of -0.14 feet of the observed events. The mean absolute error is 0.13 feet which meets the calibration goal. As mentioned above, this was done using energy only on the low flow calculations on the next two downstream bridges. Otherwise, the WSE was more than 0.5 feet above the gage WSE.

Missoula County – Missoula Model (CFR_MC_Msla) – Gage 12353000

The CFR_MC_Msla model calibrated well to USGS Gage 12353000. The channel Manning's n was adjusted to 0.032 to achieve calibration.

Table 3-21. Gage 12353000 Historical Flooding

Calibration Event	Peak Flow	Approximate Annual Chance Flood Event	WSE Difference
(Year)	(cfs)	(% AC)	(ft)
1997	55,100	4%	-0.03
1948	52,800	6%	0.02
1972	52,200	6%	0.04
2018	52,200	6%	0.04
1964	50,100	8%	0.08

WSEs calibrated with a median value of 0.04 feet of the observed events. The mean absolute error is 0.04 feet which meets the calibration goal.

3.5.9.3 Comparison to 2D Models

The 1D models that were informed by detailed 2D models were compared to the 2D models to determine agreement between the 1D and 2D models. Using the WSE output from both models, a difference raster was created. This raster is the result of the 1D model minus the 2D model. For multiple plan models, the equivalent scenario was used for the comparison. See Table 3-22 for results of this analysis. Below is a description of how the models compared.

Table 3-22. 1D to 2D WSE Comparison

AC Flood Event	1D Model – Plan	2D Model – Plan	Average Difference (ft)	Maximum Difference (ft)	Minimum Difference (ft)
1%	CFR_MC_L_1D – Regulatory	CFR_MC_L_2D – Existing Conditions	-0.2	5.3	-5.1
1%	CFR_MC_Msla_1D Regulatory	CFR_MC_Msla_2D Area 5	-0.3	5.1	-4.4
1%	CFR_MC_Msla_1D Regulatory	CFR_MC_Msla_2D MonOH	-0.3	4.4	-4.3
1%	CFR_MC_U_1D – Regulatory	CFR_MC_U_2D – Existing Conditions	-0.7	7.1	-6.7
1%	CFR_GC_L_1D – Regulatory	CFR_GC_L_2D – Existing Conditions	0.4	-5.6	6.8
1%	CFR_GC_Drum_1D - Regulatory No Levee	CFR_GC_Drum_2D -No Levee	0.1	6.7	-3.8
1%	CFR_GC_Drum_1D – Regulatory Levee	CFR_GC_Drum_2D – Levee	0.2	6.6	-3.2

Granite County – Drummond Model (CFR_GC_Drum)

The 1D and 2D model output for the Drummond model had similar flood extents and water surface elevations. The 1% annual-chance-event WSE output rasters were used to quantify the agreement between the two models. The flood extents and elevations of the WSE rasters were generally consistent between the two models. The modeled WSE of the 1D and 2D models was within 0.5 feet of each other for the majority of the modeled area. The average difference between the two models was only 0.1 and 0.2 feet for the “No Levee” and “Levee” scenarios respectively. A notable difference in the flood extents was on the dry side of NLFs. The 2D model showed these areas as dry, while the 1D model inundated these areas. This is expected, however, and the dry side of NLFs was modeled as ineffective for the 1D model.

Granite County – Lower Model (CFR_GC_L)

The 2D model in the Granite County Lower Reach is a preliminary model so not as much time was spent defining breaklines and the mesh. Despite this, the 1D and 2D model output had similar flood extents and water surface elevations. The 1% AC event WSE output rasters were used to quantify the agreement between the two models. The flood extents and elevations of the WSE rasters were generally consistent between the two models with an average difference of 0.1 feet. A notable difference in the flood extents was on the dry side of NLFs. The 2D model showed these areas as dry, while the 1D model inundated these areas. This is expected, however, and the dry side of NLFs was modeled as ineffective for the 1D model.

Missoula County – Upper Model (CFR_MC_U)

The 2D model in the Missoula County Upper Reach is a preliminary model so not as much time was spent defining breaklines and the mesh. Despite this, the 1D and 2D model output had similar flood extents and water surface elevations. The 1% annual-chance-event water surface WSE output rasters were used to quantify the agreement between the two models. The flood extents and elevations of the WSE rasters were generally consistent between the two models with an average difference of 0.7 feet. A notable difference in the flood extents was on the dry side of NLFs. The 2D model showed these areas as dry while the 1D model inundated these areas. This is expected, however, and the dry side of NLFs was modeled as ineffective for the 1D model.

