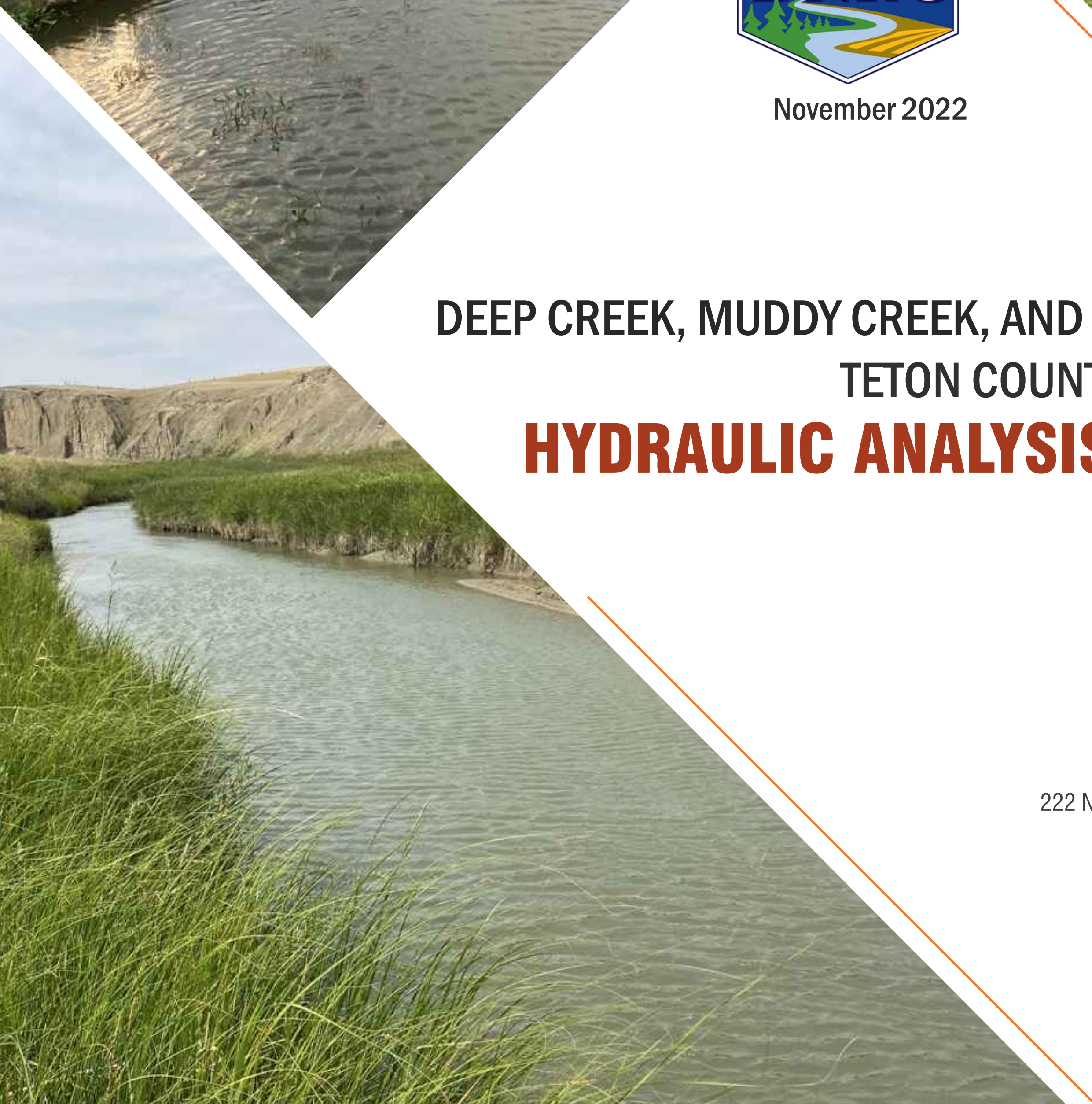

November 2022

DEEP CREEK, MUDDY CREEK, AND TRIBUTARIES
TETON COUNTY, MONTANA
HYDRAULIC ANALYSIS REPORT

Submitted to:

Montana DNRC
Water Resources Division
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Helena, MT 59620

Submitted by:

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222 North 32nd Street, Suite 700
Billings, MT 59101

DOWL

Montana Department of Natural Resources and Conservation

Deep Creek, Muddy Creek, and Tributaries
Teton County, MT

Hydraulic Analysis Report

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1.0 INTRODUCTION

As part of a Mapping Activity Statement (MAS) contract initiated by the Montana Department of Natural Resources and Conservation (DNRC), DOWL has completed enhanced-level floodplain studies for 19 flooding sources in the Teton County study area. Table 1 lists the streams included in this study which consists of 155.6 miles of 1D/2D floodplain modeling and mapping. This study will replace the existing Zone A mapping with new Zone AE without floodway. This report documents the hydraulic analyses involved in completing this floodplain study. Results of the analyses will be incorporated into the Teton County, MT, and Incorporated Areas Digital Flood Insurance Rate Map (DFIRM) and Flood Insurance Study (FIS).

This report explains the methods and information used to determine flood risks according to standards set forth by Federal Emergency Management Agency (FEMA). The hydraulic analysis for each stream includes the evaluation of the 10%, 4%, 2%, 1%, 1% plus, and 0.2% (10-yr, 25-yr, 50-yr, 100-yr, 100-yr plus, and 500-yr) annual chance (AC) flood events. DOWL completed the hydraulic analysis using the following FEMA approved data:

- LiDAR topographic data, by Quantum Spatial – 2020 (NV5, 2020)
- Field survey, hydraulic structure assessments by Morrison Maierle – 2020 (MM, 2020)
- Hydrologic Report, by Michael Baker International – 2021 (MBI, 2021)

To aid in the modeling process, DOWL has broken Deep Creek (DPC) into 2 segments and Muddy Creek (MC) into 5 segments as outlined below and referenced in subsequent sections of this report as well as on the Hydraulic Workmaps (Appendix B). This segment naming convention aligns with the nomenclature implemented in the submitted HEC-RAS simulations.

DPC Reaches

- *Reach 1*—furthest downstream; from just downstream of Pishkun Road to the confluence of the Teton River
- *Reach 2*— from 0.5 mi downstream of confluence of the North Fork Deep Creek and South Fork Deep Creek to just downstream of Pishkun Road

MC Lower Reaches

- *Reach 1*—furthest downstream; from the Teton County / Pondera County line, 3.5 mi upstream of confluence with Farmers Coulee 1 to the confluence of the Teton River

- *Reach 2*—contained entirely within Pondera County
- *Reach 3*—3.6 miles downstream of MT HWY 220/8th Ln NW to the Teton County / Pondera County line, 6 mi upstream of confluence with Farmers Coulee 1
- *Reach 4*—U.S. HWY 89 north of Bynum to 3.6 miles downstream of MT HWY 220/8th Ln NW
- *Reach 5*—Just upstream of the Rinker Creek and Muddy Creek confluence to U.S. HWY 89 north of Bynum

Table 1: Flooding Sources on Deep Creek, Muddy Creek, and Tributaries

Stream	Reach Name	Reach Length (mi)	Structures
Deep Creek	DPC-1	25.7	4
	DPC-1[1]	2.5	5
	DPC-2	20.3	4
Dog Creek	DOC-1	0.4	-
Bruce Coulee	BC-1	0.3	-
Willow Creek	WWC-1	4.6	1
Tributary to Deep Creek	TDPC-2	0.3	-
	TDPC-3	0.3	-
	TDPC-4	0.3	-
	TDPC-5	0.2	-
Quigley Creek	QC-1	0.2	-
Muddy Creek	MC-1	20.0	3
	MC-2	2.3	-
	MC-3	20.8	3
	MC-4[1]	13.0	7
	MC-5[2]	0.3	-
	MC-5[1]	19.9	6
Tributary to Muddy Creek	TMC-1	0.5	-
Farmers Coulee	FC-1	0.5	-
	FC-2[1]	2.7	1
Jones Creek	JC-2	6.6	3
Foster Creek	FOC-1	9.8	-
Farmers Ditch	FD-1	0.5	-
Miller Creek	MLC-1[1]	3.3	3
Blackleaf Creek	BLC-1	2.5	-
Clark Fork Muddy Creek	CFMC-1	0.5	-

[1] Regulatory 2D Model

[2] Supplemental Model

In addition to Deep Creek and Muddy Creek, 17 minor tributaries were modeled. Eight are tributaries to Deep Creek and nine are tributaries to Muddy Creek. Figure Set 1 provides an overview of the Deep Creek reaches, the Muddy Creek reaches, and the associated tributaries included in this hydraulic study. Thirteen minor tributaries were subsequently removed from the modeling effort as it was found that flooding on these minor tributaries are inundated by the flood events of the downstream flooding source. The minor tributaries removed from modeling are listed in Table 2.

Table 2: Removed Model Reaches

Major Waterway	Stream	Reach Name
Deep Creek	Tributary to Deep Creek	TDPC-1
	Nunemaker Coulee	NMC-1
	Battle Creek	BTC-1
Muddy Creek	Brady Canal	BDC-1
		BDC-2
	Tributary to Muddy Creek	TMC-2
		TMC-3
		TMC-4
	Tributary to Foster Creek	TFCO-1
		TFCO-2
	East Canal	EC-1
	Blind Horse Creek	BHC-1
	Rinker Creek	RC-1

The existing floodplain mapping for Teton County is available in DFIRM formatte. The effective mapping consists of 1983 Flood Hazard Boundary Maps that were spatially digitized as part of the basemap task for Teton County (MBI, 2020). The effective mapping for this study area is entirely Approximate Zone A.

2.0 WATERSHED DESCRIPTION

2.1 MUDDY CREEK UPPER REACH AND TRIBUTARIES

The upper reaches of Muddy Creek (MC-4 and MC-5) encompass an area which exhibits upstream limits near the confluence of Rinker Creek with Muddy Creek and downstream limits near MT Hwy 220/8th Lane NW—a stretch of approximately 33 miles. These upper reaches pass through rural landscapes and alongside one small town (Bynum, MT). The upper reaches exhibit noticeably more dense vegetation in the immediate overbanks with frequent scattered brush and willows with grasses, frequent agricultural fields and pastureland, and sparse rangeland with grasses and brush. The upper reaches of Muddy Creek include 6 modeled tributaries.

2.2 MUDDY CREEK LOWER REACHES AND TRIBUTARIES

The lower reaches of Muddy Creek (MC-1, MC-2, and MC-3) begin at the downstream limits of the MC upper reaches and extend approximately 43 miles downstream to the confluence with the Teton River, located about 2.5 miles west and 5.5 miles north of Dutton, MT. The lower reaches of Muddy Creek pass through rural landscapes in a defined valley for a majority of its length. On the upstream end of the lower reaches, the valley is less topographically contained and there is a noticeably higher presence of agricultural fields and pasturelands. The overbank consists of infrequent scattered trees, infrequent scattered brush and willows with grasses, frequent agricultural fields and pastureland, and sparse rangeland with grasses and brush. The lower reaches of Muddy Creek include 3 modeled tributaries.

2.3 DEEP CREEK UPPER REACH

The upper reach of Deep Creek (DPC-2) starts near the confluence of the North Fork and South Fork of Deep Creek, which is approximately 21.5 southwest of Choteau, MT. This reach extends downstream for 20.3 miles to the Pishkun Road crossing, about 15 miles north of Augusta, MT. The watershed extends northwest for about 10 miles and originates in the Sawtooth Mountain Range. The uppermost extents of the Deep Creek watershed are characterized by high-elevation, mountainous terrain with heavy timber. Closer to the Deep Creek study area, the contributing watershed terrain transitions to more mild slopes with brush, willows, native grasses, and occasional pasture lands. The overbanks along the upper reach of Deep Creek consist primarily of dense and/or scattered trees and scattered brush. Willows with grasses and pastureland or rangeland with grasses and brush are predominant near the end of the reach. The upper reach passes through primarily rural landscapes with a few building structures that fall within the modeling extents. The upper reach of Deep Creek includes no modeled tributaries.

2.4 DEEP CREEK LOWER REACH AND TRIBUTARIES

The lower reach of Deep Creek (DPC-1) begins at the downstream limits of DPC-2 and extends approximately 23 miles downstream to the confluence with the Teton River, 1 mile south of Choteau, MT. The lower reach passes through mostly rural landscapes with a few residential areas. A heavy presence of agricultural fields and pastureland persists through most of the DPC-1 study area. The overbank consists of infrequent scattered trees, scattered brush and willows with grasses, frequent agricultural fields and pastureland, and sparse rangeland with grasses and brush. There are noticeably less timbered areas with dense vegetation within the lower reach as compared to the upper reach. The lower reach of Deep Creek includes eight modeled tributaries.

3.0 CHANNEL TOPOGRAPHY

3.1 MUDDY CREEK UPPER REACH AND TRIBUTARIES

Flood flows are generally contained within the main channel along MC-5, with the exception of some overbank flooding and backwater at major roadway crossings and through the town of Bynum, MT. The furthest upstream three miles of MC-5 is a braided channel system with 100-year flood boundary widths ranging between 0.3 to 0.5 miles. Through MC-5, the channel generally maintains a 0.45% slope. Near the very downstream end of MC-5, the 100-year flood event begins to overflow the main channel and spills into the adjacent agricultural fields. Overflows onto the floodplain becomes even more pronounced along MC-4, where most of the flood flow overtops the banks which become less defined. For the furthest upstream mile of MC-4, the floodplain boundary ranges between 1,200 to 1,500 feet wide. A series of agricultural roads and ditches to the north cause overbank flow bloackages and extend the floodplain boundary northward. To the south, flood flows in MC-4 overflow the channel banks and spill into the Foster Creek drainage and nearby agricultural fields. There are two flood conveyance paths—down the Foster Creek and Muddy Creek drainages. The 100-year floodplain boundary widens to roughly 1-mile in this area at the major roadway crossings until significantly further downstream. Flood flows at the Hwy 220 crossing are routed through two roadway openings and the floodplain boundary narrows to just under 0.5 miles wide as it transitions into the lower

Muddy Creek reaches. The stream channel along MC-4 and MC-5 can be classified as exhibiting a high degree of sinuosity.

Tributaries to the upper reaches of Muddy Creek also exhibit a high degree of sinuosity. Many of these tributaries have channel slopes ranging between 0.3% and 0.6%, including Jones Creek, Farmers Ditch, and Blackleaf Creek. Clark Fork Muddy Creek (CFMC-1) generally has a steeper slope of around 1% and further steppens to 2% near the downstream end. The upstream 2.4 miles of Jones Creek is split into two channels before converging into a single channel path with flood extents between 100 feet and 500 feet wide.

3.2 Muddy Creek Lower Reach and Tributaries

The first 10 miles (from upstream) of the MC-3 channel generally has a 0.2% slope before a four-mile stretch with a channel slope of 0.13%, followed with a relatively flat channel slope of 0.04% for the remainder of MC-3. The upstream, steeper portions of MC-3 exhibit wider 100-year floodplain extents of between 1,200 feet to 2,200 feet wide with localized wider sections in flatter, agricultural areas. By contrast, the flattest portions of MC-3 exhibit the narrowest inundation extents of around 150 feet to 500 feet. This is because the lower portions of Muddy Creek Reach 3, although flatter, pass through a canyon section which dramatically confines the valley topography. The downstream-most 9.5 miles of MC-3 has flooding widths of roughly 200 feet to 500 feet with multiple oxbows. The remainder of the Muddy Creek lower reaches (MC-2 and MC-1) generally have channel slopes of about 0.2% with 100-year floodplain extents of between 250 feet and 500 feet.

FC-1, a tributary to MC-1, has a slope of 1.4% for the downstream-most 400 feet but then flattens to 0.5% for the remainder of its length. FC-1 has floodplain widths ranging between 100 feet and 150 feet, with some areas reaching 225 feet wide. TMC-1 is confined by steep terrain for the upstream half of its extents, with floodplain extents of only 20-foot to 30-foot wide. The terrain opens up along the downstream half of TMC-1 and the floodplain width more than doubles. The upper channel slope for TMC-1 is approximately 2.1% while the lower section is roughly 1.1%. Both FC-1 and TMC-1 generally have mild sinuosity.