Missoula County – Missoula Model (CFR_MC_Msla)

The 2D model for this area was generally higher than the 1D model WSE. As described above, the calibration was not consistent for both gages in the model. The WSE from the 2D model had a larger difference from the gage WSE. The average difference of the models was small with the 1D slightly lower than the 2D. Taking this into account, the 2D model was used more as a guide for the creation of the 1D model.

Missoula County – Lower Model (CFR_MC_L)

The two models have a small average difference, despite not having gage data for calibration. These models both took advantage of the downstream known water surface elevations of the Mineral County Study. Additional area was mapped in the 1D model due to NLFs and ineffective flow side channels. In general, the models are in good agreement.

3.5.10 Floodway Analysis

The scope of work included floodway analysis for the entire reach of the Clark Fork River within Granite County and Missoula County.

The equal conveyance reduction method was used to determine the floodway. Encroachments were set so that the maximum surcharge at any given cross section was 0.5 feet per Montana guidelines.

Notes on the floodway computations:

- The encroachment stations were set using the HEC-RAS program's encroachment routines. Encroachment Methods 4 and 5 were primarily used since the methods automatically adjust the encroachment stations, using equal conveyance reduction to target a specified surcharge.
- Negative surcharges were eliminated where possible, and any remaining negative surcharges are no more than -0.04 feet in magnitude (i.e., they can be rounded to zero).
- Encroachments were, at a minimum, set at the edge of water of the 1-percent-annual-chance flood event (i.e., they were never left at station zero to represent no encroachment).
- The equal conveyance reduction method occasionally produces a floodway that is unreasonable because of inconsistent floodway widths between cross sections. The floodway was manually adjusted at these locations using Encroachment Method 1 in the encroachment station editor. Surcharges were then recalculated to ensure they were less than 0.5 feet.

The locations for floodway analyses were determined through coordination by Montana DNRC with community stakeholders at the start of the project. Any new floodway mapping was done where the community has a regulatory need due to anticipated development in the area. After technical review by Montana DNRC and FEMA, the floodplain mapping and floodway delineation are made available to the community as part of the Flood Risk Review phase of the project.

The following paragraphs discuss specific/unique floodway setup required at several model sections.

Drummond (CFR_GC_Drum model)

A unique floodway setup was required for the area in the Drummond model impacted by the abandoned railroad grade described in **Sections 3.3.8** and **3.4.8**. The setup is described as follows:

- Encroachment stations determined using the "without levee" model.
- Encroachment stations determined from the "without levee" were inserted into the "with levee" model to determine the floodway elevations for the Floodway Data Table.
- Upstream of Highway 1, the right floodway extends at least to the right bank of Bergman Slough as was done for the effective FIS. This also facilitates tying in the effective Edwards Gulch floodway into the Clark Fork River floodway.

Missoula (CFR_MC_Msla model)

Section 6.19.5 of FEMA's February 2019 Levees Guidance (34) describes the procedure for floodway analysis for hydraulically significant levees on one bank. This situation is applicable to the Area 3, Area 5, and Orchard Homes levees in the Missoula reach hydraulic model. Below is a summary of the guidance outlining the modeling procedure for these locations.

- Since the Clark Fork River has an effective floodway at these locations, the initial floodway analysis is performed using the Natural Valley analysis with the effective floodway encroachment stations to verify that the allowable surcharge limits can still be met. If the initial floodway analysis results in floodway encroachment stations riverward of the levee and the allowable surcharge limits are met, the floodway can be delineated at the computed locations. For riverward floodway limits, the community can request FEMA to map the floodway limit on the landward toe of a levee for an accredited levee system.
- If the initial floodway analysis results in a floodway encroachment landward of the levee, the following analysis is performed:
    - Maintain the location of the encroachment stations on the non-leveed side and shift the leveed-side encroachment stations to the levee line. If surcharges are within allowable limits, the floodway can be delineated at the location computed in the model.
    - If surcharges exceed the maximum allowable limit, widen the regulatory floodway on the non-levee side to bring the surcharge within the allowable limit. This condition requires coordination with the State or community officials and impacted property owners.
    - If surcharges cannot be kept within allowable limits by widening the non-levee side, the surcharge can be reevaluated by comparing the results of the floodway analysis to the with-levee BFE.

3.5.11 Other Special Hydraulic Modeling Considerations

The following reaches were determined to have average flooding depths of less than one foot for significantly long reaches. Therefore, it is anticipated that these flooding sources will be mapped as shaded Zone X. No profiles have been created for these reaches. Table 3-23 highlights the flooding sources that are susceptible to shallow flooding only, along with the average flow depth.

Table 3-23. Shallow Flooding Sources

Flooding Source	Average Depth (ft)
Monroc Split	0.61

3.5.11.1 Lower Grant Creek

No layout changes were made to the HEC-RAS model used for the LOMR application on Lower Grant Creek. The only changes made were mentioned above and involve the flows used in the different flow profiles. The flow profile for the 1% and 0.5% AC events were not changed.

4 Floodplain Mapping

FEMA technical guidance documents and other resources were reviewed during the floodplain mapping process to confirm the maps and data meet FEMA requirements. The following reference documents were consulted during development of the data set:

- Data Capture Standards Technical Reference (18)
- Metadata (35)
- Physical Map Revision (36)
- FIRM Database (37)

Several maps were developed to illustrate the updates to the SFHAs in the study area. The maps are described in **Sections 4.1**, **4.3**, and **4.4** and have been provided in the appendices. Map scale, extent, and numbering match across map sets to facilitate comparisons.

4.1 Floodplain Work Maps

Floodplain mapping was produced using output from the hydraulic models and the 2019 Quantum Spatial LiDAR (4). The workmaps show the 1- and 0.2-percent-annual-chance flood event floodplain delineations as well as the floodway and are included in **Appendix A**. HEC-RAS's RAS Mapper (13) was used to extract water surface elevation data, floodway extents, and raw floodplain delineations. The raw floodplain delineations were adjusted manually in ArcMap to provide a smoothed floodplain delineation more appropriate for small scale maps and to address backwater areas, islands, holes, and slivers.

The mapped floodplain and floodway top widths of some modeled cross sections may not match the modeled top widths. There are multiple reasons for these discrepancies which include:

- Removal of small islands (<625 square feet) from mapping.
- Removal of hydraulically disconnected areas from mapping.
- Areas where engineering judgement was used to extend, taper, or trim the floodplain boundary to create a more realistic floodplain delineation.
- Tie-in areas were cross sections needed to be trimmed to avoid conflicts with other studies.

Engineering judgment was used during the mapping process in many locations to create realistic floodplain and floodway extents. Some of the common scenarios where engineering judgment was used include:

- Extending the floodplain boundary where the raw floodplain delineation was cut off between the limits of two cross sections (i.e., the raw floodplain delineation shows a straight line through an oxbow).
- Extending the floodplain boundary where the raw flooding extents terminate, but the topography shows a gradient which would cause the floodwater to continue down valley.
- Trimming the floodplain boundary to remove floodplain slivers at irrigation canals.
- Trimming or extending the floodplain boundary in backwater areas.

4.2 Tie-In Locations

The downstream end of the study ties into the Mineral County study (FEMA case 17-08-0393S). Floodplain mapping has been completed for the Mineral County study, but the study is not yet effective. The floodplain model created for this mapping in Mineral county was used to complete the Missoula County downstream end floodplain mapping. The county boundaries in this area run along the Clark Fork River centerline. The mapping from this model was exported without being trimmed by the County lines in the area to provide the Missoula County portion of the floodplain. These shapefiles will then be used to connect the Missoula and Mineral county floodplains.

Effective data tie-ins include Ninemile Creek, Sixmile Creek, La Valle Creek, Blackfoot River, Rattlesnake Creek, Flint Creek, Edwards Gulch, and Lower Grant Creek. New mapping tie-ins for this FEMA Case (20-08-0033S) are the Bitterroot River and Rock Creek. Each tie-in was integrated into the new mapping for the Clark Fork River. This involved providing connections for each tributary's floodway (if present) into the new Clark Fork floodway. The other zones were feathered to provide a natural looking shape when the two studies are combined. In areas of differing studies or BFE's a Flood Hazard Line was used to separate the two studies areas more precisely. At Lower Grant Creek, the effective Clark Fork River floodplain was much wider than the new floodplain proposed for this project. This left about a mile gap of mapping between the effective mapping end of Lower Grant Creek and the Clark Fork River. As explained above, the Lower Grant Creek LOMR model was used to create floodplain mapping in the gap area. The most downstream cross section of the LOMR model was still about 250 feet from the proposed Clark Fork floodplain. To bridge this gap, a floodplain was interpolated using the LiDAR data. In this area, the floodplain of Lower Grant Creek is not well contained, so a large area had to be interpolated for Zone X caused by multiple flow paths to the Clark Fork. Zone AE was not interpolated much outside the model cross-sections. This was done to make sure the area that was designated as Zone AE was backed by model water surface elevations.

The upstream end of the study ties into the effective Zone A mapping in Powell County.