3.3 Deep Creek Upper Reach and Tributaries

The upper reach of Deep Creek, DPC-2, generally has 1% AC floodplain widths of 600 feet to 900 feet. The furthest upstream 2 miles features an even narrower floodplain corresponding to the steeper channel slope. The furthest downstream 7.5 miles of Deep Creek has a slope of

0.3%, followed by 5 miles of 0.4% channel slope, and then steepens to 1.4% at the upstream reach. The upper end of DPC-2 is contained within a canyonized valley section, with narrower floodplain widths than other study reaches. The furthest upstream four miles has very little sinuosity but transitions to high sinuosity for the remainder of the reach.

3.4 Deep Creek Lower Reach and Tributaries

The lower reach of Deep Creek, DPC-1, has two distinct channels which split near cross section 41777. The 15.1 miles upstream of station 41777 has a channel slope of about 0.2%. The 100-year floodplain extents are generally about 0.2 miles wide with localized, shallow overbank flooding contributing to wider floodplain extents. Near the confluence with Willow Creek, the conveyance paths become more braided, in particular on the north side of Deep Creek. The channel slope downstream of station 41777 increases to roughly 0.35% before returning to 0.2% for the final two miles to the confluence. The sinuosity of DPC-1 is similar to that of DPC-2, generally with high sinuosity.

Tributaries to DPC-1, including Dog Creek, Bruce Coulee, and TDPC-2 are shorter reaches with channel slopes of about 0.7% and narrow floodplain extents. The slope of TDPC-3 is 1 to 2% downstream of the inline structure and 0.4 to 0.5% upstream of the inline structure. TDPC-4, TDPC-5, and Quigley Creek all have steeper slopes of 1.5 to 2.5%, with localized portions reaching 3.2% on Quigley Creek. Willow Creek has a milder channel slope typically ranging between 0.25% and 0.3% with a high degree of sinuosity and wider floodplain extents near its confluence with DPC-1. The other minor tributaries are much more regular with low degrees of sinuosity. The Deep Creek tributaries are generally less sinuous than those of the Muddy Creek watershed.

4.0 HYDROLOGY

Michael Baker International completed the hydrologic analyses in August 2021 (MBI, 2021a) using methods developed by the United States Geological Survey (USGS) including two-site logarithmic interpolation, drainage area gage transfer, at-site annual peak flows, and the Regional Regression Equation (RRE) method.

There were 64 proposed flow nodes for the 19 modeled flooding sources throughout the Deep Creek, Muddy Creek, and Tributaries study area. Flow nodes were typically placed in three locations throughout the study area—upstream extent of the enhanced study reach, downstream confluence of the study reach, and locations where a significant tributary enters the study reach with material increases in contributing drainage area.

The results of the hydrologic study are summarized in Appendix E for the Teton River and its tributaries. Table 3 summarizes the hydraulic flow change locations. Additional details of the hydrologic analyses (MBI, 2021a) are provided in Appendix A.

Table 3: Hydraulic Model Flow Change Locations

Stream	Reach	River Station	Peak Flow (cfs)					
			10% AC	4% AC	2% AC	1% AC	0.2% AC	1%+ AC
			10-Year	25-Year	50-Year	100-Year	500-Year	100-Year
Deep Creek	Reach 1	235+79	3,740.00	7,890.00	13,100.00	21,098.71	57,304.80	39,092.18
Deep Creek	Reach 1	229+27	3,740.00	7,890.00	13,044.12	20,177.70	51,346.35	35,666.89
Deep Creek	Reach 1	221+84	3,740.00	7,890.00	13,041.44	19,805.64	46,626.35	33,250.92
Deep Creek	Reach 1	215+96	3,740.00	7,825.81	12,452.88	18,135.17	40,207.51	29,202.36
Deep Creek	Reach 1	209+44	3,740.00	6,943.03	10,361.59	14,215.25	30,411.06	22,157.01
Deep Creek	Reach 1	202+53	3,740.00	6,848.67	9,720.58	11,732.29	22,526.95	16,666.86
Deep Creek	Reach 1	198+09	3,740.00	6,848.67	9,720.58	11,644.96	21,886.33	16,269.18
Deep Creek	Reach 1	195+97	3,740.00	7,890.00	13,100.00	21,100.00	58,000.00	39,300.00
Deep Creek	Reach 1	156+56	3,750.00	7,916.20	13,143.20	21,195.20	58,216.60	39,435.40
Deep Creek	Reach 1	93+01	3,750.00	7,148.20	11,978.20	19,722.22	56,960.50	39,435.40
Deep Creek	Reach 1	48+43	3,750.00	7,148.20	11,978.20	19,722.22	51,020.50	39,435.40

5.0 HYDRAULIC MODELING

The methodologies used to complete the hydraulic analyses of Deep Creek, Muddy Creek, and Tributaries are presented below.

5.1 HYDRAULIC ANALYSES OVERVIEW

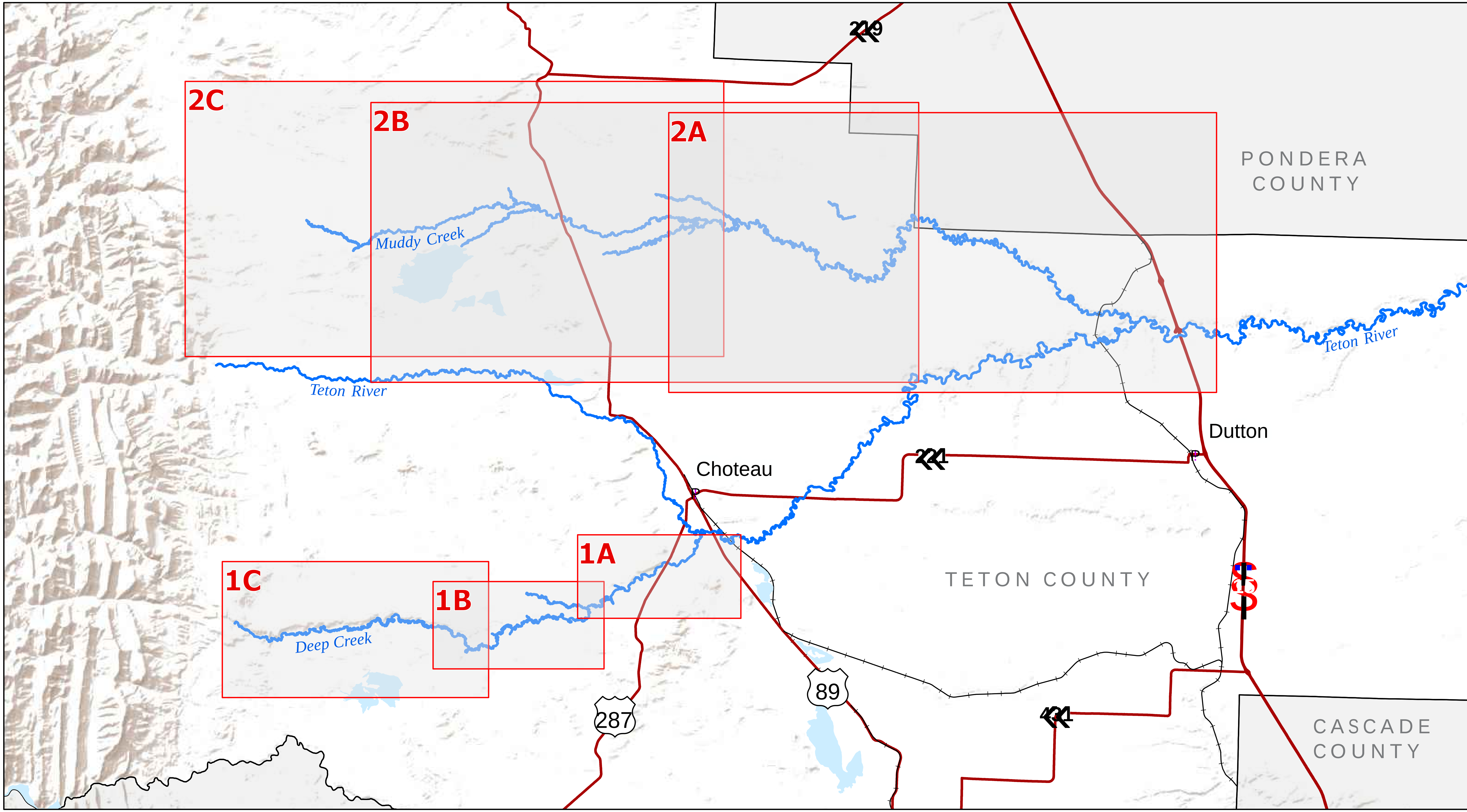
Hydraulic models for each of the study reaches were developed in accordance with guidance provided in the FEMA publication *Hydraulics: One-Dimensional Analysis* (FEMA, 2016a) and *Hydraulics: Two-Dimensional Analysis* (FEMA, 2016b). DOWL used CivilGEO GeoHECRAS version 3.1.0.1381 (CivilGeo, 2021) in conjunction with HEC-RAS version 6.1.0 (USACE, 2021a) to develop the hydraulic models. Cross sections, structure crossings, and lateral weirs represented in the 1D models were developed in accordance with the *HEC-RAS River Analysis System User's Manual, Version 6.1.0* (USACE, 2021b)(USACE, 2021c).

Three modeling approaches were employed: 1D Regulatory, 2D Regulatory, and 1D Regulatory informed by 2D (all without floodway). The only 1D Regulatory informed by 2D reach of modeling is the two miles of DPC-1 at the downstream end. Figure Set 1 shows where each modeling approach was used. Table 6 summarizes the model reach lengths for each stream.

Traditional 1D regulatory models were developed for Enhanced reaches with the exception of five which necessitated 2D modeling to accurately simulate the hydraulic complexities, including highly braided channels and numerous split flows. The following reaches were modeled with a 2D regulatory approach:

- Muddy Creek Reach 5 (MC-5)
- Muddy Creek Reach 4 (MC-4)
- Miller Creek
- Farmer's Coulee 2 (FC-2)
- Downstream split on Deep Creek Reach 1 (DPC-1)

1D and 2D Regulatory modeling approaches are documented in Sections 0 and 5.8, respectively. The 1D Regulatory informed by 2D modeling discussion is detailed in Section 6.2.1.



Waterways
Exhibit Extents
County Boundaries
Towns
Railroads
Highways

Data Frame Properties:

Projection: MONTANA STATE PLANE
Units: INTERNATIONAL FEET
Scale: 1 INCH = 4 MILES
Basemap: WORLD TERRAIN (ESRI)

0 2 4 8 Miles

TETON COUNTY
MONTANA

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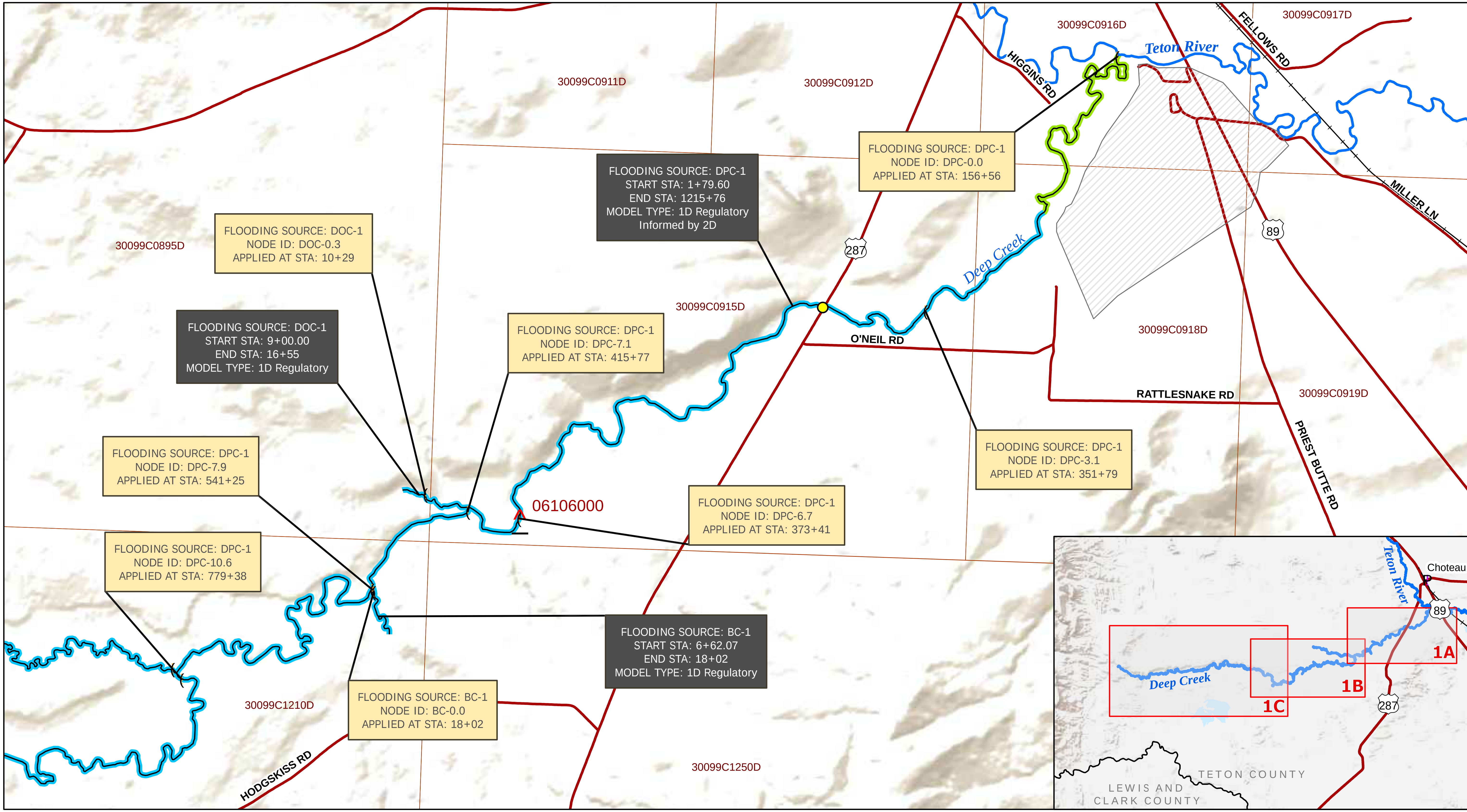
Teton Countywide Floodplain Study

Figure Set 1 : *Project Overview*



Model Type
- 1D Regulatory
- 1D Regulatory Informed by 2D
- 2D Model Extent
- Hydrologic Flow Change Location
- Hydraulic Structure
- FEMA FIRM Panel
- USGS Streamflow Gage
- Towns
- Teton River

Data Frame Properties:

Projection: MONTANA STATE PLANE
Units: INTERNATIONAL FEET
Scale: 1 INCH = 0.5 MILES
Basemap: WORLD TERRAIN (ESRI)

0 0.5 1 Miles

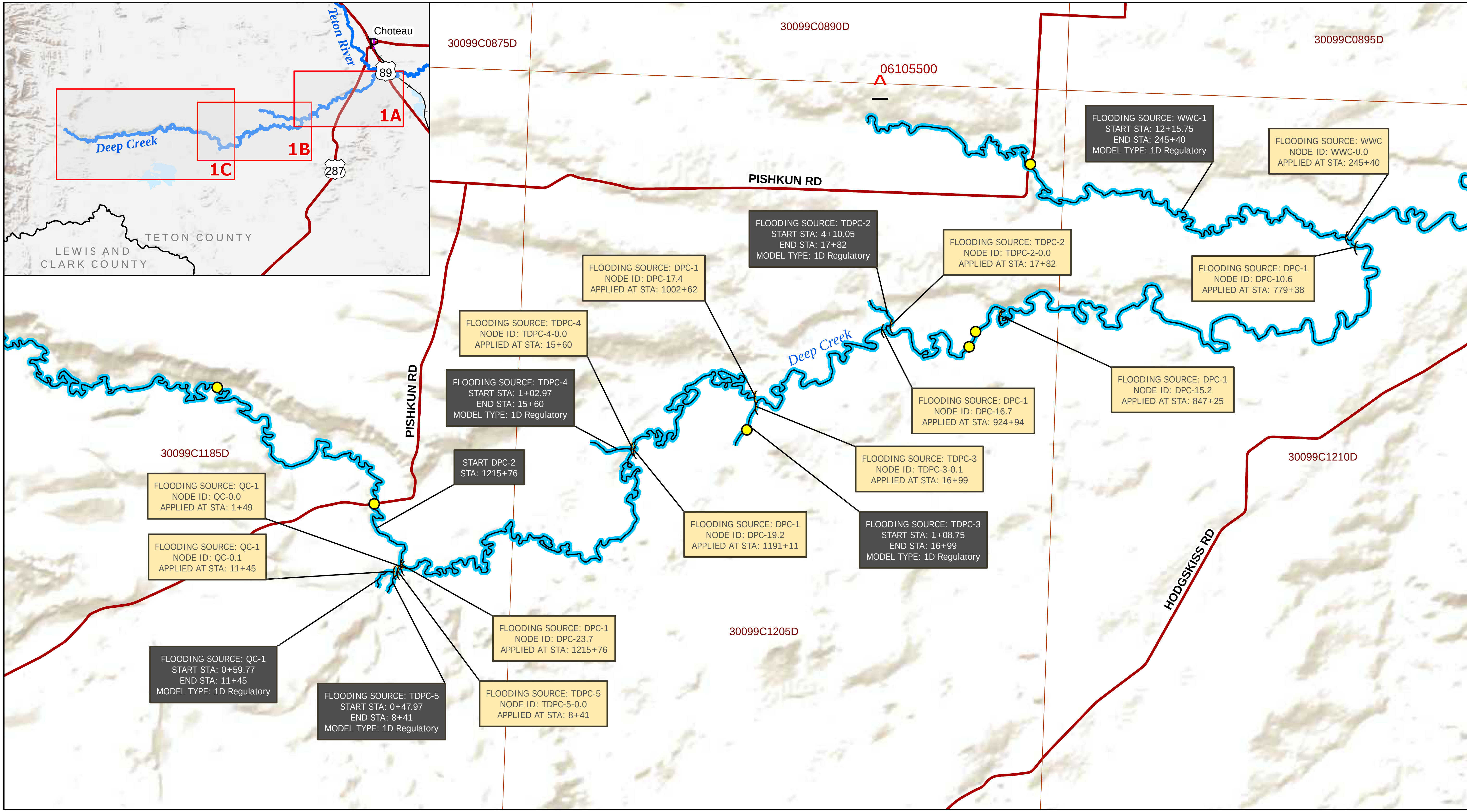
TETON COUNTY
MONTANA

DOWL

MONTANA DNRC

Teton Countywide Floodplain Study

Figure 1A: *Project Overview Deep Creek*



Model Type

1D Regulatory

(Hydrologic Flow Change Location

Hydraulic Structure

FEMA FIRM Panel

USGS Streamflow Gage

Towns

Data Frame Properties:

Projection: MONTANA STATE PLANE
Units: INTERNATIONAL FEET
Scale: 1 INCH = 0.5 MILES
Basemap: WORLD TERRAIN (ESRI)

0 0.5 1 Miles

TETON COUNTY MONTANA

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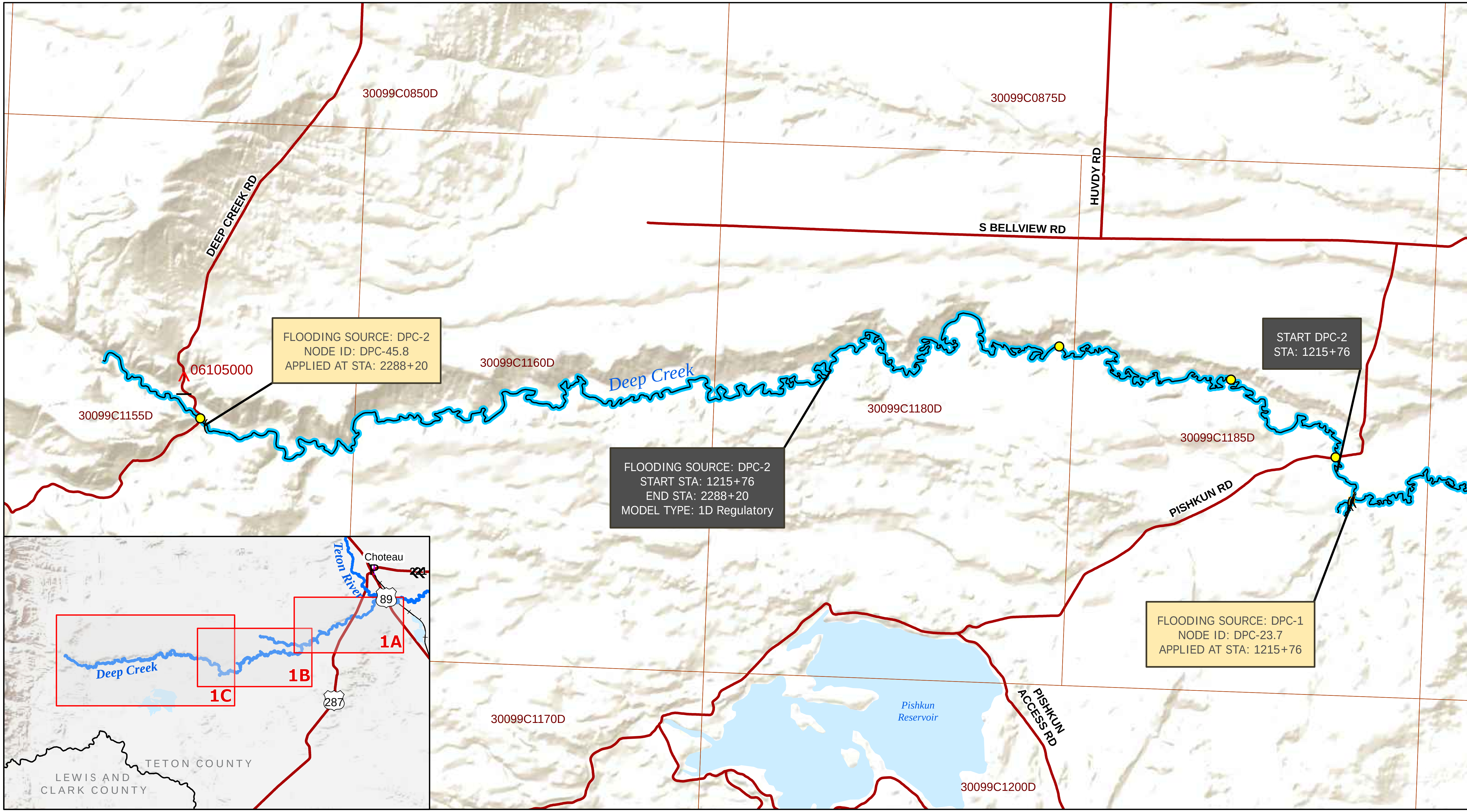
Teton Countywide Floodplain Study

Figure 1B: *Project Overview Deep Creek*



Model Type
- 1D Regulatory
- Hydrologic Flow Change Location
- Hydraulic Structure
- FEMA FIRM Panel
- USGS Streamflow Gage
- Towns

Data Frame Properties:

Projection: MONTANA STATE PLANE
Units: INTERNATIONAL FEET
Scale: 1 INCH = 0.75 MILES
Basemap: WORLD TERRAIN (ESRI)

0 0.75 1.5 Miles

TETON COUNTY
MONTANA

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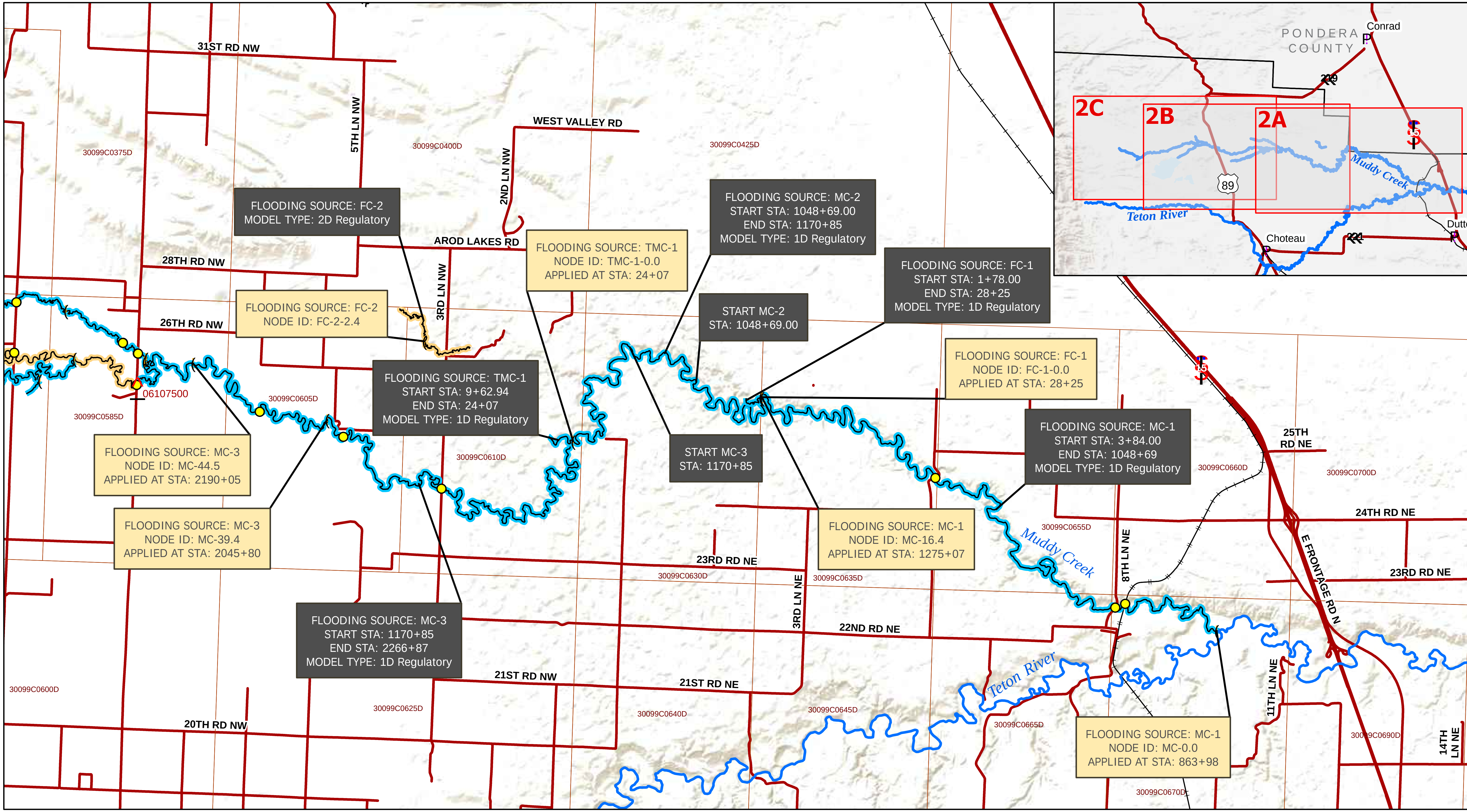
Teton Countywide Floodplain Study

Figure 1C: *Project Overview Deep Creek*



Model Type

1D Regulatory
2D Regulatory

Hydrologic Flow Change Location
Hydraulic Structure
FEMA FIRM Panel

USGS Streamflow Gage
Towns
Teton River

Data Frame Properties:

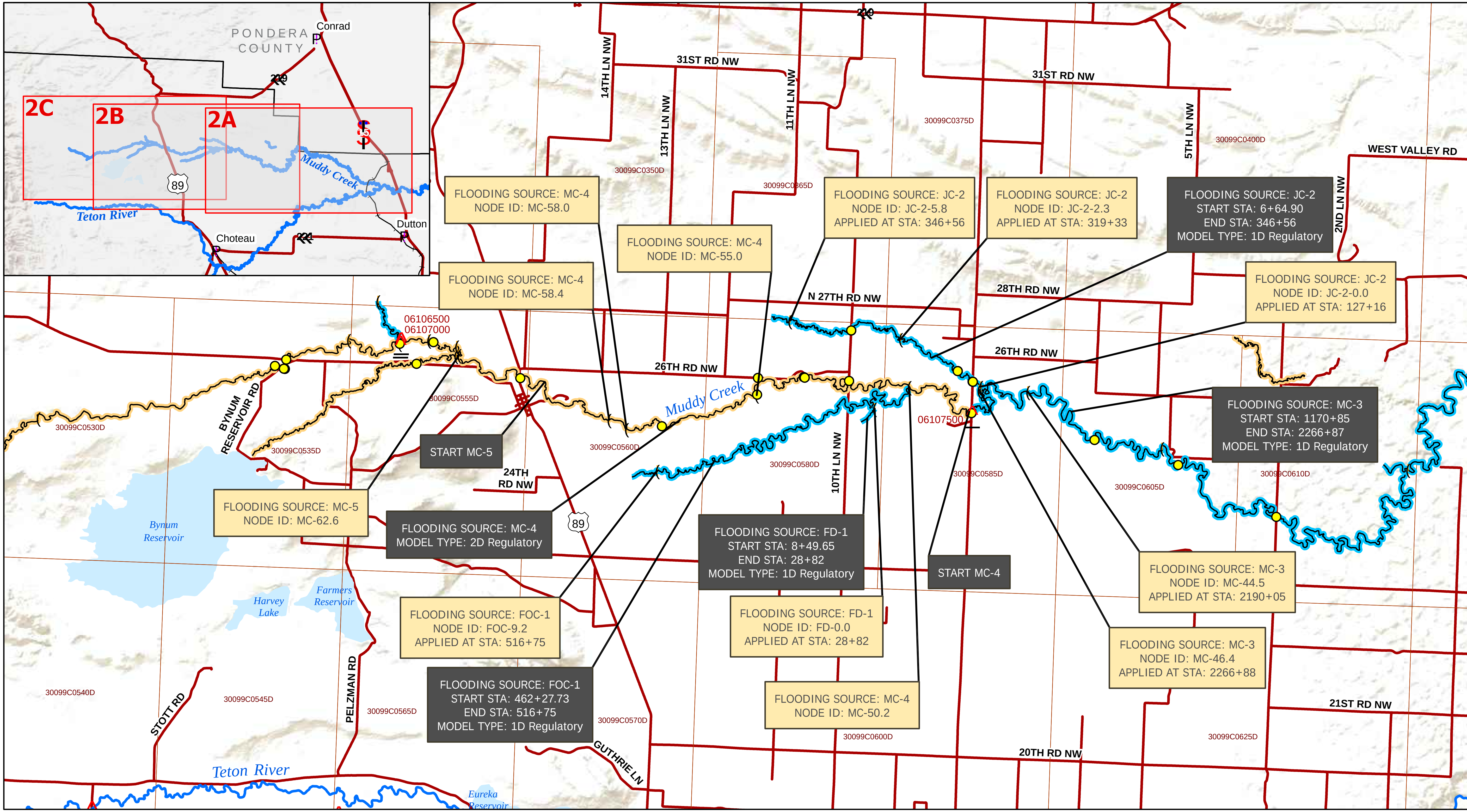
Projection: MONTANA STATE PLANE
Units: INTERNATIONAL FEET
Scale: 1 INCH = 1.5 MILES
Basemap: WORLD TERRAIN (ESRI)

0 1.5 3 Miles

TETON COUNTY MONTANA
DOWL
MONTANA DNRC

Teton Countywide Floodplain Study

Figure 2A: *Project Overview Muddy Creek*



Model Type

- 1D Regulatory
- 2D Regulatory
- Hydrologic Flow Change Location
- Hydraulic Structure
- FEMA FIRM Panel
- USGS Streamflow Gage
- Towns
- Teton River

Data Frame Properties:

Projection: MONTANA STATE PLANE
Units: INTERNATIONAL FEET
Scale: 1 INCH = 1.5 MILES
Basemap: WORLD TERRAIN (ESRI)