4.3 Changes Since Last FIRM Mapping – 1-Percent-Annual-Chance Flood Event Comparison

The Changes Since Last FIRM (CSLF) dataset and maps compare the effective 1-percent-annual-chance flood event on the effective maps to the 1-percent-annual-chance flood event proposed by this study. CSLF maps will be produced after approval of floodplain mapping.

4.4 Changes Since Last FIRM Mapping – Floodway Comparison

The CSLF – Floodway Comparison dataset and maps compare the effective floodway to the floodway proposed by this study. These maps will be produced after approval of floodplain mapping.

4.5 Floodplain Boundary Standard Audit

The Floodplain Boundary Standard (FBS) audit compares the water surface elevations from a hydraulic model to the terrain data to verify that the floodplain delineations are accurate. The FBS process outlined in FEMA's Guidance for Flood Risk Analysis and Mapping: Floodplain Boundary Standards guidance (38) was followed to complete the FBS audit. The Clark Fork River study area within Granite County is designated as a Risk Class C. The Clark Fork River Study near the City of Missoula is designated as Risk Class A. The rest of the area within Missoula County is designated Risk Class C. The FBS guidance document states that 95%, 90%, and 85% of the audit points must have their computed water surface elevation and the ground elevation within ± 1.0 foot to meet the delineation reliability standards for an enhanced level study categorized as a Risk Class A, B, and C, respectively.

The FBS audit's pass rate for the reaches are initially computed without excepting any points. If the pass rate was not achieved for an areas Risk Class, points can be excepted from the analysis. Excepts used for this project are shown in the table below and is also a point shapefile created for each model area:

Table 4-1. FBS Excepts

Except	Validation	Comment
1	GS_Except	Backwater
2	GS_Except	Floodway Trimming
3	GS_Except	Model Junction
4	GS_Except	Confluence
5	GS_Except	Outside 1D Extents
6	GS_Except	Gravel Pit
7	HYRDO_STRCT	Structure Name

All reaches required point exclusions to meet the pass rate. For the most part these exceptions are caused by the incised river valley that most Clark Fork River travels in. With a deep and narrow floodplain, the floodway spans most of the floodplain and creates small slivers of Zone AE on each side that need to be trimmed off to meet FEMA mapping guidance. Once these slivers are removed, the steep valley sides change elevation dramatically and cause the audit point to fail its reliability standard. These points are moved only a few feet sometimes but given the cliff-like boundaries of the floodplain, it can make a difference of a few feet of elevation. Other areas that needed excepts include gravel pit areas that have manmade terrain.

4.6 Flood Depth Grids

Flood depth grids will be produced as part of a Flood Risk Products submittal after approval of floodplain mapping.

Flood depth grids are created for the 10-, 4-, 2-, 1-, 1 plus-, and 0.2-percent-annual-chance flood events to show the inundation depths across the study area. FEMA's Guidance for Flood Risk Analysis and Mapping: Flood Depth and Analysis Grids (39) will be referenced to create the dataset. The depth grids represent the raw output from RAS Mapper and will not be manipulated for use as regulatory level products per Exhibit A of Contract WO-AESI-199.

4.7 Water Surface Elevation Grids

Water surface elevation grids will be produced as part of a Flood Risk Products submittal after approval of floodplain mapping.

Water surface elevation grids are created for the 10-, 4-, 2-, 1-, 1 plus-, and 0.2-percent-annual chance flood events to show the water surface elevations across the study area. FEMA's

Guidance for Flood Risk Analysis and Mapping: Flood Depth and Analysis Grids (39) will be referenced to create the dataset. The water surface elevation grids represent the raw output from RAS Mapper and have not been manipulated to be used as regulatory level products per Exhibit A of Contract WO-AESI-199.

5 Flood Insurance Study

The FIS Text, Floodway Data Tables, and Water Surface Elevation Profiles were created for the FIS and are described in **Sections 5.1**, **5.2**, and **5.3**, respectively.

The following references were used to create the products:

- Technical Reference: FIS Report (40)
- Guidance for Flood Risk Analysis and Mapping: Flood Insurance Study Report (41)

The FIS Text, Floodway Data Tables, and Water Surface Elevation Profiles described below were created using FEMA's latest format specifications.

5.1 FIS Text

The relevant FIS tables have been populated with data from this study and have been provided with the submittal of this report.

5.2 Floodway Data Tables

Floodway Data Tables are provided in **Appendix D**.

5.3 Water Surface Elevation Profiles

The water surface elevation profiles show the 10-, 4-, 2-, 1-, and 0.2-percent-annual-chance flood events and also the 1-percent-plus-annual-chance event. These are included in **Appendix B**.

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