0 1.5 3 Miles

TETON COUNTY MONTANA

DOWL

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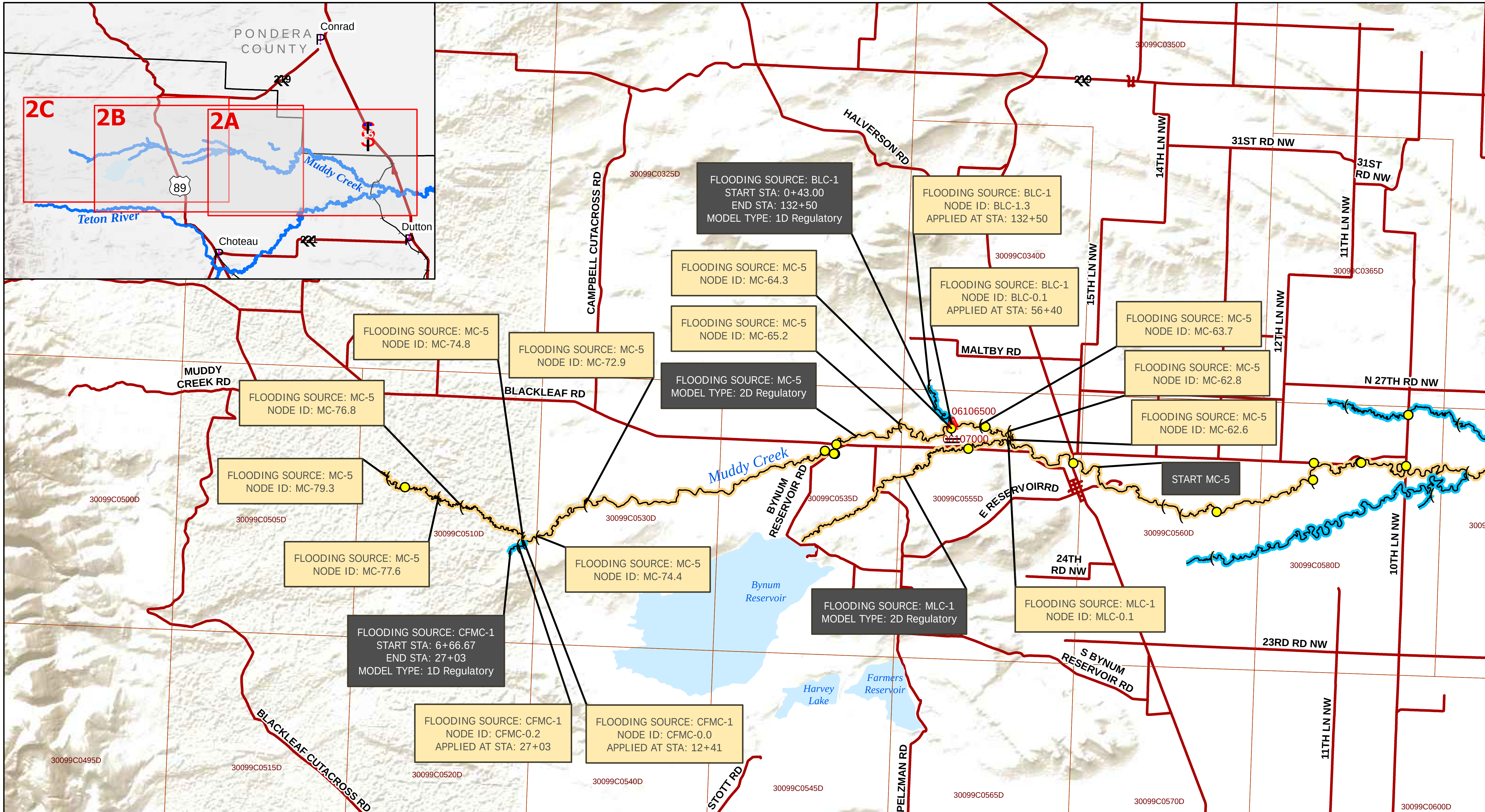
Teton Countywide Floodplain Study

Figure 2B: *Project Overview Muddy Creek*



Model Type

- 1D Regulatory
- 2D Regulatory

- Hydrologic Flow Change Location
- Hydraulic Structure
- FEMA FIRM Panel

- USGS Streamflow Gage
- Towns

Data Frame Properties:

Projection: MONTANA STATE PLANE
Units: INTERNATIONAL FEET
Scale: 1 INCH = 1.5 MILES
Basemap: WORLD TERRAIN (ESRI)

0 1.5 3 Miles

TETON COUNTY MONTANA

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Teton Countywide Floodplain Study

Figure 2C: Project Overview Muddy Creek

5.2 TOPOGRAPHIC MAPPING ACQUISITION

The LiDAR (NV5, 2020) and field survey (MM, 2020) data were provided in the Montana State Plane coordinate system with a Lambert Conformal Conic projection. Both data sets are referenced horizontally to the North American Datum of 1983 (NAD83-2011) and vertically to the North American Vertical Datum of 1988 (NAVD88). LiDAR units were reported in feet. The field survey was reported with horizontal units of international feet and vertical units of U.S. feet.

5.2.1 Topographic Elevation Data

Aerial topographic survey data (NV5, 2020) was collected in April through July 2020 by NV5 GeoSpatial (formerly Quantum Spatial, Inc.) for approximately 1,505 square miles and encompasses all of Teton County, MT. Roughly 60% of the data collection is represented by QL1 data (≤ 8 pulses/m^2) while the remaining 40% is QL2 data (≤ 2 pulses/m^2). In general, the Deep Creek, Muddy Creek, and Tributaries hydraulic study zones are represented with QL1 data. LiDAR data acquisition was targeted for low flow, leaf-off conditions to ensure maximum ground exposure and data reliability.

As part of the final deliverable, NV5 Geospatial provided a Hydroflattened DEM in GeoTIFF format—the hydroflattening process is essential to floodplain studies as it mitigates for erroneous water surface elevations resulting from erratic absorption of LiDAR light pulses in water bodies. The Hydroflattened DEM is especially important for the Deep Creek, Muddy Creek, and Tributaries study area because no bathymetric data was collected for this study. Additional information on the topographic survey data is provided in Appendix A (Teton County, Montana LiDAR Technical Data Report – Quantum Spatial, an NV5 Company, October 2020).

Terrain data available from the USGS 3D Elevation Program (3DEP; formerly known as National Elevation Dataset) is also used (USGS, 2021). 3DEP data sources were utilized upstream of MC-5 where LiDAR data was not provided by NV5 GeoSpatial, as discussed in Section 6.0.

5.2.2 Structure Inventory

A Teton County structure survey was completed by Morrison-Maierle, from September to November, 2020 with a supplemental survey that took place in December 2021 (MM, 2020). Information collected for each structure includes structure type, dimensions, material, and backwater potential. The structure inventory for the Deep Creek, Muddy Creek, and Tributaries study area includes 80 structures which are described in the report provided in Appendix A. 70 of these structures were collected during the initial survey data capture while the additional 10 structures were picked up with the supplemental survey in December 2021. Of these 80, 35 total structures were modeled by DOWL. Many of the structures were not modeled due to being distant from the floodplain and some structures were related to models that were removed from the study. There was one structure, ID DEE_070 on Deep Creek Reach 1, that was not modeled despite existing within the floodplain. A majority of the flooding discharges along Deep Creek at this location exists in the overbanks, and there is a complex confluence with Willow Creek directly nearby which further makes the 1D cross section layout challenging. Due to these two factors, DOWL deemed it reasonable to not model the DEE_070 structure as it exhibits minimal hydraulic impacts holistically.

In total, 17 of the 35 structures were modeled in 1D; the remaining 18 were modeled in 2D. Sections 5.4.6 and 5.8.4 of this report discuss the 1D structure and 2D structure modeling, respectively.

DOWL also completed a field review of the study area in June, 2021 to gather real-world observational data to aid in the hydraulic modeling phase. One component to this field visit was gathering additional measurements for roadway crossings in near the downstream end of Deep Creek, knowing that the flowpaths would likely become complex in that region during the modeling phase. DOWL collected measurement data for four additional structures near the confluence of Deep Creek and the Teton River during their field visit as well as brought back observational data to aid in Manning's roughness selection.

5.3 MANNING'S ROUGHNESS COEFFICIENTS

A two-step process was used in establishing Manning's roughness coefficients (n) for the Teton County study area. The first step consisted of general classification of the appropriate landcover types and their associated typical roughness coefficients based on field observations, aerial photography (NAIP, 2019), National Land Cover Database (USGS,2019) descriptions, and recommended values in *Open-Channel Hydraulics* (Chow, 1959). The second step involved refinement of the initial Manning's roughness coefficients based on a collective assessment of multiple team members, including a senior water resources engineer. A primary goal during this refinement step was to remove judgement bias from individual team members. The following two sections describe this Manning's n selection process in more detail.

5.3.1 Initial Assignment of Manning's Roughness Coefficients Based on Machine Learning Image Analysis

The initial assignment of Manning's roughness coefficients (n) was completed via a machine learning approach in ArcMap version 10.5.1 (ESRI, 2016) which applies a supervised classification of image pixels into user-specified landcover types. The aerial images used were 2019 National Agricultural Imagery Program (NAIP) imagery obtained from the Montana State Library data repository (NAIP, 2019). The user-specified landcover types are considered "training samples" for the supervised classification, and each group of "training samples" were evaluated by multiple members of the study team to ensure those "training samples" encompassed all appropriate landcover types. The supervised classification process involves a series of post-classification processes which ultimately generate clean, smooth landcover polygon boundaries which can then be assigned appropriate attribute values including minimum, typical, and maximum Manning's roughness coefficients. Initial Manning's roughness assignment was broken into two quantification categories: channel and overbanks roughness. Channel roughness assignment was created by quantifying the various reach slopes and their associated landcovers from field observations/photos and aerial imagery, ultimately correlating these reaches to similar streams in *Roughness Characteristics of Natural Channels* (USGS, 1967). Channel roughness coefficients from previous, approved hydraulic studies were also utilized for the initial designations. Minimum, typical, and maximum overbank roughness coefficients for the initial overbank assessment were based on field observations/photos, aerial photography, NLCD 2019 descriptions (USGS, 2019), and review of *Open-Channel Hydraulics* (Chow, 1959).

5.3.2 Refinements Based on Collective Assessment

The initial Manning's roughness assignments for both channel and overbank areas were distributed to multiple study team members for review. Team members independently assigned their selection of appropriate roughness coefficients for channel and overbank areas throughout the study area. This process eliminated the potential for individual judgement bias. Each team member was provided the same resources for selecting appropriate values. After the individual selections were made, the team members met multiple times to arrive at consensus agreement on the most appropriate values. The values derived from this collective assessment process were generally used throughout all models to represent channel and overbank roughness. As model development progressed, some of these assignments of Manning's roughness coefficients were adjusted to reflect unique characteristics such as channel slope, localized overbank vegetation, and changing channel widths. The selected channel and overbanks roughness coefficients for 1D and 2D models are summarized in Table 4 and Table 5, respectively. Section 5.9 detail the efforts to validate the selected Manning's Roughness values.

Table 4: Channel Roughness Values

Stream	Channel Roughness Value
Deep Creek	0.04-0.05
Blackleaf Creek	0.05-0.065
Bruce Coulee	0.05
Clark Fork Muddy Creek	0.065
Dog Creek	0.05-0.065
Farmers Coulee 1	0.05-0.065
Farmers Coulee 2	0.045-0.065
Farmers Ditch	0.045
Foster Creek	0.065
Jones Creek	0.035-0.065
Muddy Creek	0.03-0.065
Quigley Creek & Trib to Deep Creek 5	0.050-0.065
Tributary to Deep Creek 2	0.035-0.065
Tributary to Deep Creek 3	0.050-0.065
Tributary to Deep Creek 4	0.050-0.065
Tributary to Muddy Creek 1	0.065
Willow Creek	0.05-0.065

Table 5: Overbank Roughness Values

Landcover Description	Manning's "n" Range	Typical Assigned Value
Agricultural Fields	0.025 - 0.065	0.04
Dense Trees	0.08 - 0.20	0.10
Rangeland with Grasses and Brush	0.03 - 0.06	0.045
Scattered Brush/Willows with Grasses	0.04 - 0.07	0.05
Scattered Trees	0.05 - 0.12	0.07
Development	0.07 - 0.11	0.09
Pasture/Grasses	0.035 - 0.065	0.045
Pavement/Gravel	0.013 - 0.025	0.016

5.4 1D Hydraulic Model Development

5.4.1 Profile Baseline

The Hydro Lines developed for the Hydrologic Analysis (MBI, 2021) were used to create preliminary profiles for hydraulic modeling. Stream centerlines were adjusted to better align with the channel in complex areas primarily along the Deep Creek and Muddy Creek reaches. These adjustments were made such that the stream centerlines would better match the path of flood flows rather than the meandering low-flow channel. The channel centerline was established using the LiDAR data (NV5, 2020) and 2019 NAIP aerial images (NAIP, 2019). River stationing is referenced to the confluence with the downstream creek or river ("Reference Stream"), measured in feet. Starting and ending stations are shown in Table 6. The individual reach profile baselines are displayed on the work maps provided in Appendix B.

5.4.2 Boundary Conditions

The HEC-RAS models were evaluated under the assumptions of subcritical flow and no backwater influence from other flooding sources. Normal depth was used as the downstream boundary condition for determining the water surface elevation at the downstream limit of most 1D Regulatory HEC-RAS models. Exceptions to the normal depth boundary conditions for 1D Regulatory models include the following:

- MC-3, MC-2, DPC-2—these reaches use known water surface elevations as downstream boundary conditions (MC-3 uses known WSELs from MC-2, MC-2 from MC-1, etc.)

The slopes used to calculate the normal depth were obtained from the provided LiDAR data (NV5, 2020) and are shown for each creek in Table 6.

5.4.3 Cross Section Geometry

The terrain data used in developing the HEC-RAS models was extracted from the LiDAR data gathered by NV5 GeoSpatial (NV5, 2020). GeoHECRAS (CivilGeo, 2021) was used to place cross sections perpendicular to the direction of flow, and cross section extents were established to encompass the water surface of the 0.2% AC flood event.

Typically, cross sections are placed with a target overbank spacing of 50 to 200 feet for tributaries and 300 to 700 feet for larger tributaries and main waterways such as Deep Creek and Muddy Creek. Overbank spacing guided cross section placement due to the highly sinuous nature of many of the streams. There are numerous locations throughout this study where the channel flow length greatly exceeds the overbank flow length due to high channel sinuosity. Figure 1 displays an example of this along Deep Creek.

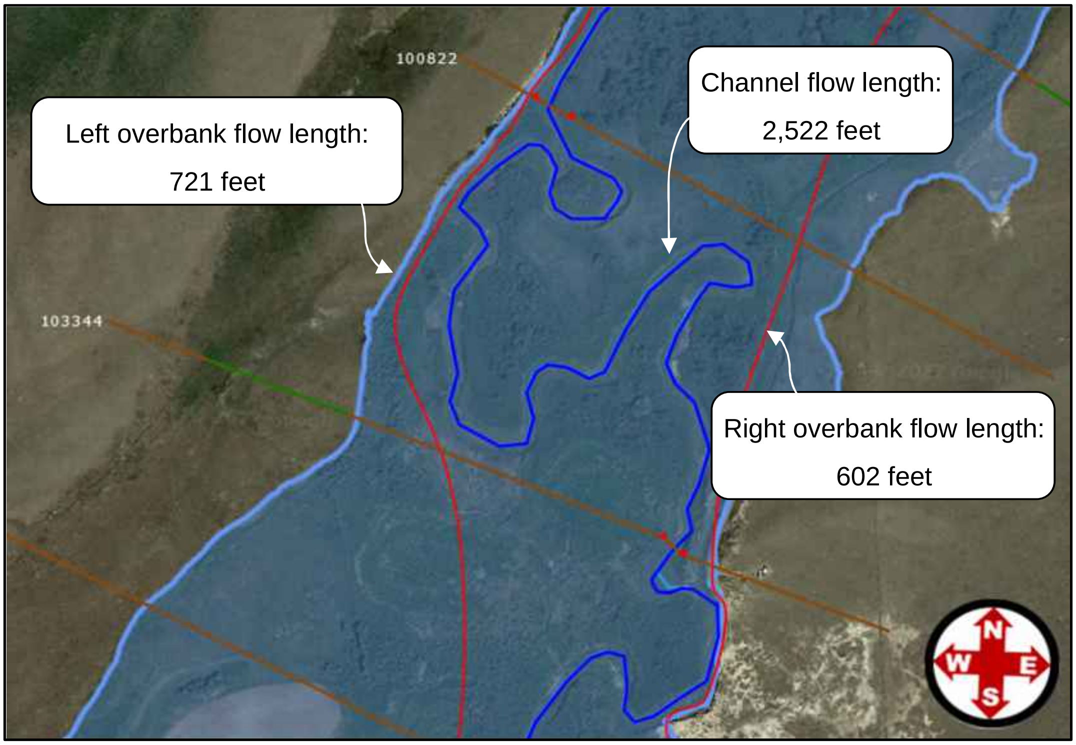

Figure 1: Localized High Sinuosity along DPC-1

Additional cross sections were added at key locations along the reach including structure crossings, breaks in channel slope, abrupt changes in floodplain width, and changes in flow direction. Several cross sections in the larger tributary floodplain models are spaced closer than the target spacing of 300 to 700 feet for these reasons. Denser cross section placement was also used due to model complexities in areas with low flowrates or high channel sinuosity.

Contraction and expansion coefficients were generally set at 0.1 and 0.3, respectively. For cross sections near bridge structures, the contraction and expansion coefficients were set to 0.3 and 0.5.

5.4.4 Non-Conveyance Areas

Ineffective flow limits near bridges, culverts, and natural constrictions are generally set to approximate a 1:1 contraction upstream and a 2:1 expansion downstream. The expansion and contraction limits extend from the bridge faces and the ends of the culverts. Exceptions to these typical applications include structures with significant overtopping and where there are changes in flow direction near structure openings. Review of the modeled cross sections also reveals numerous depression areas and narrow side channels that are not hydraulically connected to the main channel. These areas were also classified as ineffective to simulate hydraulic conveyance more accurately. Further explanations of the assumed ineffective flow limits are provided in Appendix E.

5.4.5 Blocked Obstructions

There are two applications where the blocked obstructions feature in HEC-RAS (USACE, 2021a) was used. The first is to account for the hydraulic effects of structures. The second is pronounced undulation of the terrain as represented by the LiDAR data (NV5, 2020) which would block effective flow in a similar manner as structures. An example of the second application is blocking-out the bottom of abandoned oxbow channels which are not effective in floodplain conveyance. Cross sections with blocked obstructions are documented in Appendix E.

5.4.6 Hydraulic Structures

There are 17 crossing structures modeled in the 1D study area (including inline weirs and diversions). Crossings were defined in the hydraulic model using information provided in the survey report, hydraulic structure assessment, LiDAR data (NV5, 2020), and photographs obtained during field visits. The field survey and structure assessment included information for all of these structures. Table 6 summarizes the number of structures within each reach. A more detailed summary of the 1D modeled structures is presented in Table 7. The ‘Structure ID’ corresponds to the structure identification numbers from the hydraulic structure assessment completed by Morrison Maierle (MM, 2020). A sampling of the photographs from the hydraulic structure assessment, which were used to assist in model development, are shown as follows.

Example structures contained in 1D models—

Deep Creek Head Gate

DEE_0150_SI_USFACE

Brady Canal Gated Weir

BRA_020_SI_USFACE

Jones Creek Bridge

JOM_020_SI_DSFACE

Deep Creek Pishkun Rd Bridge

DEE_0160_SI_DSFACE

Jones Creek 10th Lane NW Culvert

JOM_030_SI_USFACE

Farmer's Coulee Culvert Crossing

FAR_010_SI_USFACE

Table 6: Hydraulic Modeling Summary

Stream Name	Reach Name	Reach Length (mi)	Modeling Approach	Start Station	End Station	Reference Stream	Boundary Condition	Slope (ft/ft)	Structures		
									Bridge	Culvert	Inline Weir
Deep Creek	DPC-1	25.7	1D Regulatory	1+79.60	1215+76.00	Teton River	Normal Depth	0.0025	3	---	---
	DPC-1 Reg 2D	2.5	2D Regulatory	---	---	Teton River	Normal Depth	0.0250	---	1	---
	DPC-2	20.3	1D Regulatory	1215+76.00	2288+20.00	DPC-1	Known WSELs [A]	---	3	---	1
Dog Creek	DOC-1	0.4	1D Regulatory	8+99.60	16+55.00	DPC-1	Normal Depth	0.0058	---	---	---
Bruce Coulee	BC-1	0.3	1D Regulatory	6+62.07	18+02.00	DPC-1	Normal Depth	0.0062	---	---	---
Willow Creek	WWC-1	4.6	1D Regulatory	12+15.75	245+40.00	DPC-1	Normal Depth	0.0029	1	---	---
Tributary to Deep Creek	TDPC-2	0.3	1D Regulatory	4+10.05	17+82.00	DPC-1	Normal Depth	0.0082	---	---	---
	TDPC-3	0.3	1D Regulatory	1+08.75	16+99.00	DPC-1	Normal Depth	0.0150	---	---	---
	TDPC-4	0.3	1D Regulatory	1+02.97	15+60.00	DPC-1	Normal Depth	0.0468	---	---	---
	TDPC-5	0.2	1D Regulatory	0+47.97	8+41.00	QC-1 Lower	Known WSELs [A]	---	---	---	---
Quigley Creek	Upper	0.2	1D Regulatory	2+38.00	11+45.00	QC-1 Lower	Known WSELs [A]	---	---	---	---
	Lower	0.03	1D Regulatory	0+59.77	1+49.00	DPC-1	Normal Depth	0.0023	---	---	---
Muddy Creek	MC-1	20.0	1D Regulatory	12+65.15	1048+69.00	Teton River	Normal Depth	0.0017	2	1	---
	MC-2	2.3	1D Regulatory	1048+69.00	1170+85.00	MC-1	Known WSELs [A]	---	---	---	---
	MC-3	20.8	1D Regulatory	1170+85.00	2266+87.00	MC-2	Known WSELs [A]	---	1	2	---
	MC-4	13	2D Regulatory	---	---	MC-3	Normal Depth	0.0040	3	4	---
	MC-5	19.9	2D Regulatory	---	---	MC-4	Normal Depth	0.0043	4	1	1
Tributary to Muddy Creek	TMC-1	0.5	1D Regulatory	9+62.94	24+07.00	MC-3	Normal Depth	0.0143	---	---	---
Farmers Coulee	FC-1	0.5	1D Regulatory	1+77.98	28+25.00	MC-1	Normal Depth	0.0055	---	---	---
	FC-2	2.7	2D Regulatory	---	---	MC-3	Normal Depth	0.0080	---	1	---
Jones Creek	JC-2	6.6	1D Regulatory	6+64.90	346+56.00	MC-4	Normal Depth	0.0023	---	3	---
Foster Creek	FOC-1	9.8	1D Regulatory	462+27.73	516+75.00	MC-4	Normal Depth	0.0035	---	---	---
Farmers Ditch	FD-1	0.5	1D Regulatory	8+49.65	28+82.00	FOC-1	Normal Depth	0.0050	---	---	---
Miller Creek	MLC-1	3.3	2D Regulatory	---	---	MC-5	Normal Depth	0.0050	---	3	---
Blackleaf Creek	BLC-1	2.5	1D Regulatory	4+77.62	132+50.00	MC-5	Normal Depth	0.0047	---	---	---
Clark Fork Muddy Creek	CFMC-1	0.5	1D Regulatory	6+66.67	27+03.00	MC-5	Normal Depth	0.0122	---	---	---

Table 7: Summary of 1D Hydraulic Structures

Survey / Inventory Structure ID	Stream	Reach	Station	Description	Structure Type	Bridge Data					Culvert Data			
						Span Length (ft)	Bridge Width (ft)	Number of Spans	Pier Coefficients (Cd, K)	Modeling Approach	Length (ft)	Shape	Type	Dimensions (Span x Rise)
DEE_020	Deep Creek	Reach 1	197+48	HWY 287 Crossing	Bridge	60.3	28	3	2, -	Pressure	-	-	-	-
DEE_070	Deep Creek	Reach 1	555+68	*Not Modeled* [1]										
DEE_090	Deep Creek	Reach 1	804+24	Private Crossing	Bridge	28	11	1	-	Pressure	-	-	-	-
DEE_100	Deep Creek	Reach 1	809+68	Private Crossing	Bridge	37	14.5	1	-	Pressure	-	-	-	-
DEE_160	Deep Creek	Reach 2	1228+57	Pishkun Road	Bridge	45	23	1	-	Pressure	-	-	-	-
DEE_170	Deep Creek	Reach 2	1346+27	Irrigation Diversion Structure	Diversion	-	-	-	-	-	-	-	-	-
DEE_180	Deep Creek	Reach 2	1510+22	Pedestrian Private	Bridge	39	10	1	-	Pressure	-	-	-	-
DEE_190	Deep Creek	Reach 2	2222+59	Deep Creek Road	Bridge	88	24	2	1.2, 0.9	Pressure	-	-	-	-
WIL_030	Willow Creek	Willow Creek	158+47	Road Crossing	Bridge	60	20	3	1.2, 1.05	Pressure	-	-	-	-
MC_010	Muddy Creek	Reach 1	163+03	Railroad Crossing	Bridge	952	26	18	2	Energy	-	-	-	-
MC_020	Muddy Creek	Reach 1	175+49	8th Ln NE Rd Crossing	Culvert	-	-	-	-	-	59.5	Arched Pipe	CSP	9'x7'
												Arched Pipe	CSP	9'x7'
												Arched Pipe	CSP	9'x7'
												Circular	CSP	6'
MC_030	Muddy Creek	Reach 1	523+77	5th Ln NE Rd Crossing	Bridge	143	26	2	1.33	Pressure	-	-	-	-
MUD_040	Muddy Creek	Reach 3	1790+40	3rd Lane Northwest	Bridge	82	24	2	1.33	Energy				
MUD_050	Muddy Creek	Reach 3	1998+39	Private Driveway	Culvert	-	-	-	-	-	28	Circular	CSP	5'
											24	Circular	CSP	5'
											24	Ellipse	Concrete	1.75' x 1'
											24	Ellipse	Concrete	1.75' x 1'
MUD_060	Muddy Creek	Reach 3	2165+92	Ranch Access	Culvert	-	-	-	-	-	40	Ellipse	Concrete	8.2' x 5.5'
											40	Circular	CSP	4.5'
JOM_010 [2]	Jones Creek	Jones Creek	16+85	Hwy 220 Crossing	Culvert	94.5	34	1	-	Energy	34	Box	Concrete	94.5' x 10.1'
JOM_020 [2]	Jones Creek	Jones Creek	42+59	Private Crossing	Culvert	-	-	-	-	-	20	Circular	CSP	3'
JOM_030 [2]	Jones Creek	Jones Creek	209+56	10th Lane NW Crossing	Culvert	-	-	-	-	-	40	Pipe Arch	CSP	5'x6.5'

[1] Structure not modeled due to overbank control and complex confluence with Willow Creek
[2] Jones Creek structures also modeled as part of the MC-4, 2D Regulatory model

5.5 Lateral Weirs

Lateral weirs are implemented to simulate flows spilling out of the main channel at various locations throughout the Teton County study area. Table 8 summarizes the lateral weir location, the physical condition being modeled, and the assumed weir coefficient. Lateral weir coefficients were selected from the *Hydrologic Engineering Center (HEC) 2D Modeling User's Manual* (USACE, 2021c). There is a software bug with HEC-RAS Version 6.1 that does not allow the modeler to toggle optimization. However, the newest Version (6.2) allows for optimization toggling and will be used for future hydraulic tasks.

Table 8: Lateral Weirs

Stream	Reach Name	Weir Starting Station	Physical Condition	Weir Coefficient	Optimized (Y/N)
Deep Creek	Reach 1	48+26	Natural high ground barrier	0.86	N
		113+73	Natural high ground barrier	0.86	N
		236+78	Roadway overtopping and easily submerged	1.70	Y
		578+18	Overland Flow Escaping Channel	0.39	N
TDPC-2	TDPC-2	17+46	Roadway overtopping and easily submerged	1.70	N
TDPC-1	TDPC-1	16+52	Overland flow escaping channel	0.39	N
Quigley Creek	Upper	7+34	Natural high ground barrier	0.86	N
TDPC-5	TDPC-5	8+20	Natural high ground barrier	0.86	N
Muddy Creek	MC-1	309+17	Natural high ground barrier	0.86	N
		834+57	Natural high ground barrier	0.86	N
Muddy Creek	MC-3	2220+28	Natural high ground barrier	0.39	N
		2135+23	Natural high ground barrier	0.39	N

Stream	Reach Name	Weir Starting Station	Physical Condition	Weir Coefficient	Optimized (Y/N)
Muddy Creek	MC-3	2123+83	Overland flow escaping channel	2.60	N
		2120+60	Natural high ground barrier	0.39	N
		2223+96	Natural high ground barrier	0.39	N
Farmer's Ditch	FD-1	12+12	Overland flow escaping channel	2.60	N
Muddy Creek	MC-3	1956+64	Natural high ground barrier	0.86	N
		1968+11	Natural high ground barrier	0.86	N
		2102+83	Natural high ground barrier	0.39	N
		2135+23	Natural high ground barrier	0.39	N

Many of the lateral weirs listed in Table 8 are not optimized and flow is therefore not lost from the reach main stem, either out of the hydraulic system or into a neighboring reach. Non-optimized lateral weirs may also be used when insignificant flowrates (typically less than 5% of the total flow) are leaving the main channel. In these instances, the small flowrates are assumed to be contained within the main channel. This results in minor conservatism in the resulting water surface elevation and associated mapping along the mainstem. An example application of these lateral weirs is illustrated in Figure 2 and 3.

In Figure 2, the left overbank lateral weir is used as a tool to limit the modeled flooding extents in those instances where minor flows escape the main channel and would fan out onto adjacent flat terrain. The use of a non-optimized lateral weir simplifies what would otherwise be a complex 1D cross section configuration. The lateral weir in the example here represents only 4.8% (46 cfs) of the total overtopping flow during the 0.2% AC event.

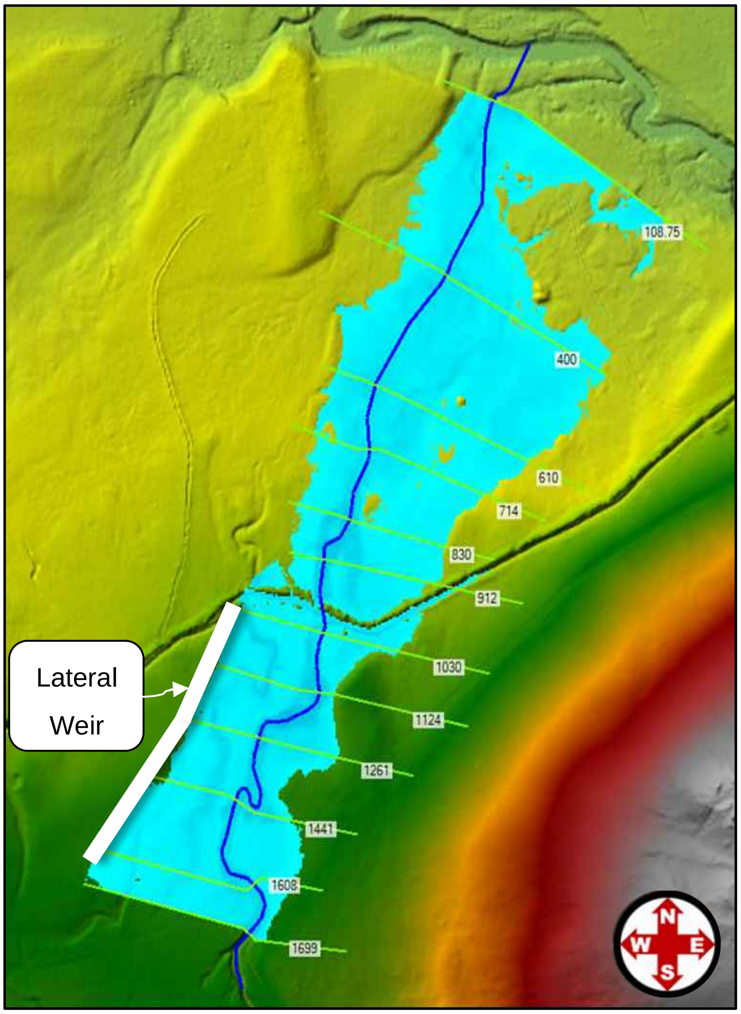

Figure 2: TDPC-3 Lateral Weir with 0.2% AC Flood Depth Map

Figure 3 illustrates another example where a non-optimized weir is useful. The northern lateral weir represents 28.8% (6,618 cfs) of the total overtopping flow during the 0.2% AC event. Typically, this large proportion of discharge would warrant optimization; however, as shown by the arrows in Figure 3, discharge escaping the main channel would be redirected by terrain blockage back to the main channel. By trimming the cross sections to the lateral weir rather than extending them far northward to capture the flows without a lateral weir, the WSEL in the channel is conservatively approximated and the cross section configuration is simplified. The mapping boundaries at this location will be appropriately adjusted during the mapping phase. By contrast, the southern lateral weir only represents 0.8% (186 cfs) of the total overtopping flow during the 0.2% AC event. This lateral weir is also non-optimized since the overtopping flows are minor.

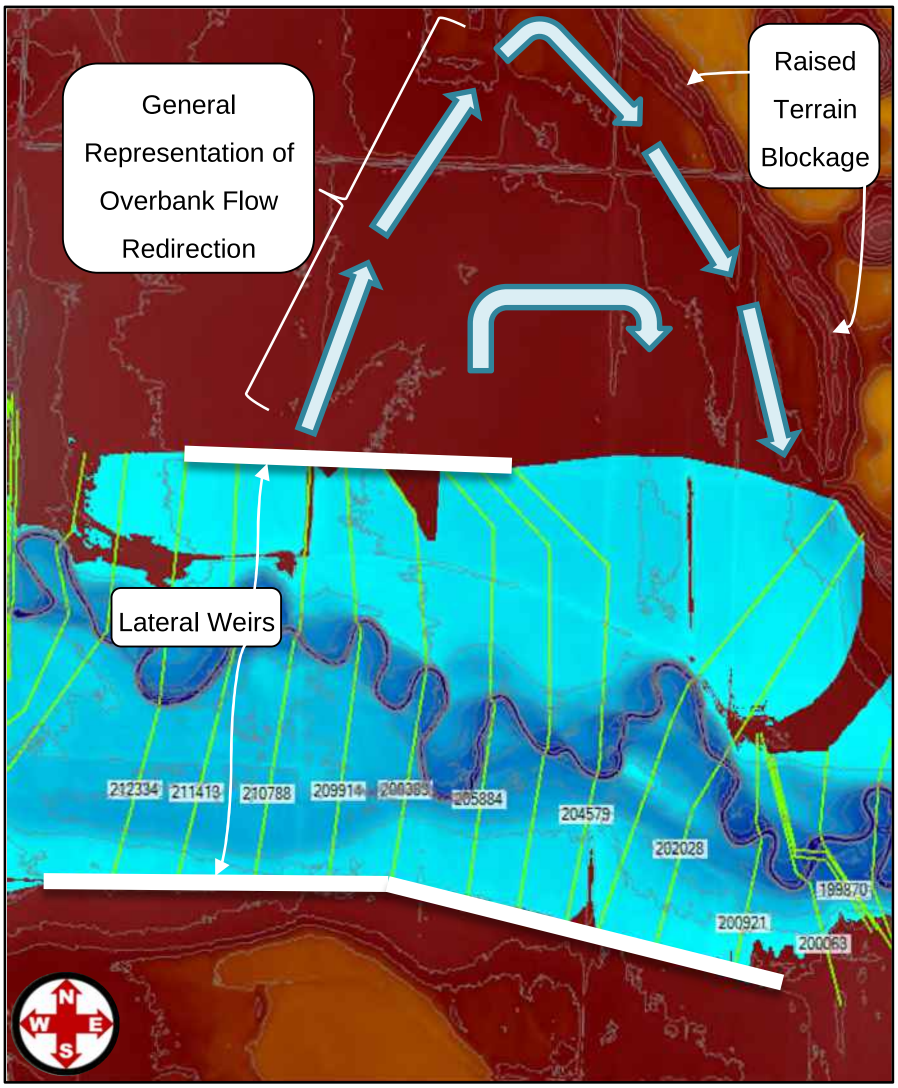

Figure 3: MC-3 Lateral Weir with 0.2% AC Flood Depth Map

5.6 CRITICAL DEPTHS

There are several locations within the various hydraulic models where the water surface appropriately defaults to critical depth. Appendix E contains additional details and summarizes the computed critical depths, the cross-section location, and the explanation for why critical depth is a reasonable solution. Many of these occur at cross sections immediately downstream from bridges and for flood profiles where bridge overtopping occurs. Critical depth is reasonable in these instances because flow over a non-submerged weir can be expected to pass through critical depth. Other instances of critical depth are associated with steep channel reaches or where surrounding topography severely constricts the effective flow geometry, increasing water velocities, and accelerating the flow to critical depth.

5.7 MODEL CONNECTIONS

As specified by Standard Identification Number (SID) 65 of *FEMA's Flood Risk Analysis and Mapping, Rev. 11* (FEMA, 2019d), BFEs at modeled connection points must be within 0.5 feet. DOWL ensured that all contributing reaches meet this 0.5-foot requirement. The WSELs of the regulatory event were compared between the downstream cross section (contributing reach) and the interpolated WSEL between bounding cross sections (controlling reach). The five 2D Regulatory models were developed well within the proposed boundary of the controlling reaches and 2D meshes extended sufficiently far enough into the controlling extents. Table 9 summarizes 1D connection points as well as the WSEL difference. The connection point between Willow Creek and Deep Creek Reach 1 exhibits a WSEL difference that is out of tolerance. A gutter line will be placed at this confluence to guide controlling water surfaces from either flooding source.

Table 9: 1D Model Tie-In Connection Points

Flooding Source	Controlling Waterway	Downstream WSEL (ft) [A]	Tie-In WSEL (ft) [B]	WSEL Difference (ft)
DPC-1	Teton River	3784.2	3784.3	-0.1
DOC-1	DPC-1	3909.6	3910.7	-1.1
BC-1		3924.6	3925.2 [C]	-0.6
WWC-1		3958.2	3958.1 [C]	0.1
TDPC-2		4026.9	4027.0	-0.1
TDPC-3		4045.2	4047.7	-2.6
TDPC-4		4064.9	4065.1	-0.2
QC-1 and TDPC-5		4110.7	4110.4	0.4
MC-1	Teton River	3391.1	3390.7	0.4
TMC-1	MC-3	3682.0	3684.0	-2.1
FC-1	MC-1	3565.2	3568.3	-4.0
JC-1	MC-4	3785.9	3789.2 [D]	-3.3
FOC-1		3900.7	3901.0 [D]	-0.4
FD-1	FOC-1	3818.5	3819.0 [D]	-0.5
BLC-1	MC-5	4036.7	4037.0 [D]	-0.3
CFMC-1		4328.9	4329.0 [D]	-0.1

[A] 1% AC regulatory WSEL at the most downstream cross section of the flooding source

[B] Interpolated 1% AC regulatory WSEL between bounding controlling cross sections

[C] WSEL was pulled from closest cross section

[D] WSEL pulled from 2D model and associated BFE lines

5.8 2D Hydraulic Model Development

5.8.1 Boundary Conditions

Inflow hydrographs were used to define flows entering the system. Internal boundary conditions were developed by adding the flow rate difference between the flow change locations to the respective inflow hydrographs. Table 10 shows the total ramp-up time and total simulation time for each 2D Regulatory model. The flood flow was held constant after the ramp-up period until the downstream boundary condition reached steady-state. External boundary conditions are established at the most downstream cross section of the upstream 1D model.

Table 10: Summary of 2D Simulation Times

Flooding Source	Ramp Up Time (hr)	Total Simulation Time (hr)
DC-1	14	24
MLC-1	1	24
MC-4	5	16
MC-5	3	12
FC-2	4	12

Flows exiting the system are simulated assuming normal depth, and the corresponding stream slope was determined by measuring the downstream terrain slope. These boundary conditions are established at the downstream confluences with the appropriate connecting 1D reach. Table 11 summarizes the boundary conditions for each 2D model.

Table 11: Summary of 2D Boundary Conditions

Flooding Source	Boundary Condition ID	Control	Description (Slopes in units of ft/ft)
DC-1	US	Flow Hydrograph	1D Connection
	DS	Normal Depth	0.0250
MLC-1	BC-01	Flow Hydrograph	Steady-state
	M-19_Outflow	Normal Depth	0.0050
MC-4	MC-58.4	Flow Hydrograph	Steady-state
	MC-58.0	Flow Hydrograph	Steady-state
	MC-50.2	Flow Hydrograph	Steady-state
	MC-46.4	Flow Hydrograph	Steady-state
	MC-55.0	Flow Hydrograph	Steady-state
	MC-44.5	Flow Hydrograph	Steady-state
	MC-62.6	Flow Hydrograph	Steady-state
	Outlet BC	Normal Depth	0.0040
	Side Outlet	Normal Depth	0.0180
MC-5	MC-79.3a	Flow Hydrograph	Steady-state [1]
	MC-65.2	Flow Hydrograph	Steady-state
	MC-74.8	Flow Hydrograph	Steady-state
	MC-77.6	Flow Hydrograph	Steady-state
	MC-72.9	Flow Hydrograph	Steady-state
	MC-76.8	Flow Hydrograph	Steady-state
	MC-64.3	Flow Hydrograph	Steady-state

Flooding Source	Boundary Condition ID	Control	Description (Slopes in units of ft/ft)
	MC-63.7	Flow Hydrograph	Steady-state
	MC-62.6	Flow Hydrograph	Steady-state
	MC-74.4	Flow Hydrograph	Steady-state
	MC-79.3b	Flow Hydrograph	Steady-state [1]
	Outlet BC2	Normal Depth	0.0043
	Outlet BC	Normal Depth	0.0048
FC-2	FC-2 Inflow	Flow Hydrograph	Steady-state
	FC-2 Flow Change	Flow Hydrograph	Steady-state
	BC-03	Normal Depth	0.0010
	FC-2 Outlet	Normal Depth	0.0080

[1] Steady-state discharges informed by the 3DEP model as described in Section 6.0

5.8.2 2D Flow Options

For 2D modeling computations, HEC-RAS (USACE, 2021a) allows the user to specify one of the following equation sets: Diffusion Wave or Full Momentum. For improved model stability and final results, the Full Momentum equation set was used for the 2D Regulatory models. Full Momentum allows for implicit (SWE-ELM) or explicit (SWE-EM) solution options for shallow water equations. The SWE-EM requires smaller computational time steps to reach solution convergence, which increases model run time without significant accuracy increases. The SWE-ELM solution option was selected which provides an optimal balance between model utility and hydraulic accuracy. Using the SWE-ELM equation set in conjunction with the Courant Adjust Time Step reduced the continuity error and removed velocity “hot spots” within the mesh. Courant maximum and minimum values were selected based on *HEC-RAS 2D User’s Manual, Chapter 4* (USACE, 2021c) for this equation set. Initial conditions were used for all 2D models for stabilization purposes—flow was gradually added to the model over the ramp up periods.

5.8.3 Mesh and Breaklines

A cell size of 100 feet was used for the 2D Regulatory models. This cell size is consistent with studies conducted by MBI on the Milk River partition plan (MBI, 2021b)—100 feet allows for high enough detail around buildings and complex flow locations while still optimizing model run time and overall modeling efficiency.

Breaklines were placed in areas where higher hydraulic detail was required and to prevent “leaking” cells. These areas include roadways, berms, spill points, ditch banks, and low flow channels, among others. Cell spacing along breaklines was generally kept at 50 feet, again consistent with studies conducted by MBI on the Milk River partition plan.

5.8.4 Hydraulic Structures

Culverts and inline weirs were modeled using SA/2D connections. The terrain was adjusted at these locations to remove the road embankments and to place the culvert at the surveyed invert. HEC-RAS 6.1.0 (USACE, 2021a) can model bridges directly inside 2D flow areas for low flow and high flow scenarios. Drawing the bridge centerline establishes the bridge location inside the 2D flow area. The user inputs structure data such as the low chord and high chord elevations, deck width, and pier geometry. The software generates four cross-sections for the bridge: two external and two internal. Using the input bridge data, cross-sections, and modeling approaches selected by the user, HEC-RAS creates a set of rating curves for the bridge. According to the *HEC-RAS 2D User's Manual, Chapter 3*, (USACE, 2021c) these rating curves determine the difference in water surface elevation through the bridge for all cells used to model the bridge. The water surface difference equates to a force that is distributed to the cells along the bridge centerline and input into a modified version of the momentum equation. The bridge curves are used to obtain friction, pressure, and spatial acceleration forces for the cells—2D equations are then solved in routine fashion.

Structure MUD_0210 on MC-5 is an example of the advanced utility made available with the new 2D bridge modeling routine available. As shown in Figure 4, the MUD_0210 flume has 41 piers. In the older HEC-RAS versions—those without a 2D bridge modeling routine—this structure would need to be modeled as 41 separate box culverts, demonstrating the increased modeling capability provided by the new bridge modeling routine.

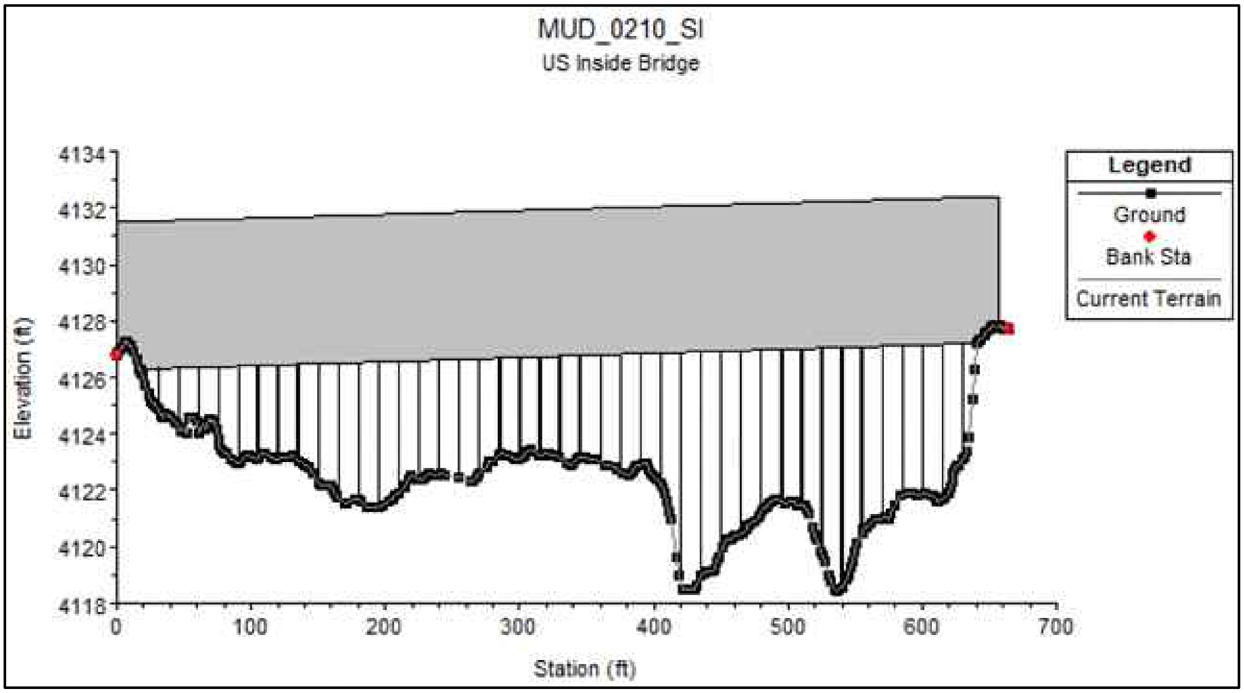

Figure 4: Structure MUD_0210 Demonstrating 2D Bridge Modeling Capabilities

Table 12 summarizes the 2D hydraulic structures. A sampling of the photographs from the hydraulic structure assessment, which were used to assist in model development, are shown as follows (MM, 2020).

Example structures contained in 2D models—

Muddy Creek Flume

MUD_0210_SI_OTXS

Muddy Creek Headgate

MUD_0180_SI_DSFACE_GATE

Muddy Creek 3rd Ln NW Bridge

MUD_040_SI_USFACE

Muddy Creek Pedestrian Bridge

MUD_090_SI_DSFACE

Muddy Creek Culvert

MUD_050_SI_USFACE

Muddy Creek Blackleaf Rd Culvert

MIL_010_SI_USFACE

Table 12: Summary of 2D Hydraulic Structures

Structure ID	Stream	Description	Feature Type	Modeling Approach	Bridge Data	Culvert Data			
					Pier Width (ft)	Length (ft)	Shape	Type	Dimensions (Rise x Span)
---	Deep Creek (DPC-1)	Private - Measured during DOWL field review	Culvert	---	---	81	Circular	Concrete	3'
EAS_010	Muddy Creek (MC-4)	Irrigation Ditch on 26th Rd NW	Culvert	---	---	28	Circular	CSP	4'
MUD_0100	Muddy Creek (MC-4)	Kesler Ranch Internal Access	Culvert	---	---	23	Circular	CSP	3'
MUD_0130 & MUD_0125	Muddy Creek (MC-4)	Private	Culvert	---	---	24	Circular	CSP	1.5'
						22	Circular	Concrete	2'
						22	Circular	Concrete	2'
MUD_0140	Muddy Creek (MC-4)	Hodgskiss Ranch Internal Access Road	Culvert	---	---	30	Circular	CSP	4.5'
MUD_070	Muddy Creek (MC-4)	Highway 220	Bridge	Energy/Momentum (Cd = 2)	two piers, each 3'	174 span, 31 width	---	---	---
MUD_080	Muddy Creek (MC-4)	10th Ln	Bridge	Energy	two piers, each 4.125'	125 span, 44 width	---	---	---
MUD_090	Muddy Creek (MC-4)	Kesler Ranch Internal Access	Bridge	Energy/Momentum (Cd = 2)	four piers, each 0.7'	105 span, 13 width	---	---	---
MUD_0170	Muddy Creek (MC-5)	Highway 89	Bridge	Energy/Momentum (Cd=1.2)/Yarnell (K=0.9); Pressure	four piers, each 1.5' with 3.9' cap	315 span, 45 width	---	---	---
MUD_0180	Muddy Creek (MC-5)	Irrigation Diversion	Diversion, width = 3' (Cd= 2.6)	---	---	---	---	---	---
MUD_0190	Muddy Creek (MC-5)	Private Ranch Road	Bridge	Energy/Momentum (Cd=1.2); Pressure	---	45 span, 13.7 width	---	---	---
MUD_0200	Muddy Creek (MC-5)	Blackleaf Road	Bridge	Energy/Momentum (Cd=1.2); Pressure	---	33 span, 21 width	---	---	---
MUD_0210	Muddy Creek (MC-5)	Flume Crossing	Bridge	Energy/Momentum (Cd=2)/Yarnell (K=1.25); Pressure	41 piers, each 0.5'	---	---	---	---
MUD_0250	Muddy Creek (MC-5)	Miller Colony Internal Access Road	Culvert	---	---	16	Circular	CSP	5'
FAR_010	Farmers Coulee (FC-2)	Private	Culvert	---	---	66	Circular	CSP	5.1'
MIL_010	Miller Creek (MLC-1)	Private	Culvert	---	---	48	Circular	CSP	5'
MUD201	Miller Creek (MLC-1)	Private	Culvert	---	---	40	Circular	CSP	4.5'
						40	Circular	Concrete	5.5'
MUD202	Miller Creek (MLC-1)	Private	Culvert	---	---	2	Box	Concrete	3' x 5'
						2	Box	Concrete	3' x 5'

5.9 Model Validation

In Fall 2021, the Montana Department of Transportation (MDT) provided DOWL with information from three historic floods in the Teton County area for the 1964, 1975, and 2019 floods (MDT, 2021).

- 1964: combination of heavy rains and rapid snowmelt in conjunction with dams, roads, and railroads washing out (largest flood in Teton County's recorded history)
- 1975: snowmelt runnoff from deep snow accumulation combined with rainfall
- 2019: higher than average snowpack in conjunction with a heavy rain storm in the mountains west of Choteau, MT

There are two active USGS gages on the Teton River in the general vicinity of the study area; other historic USGS gages in the area along Deep Creek, Teton River, Willow Creek, and Spring Creek have been inactive since the mid-1920s. Figure 5 shows the relative proximity of the two active gages:

- 06102500—Teton River bl South Fork nr Choteau MT
- 06108000—Teton River near Dutton MT

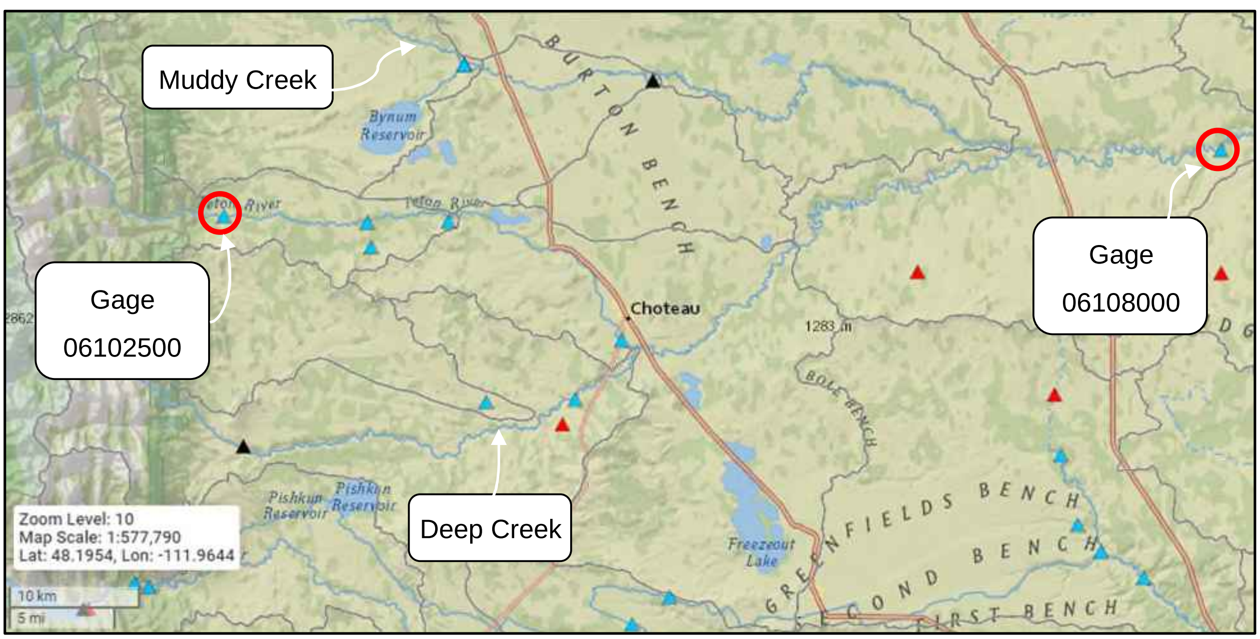

Figure 5: Location of USGS gages Used for Validation Modeling

As shown in Figure 5, the two gages are a significant distance away from the study area model reaches. The flood data for these two gages was nonetheless used, in conjunction with the flood history provided by MDT, as a reasonableness check of the hydraulic modeling parameters (i.e., Manning's roughness). Flood flow frequency values from the *Scientific Investigations Report* (USGS, 2018) were used to estimate the return interval for the three flood events. Table 13 provides a breakdown of calculated return interval for the two USGS gages and the average return interval used in evaluating the reasonableness of the flood modeling simulations.

Table 13: Summary of Usable Return Intervals for Validation Modeling

USGS Gage	Calculated Return Interval		
	1964	1975	2019
06102500, near Choteau MT	722	(no data)	18
068108000, near Dutton MT	366	60	24
	Average Return Interval to use for Validation		
	544	60	21

Observations of flooding at particular structures as provided by MDT for the particular flood events were used for this evaluation. Flood flows for the historic flood simulation runs were estimated through interpolation from logarithmic scale flood-frequency graphs (10%, 2%, 1% AC, etc.) for the study watersheds. These historic flood simulations were performed for Deep Creek, Muddy Creek, Willow Creek, and Jones Creek.

Flooding information related to the 1964 and 1975 events for Deep Creek, Muddy Creek, and Tributaries hydraulic structures is primarily available through written descriptions and photos. The 1964 flood event was particularly devastating. Six locations (two at the Highway 287 bridge on Deep Creek and four along various crossings of Muddy Creek) have written descriptions of flood impacts. Many of the descriptions simply read "bridge washed out". Along with the written descriptions, aerial and ground level photos provide visual evidence of the destruction from the 1964 flood:

Figure 6: 1964 Flood Photo on Deep Creek, Hwy 287 (Structure DEE_020_SI)

Figure 7: Upstream Face of Structure MUD_020_GPS with Historic Bridge Bents

Historic flood simulations (1964/544-yr event and 1975/60-yr event) were performed. For those structures described as "washed out" from the information provided by MDT, the historic flood model simulations show water surface elevations far in excess of the overtopping elevation of these structures. In some cases, model-simulated overtopping depths exceeds 10 feet. For example, information for the 8th Ln NE flooding on MC-1 (structure ID MUD_020_GPS) indicates that the bridge "washed out" during the 1964 flood event. Photos from the survey data provided by MM show the historic bridge bents still in the Muddy Creek channel:

Overtopping depths for the 1964/544-year return interval flood are roughly 10 feet over the roadway at the existing culverts. This was a consistent finding for all the validation sites described as being "washed out" during extreme floods like those in 1964 and 1975.

The 2019/21-year flood event was used for 1D model validation simulations on Willow Creek, Jones Creek, and MC-3 and for 2D-model validation simulations on Muddy Creek. Flooding information provided by MDT from the 2019 event primarily consist of ground level flood photos accompanied by brief observation notes.

Muddy Kennedy Creek north of Babb on Highway 89 is in full flood as it carries tons of debris over the approach road to this steel bridge. The bridge dropped into the river bed finally. George Goggins photo.

Figure 8: 1964 Flood Photo on Muddy Creek, Highway 89 (Structure MUD_0170_GPS)

Without actual flowrates at each particular site, and associated surveyed WSELs, it is not possible to explicitly calibrate to this flood event. However, the model-simulated water surface elevations appear to be within about a foot of the observed water surface elevations based on rough approximations from flood photos and corresponding structure survey sketches. The model validation simulations for the 2019 flood yielded water surface elevations that generally seemed reasonable based on the flood photos and observations.

It is concluded that the hydraulic modeling parameters (i.e. Manning's roughness) utilized provide reasonable representations for these floodplain delineation studies.

6.0 UNIQUE HYDRAULIC MODELING SCENARIOS

6.1 TETON COUNTYWIDE STUDY AREA PROFILE BASELINE REALIGNMENT

Numerous reaches throughout the study area exhibit tortuous sinuosity. For areas with particularly extreme sinuosity, the overbank flow path for larger events (i.e., greater than 4% AC events) dominates the main channel flow path. Modeling this extreme sinuosity in 1D resulted in overly complex cross section configurations and diminishes the ability to accurately model overbank flow behavior. The profile baseline was therefore adjusted in several locations to better represent the hydraulics of larger flood events. Figure 9 and Figure 10 illustrate this baseline adjustment for DPC-2 and MC-3, respectively.

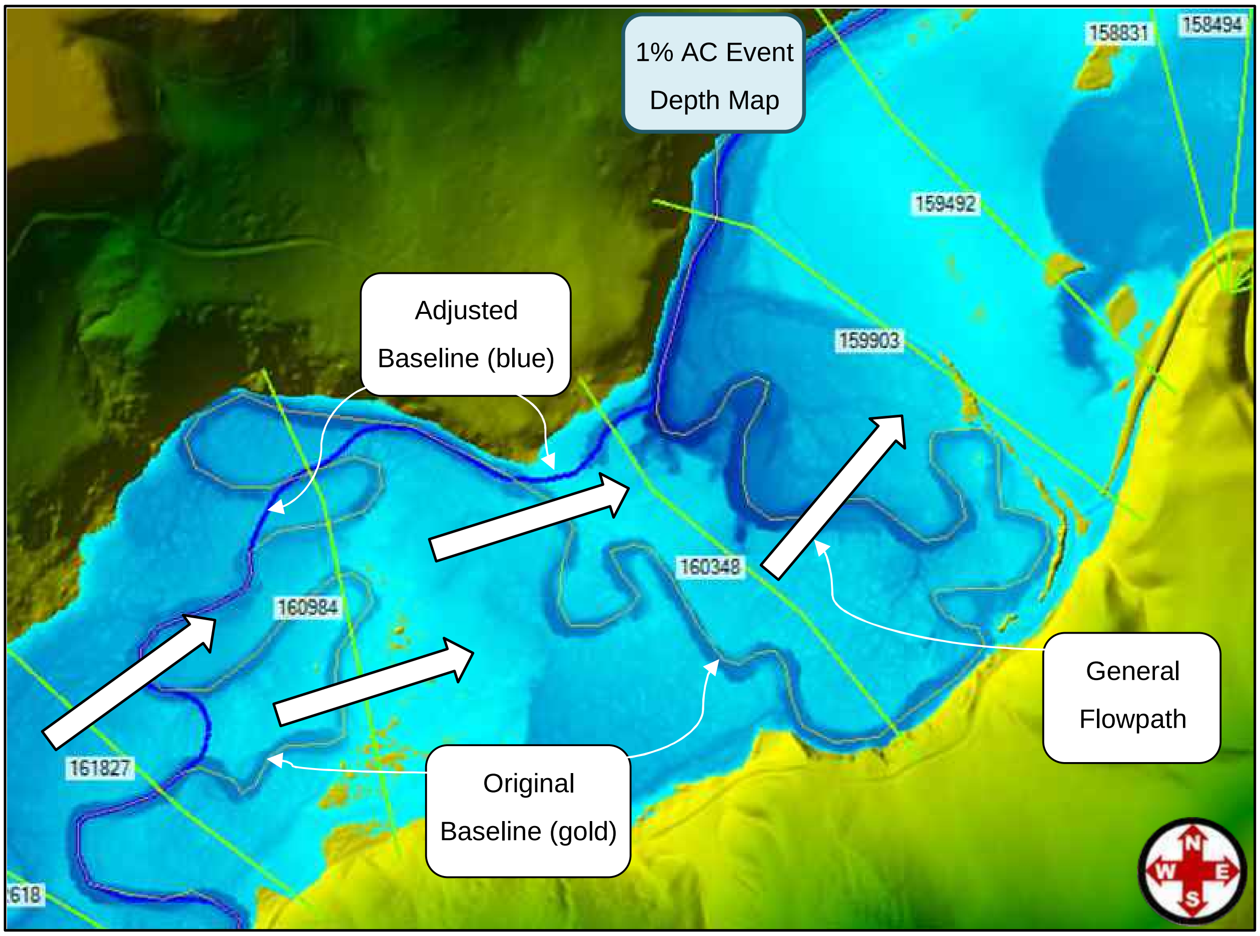

Figure 9: Profile Baseline Adjustment on DPC-2

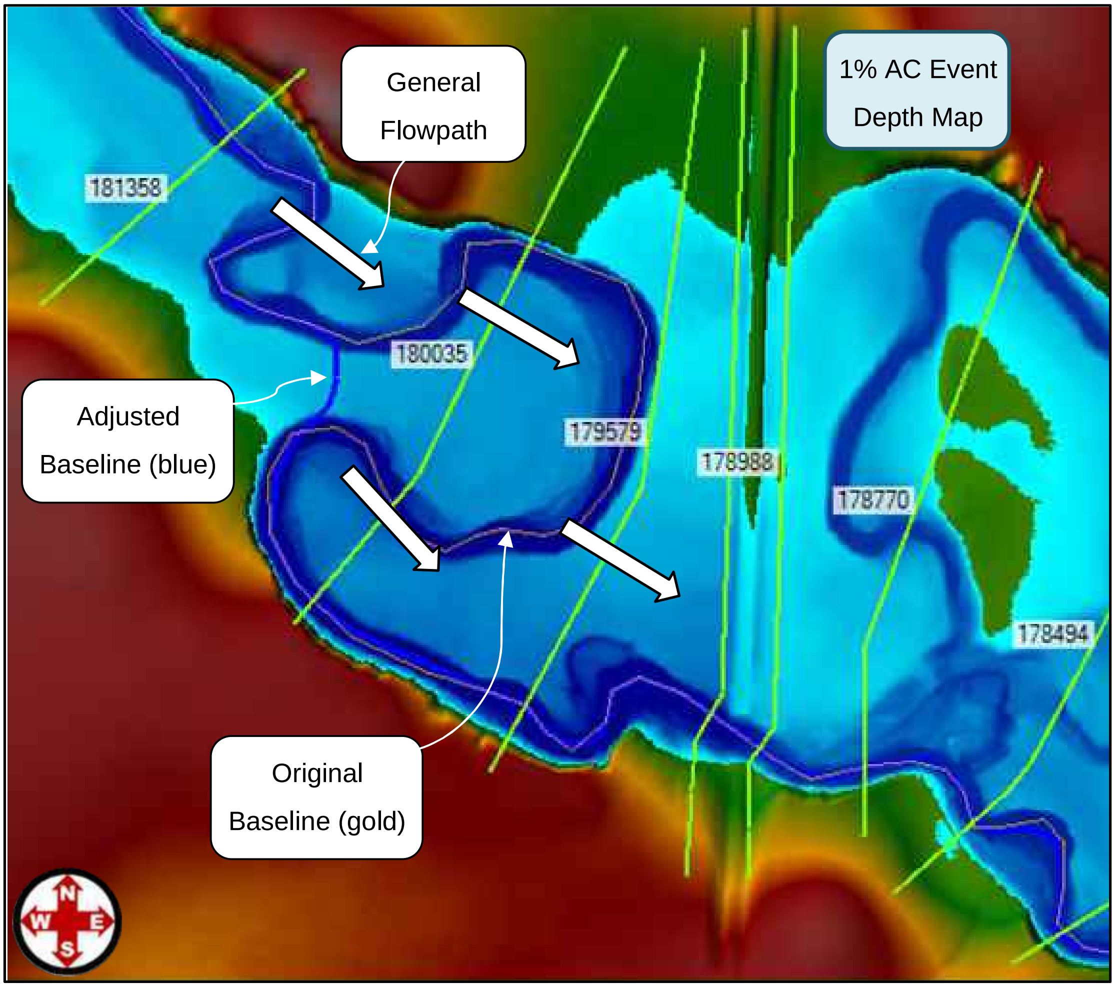

Figure 10: Profile Baseline Adjustment on MC-3

6.2 DEEP CREEK AND TRIBUTARIES

6.2.1 Using 2D Hydraulics to Inform Downstream Complexities on DPC-1

About a mile downstream of the Highway 289 crossing on DPC-1, the flooding extents split into two separate drainage paths—one following the overflow flood path as repesented by the Hwy 289 lateral weir described in Section 5.5. This model area becomes overly complex to be accurately represented by a 1D model. A combination of a 2D Regulatory and 1D Regulatory Informed by 2D was therefore used for the downstream end of DPC-1. A lateral weir and a profile line were used in the 1D and 2D models, respectively, at a high point in the terrain between the split flow reaches. The results from the more detailed 2D model were then used to inform the 1D representation. Figure 11 provides an overview of the 2D flooding extents for the 1% AC event overlain by the 1D cross sections, DPC-1 baseline, and lateral weir.

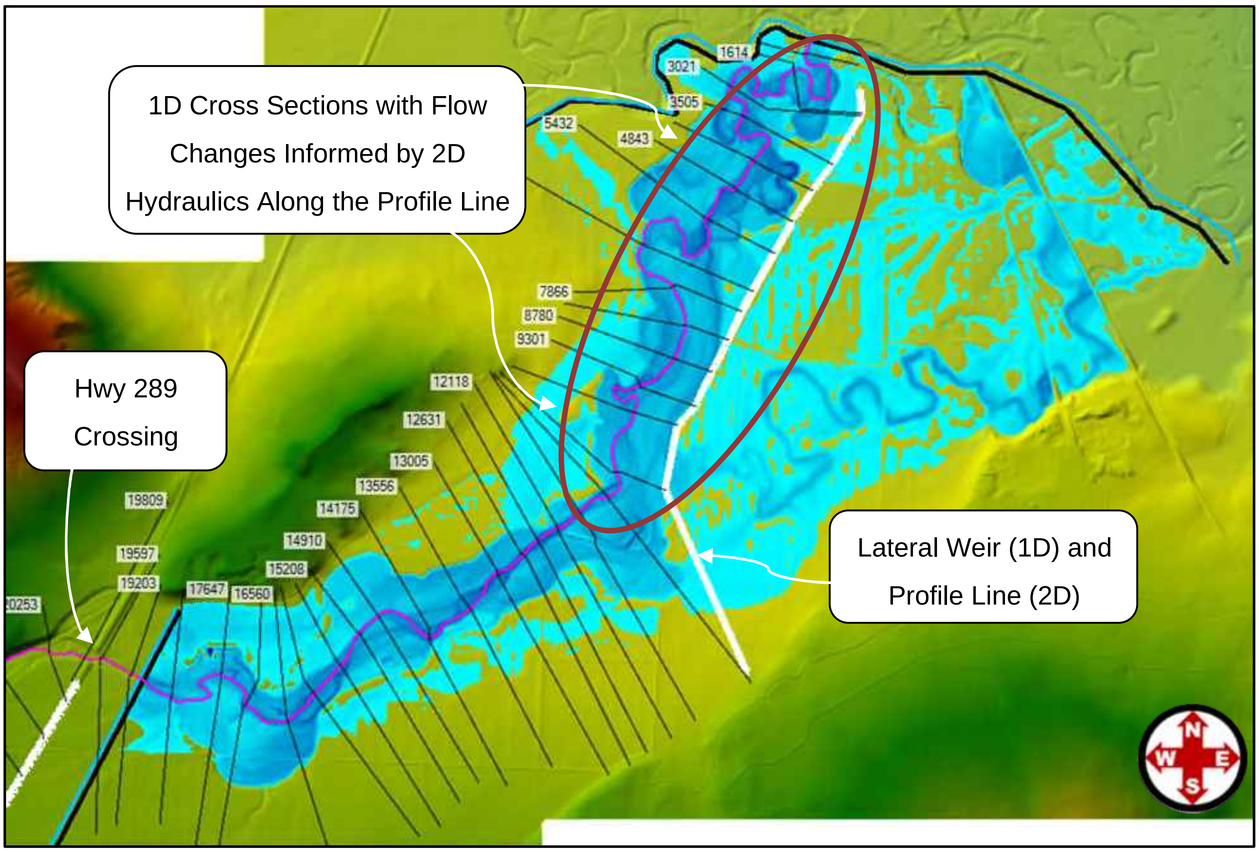

Figure 11: Downstream DPC-1 Informed by 2D Hydraulics

6.2.2 Willow Creek LiDAR Adjustment

The Pishkun Road bridge (Structure ID WIL_030_SI) over Willow Creek is shown in Figure 12.

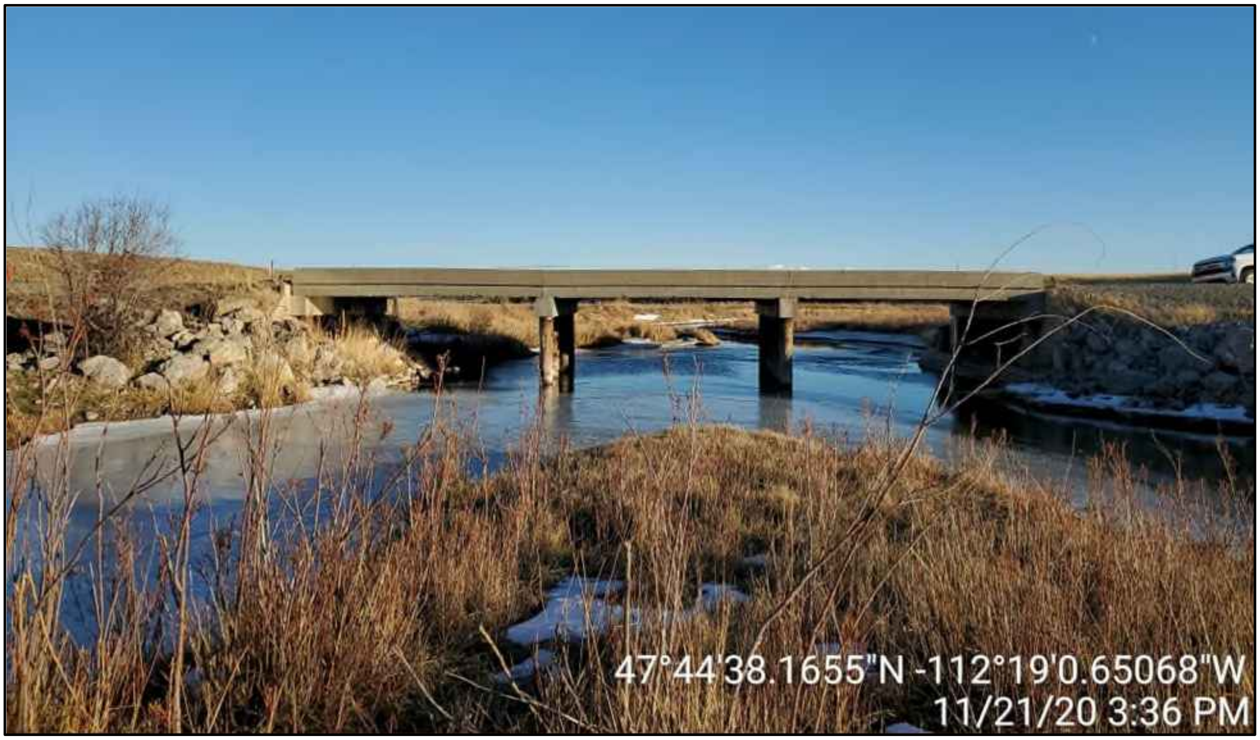

Figure 12: Pishkun Road Bridge (WIL_030_SI) Over Willow Creek

From the survey sketches provided by MM, the channel thalweg measures 15 feet below the bridge low chord elevation. The LiDAR data (NV5, 2020), which is not capable of representing the below-water bathymetry, only indicates 6 feet from the channel thalweg to the low chord. This discrepancy would represent a dramatic reduction in flow area and significantly impact the accuracy of the bridge hydraulic computations and overtopping extents. The bathymetry in the localized vicinity of the bridge was therefore adjusted to reflect the MM survey data. This adjustment was limited to the localized area of the bridge crossing and quickly transitions to tie in with the LiDAR surface a short distance downstream of the bridge opening. This misrepresentation of the LiDAR data was found to be unique to the Pishkun Road bridge crossing.

6.3 Muddy Creek and Tributaries

6.3.1 Confirming Rinker Creek Inundation with 3DEP Terrain Modeling

Rinker Creek is at the far upstream end of the MC-5 reach and near the edge of the available LiDAR data (NV5, 2020), as shown in Figure 13:

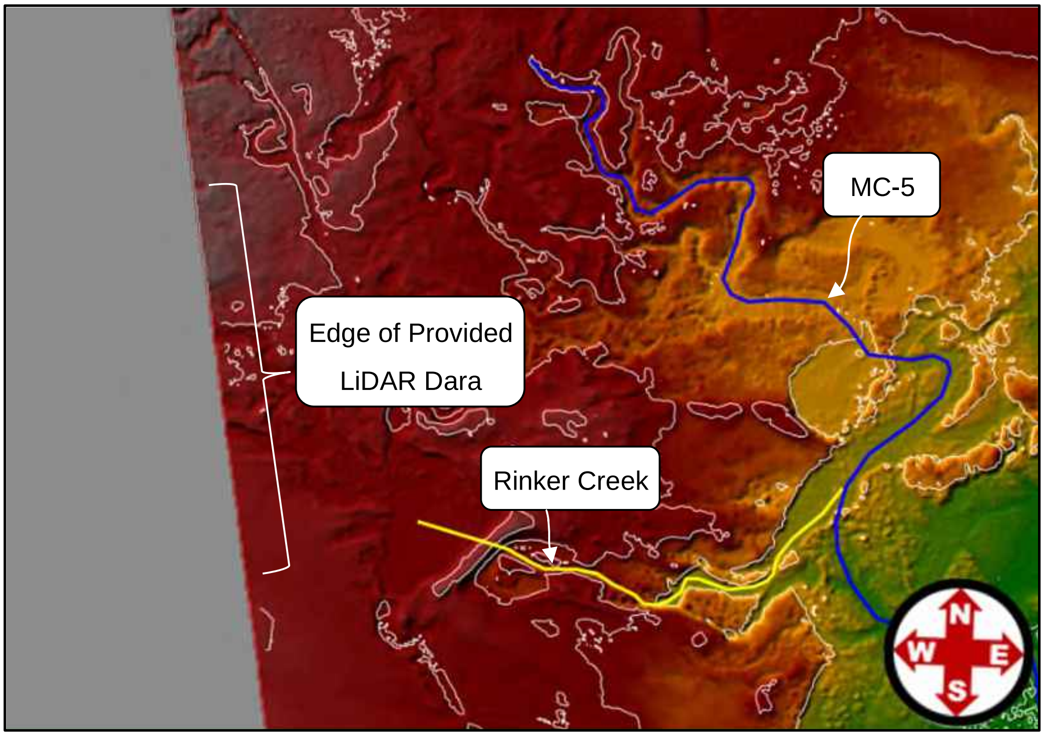

Figure 13: Rinker Creek and the Upstream End of MC-5

Through preliminary model runs on MC-5, it became apparent that Rinker Creek would likely be completely inundated by the flooding extents of MC-5. To confirm this, the MC-5 model extents needed to be expanded upstream. However, as shown in Figure 13, not enough LiDAR data is available to accomplish this, especially considering the model space needed to achieve a steady state split flow condition down the Rinker Creek and MC-5 reaches. DOWL coordinated with DNRC regarding an alternate method for confirming that Rinker Creek is fully inundated using terrain data from the 3DEP (USGS, 2021). The 3DEP terrain data consists of 10-meter resolution cell which would not be appropriate for floodplain delineation but is sufficiently accurate to confirm the assumption. These 3DEP data were readily available for the analysis.

DOWL developed the 2D 3DEP model using the same approach as a 2D regulatory model. The same flowrates determined from the hydrology nodes were applied at the inflow boundary condition to the 2D 3DEP model, and two profile lines (PL-15 and PL-16) were added immediately downstream of the identified terrain split between Rinker Creek and MC-5. The 2D 3DEP model layout together with the 100-year WSEL results, are shown in Figure 14. The profile lines were positioned to determine the conveyance on either side of the terrain split upstream of Rinker Creek. The discharges determined from the profile lines were applied as the inflow boundary condition flowrates for the 2D Regulatory model of MC-5. Through this modeling, it was confirmed that the 100-year WSEL extents of Muddy Creek completely inundate Rinker Creek. Rinker Creek was therefore removed as a modeled tributary and is encompassed within the 2D Regulatory model of MC-5. The 2D 3DEP model will be submitted as a supplemental model with this hydraulics data capture.

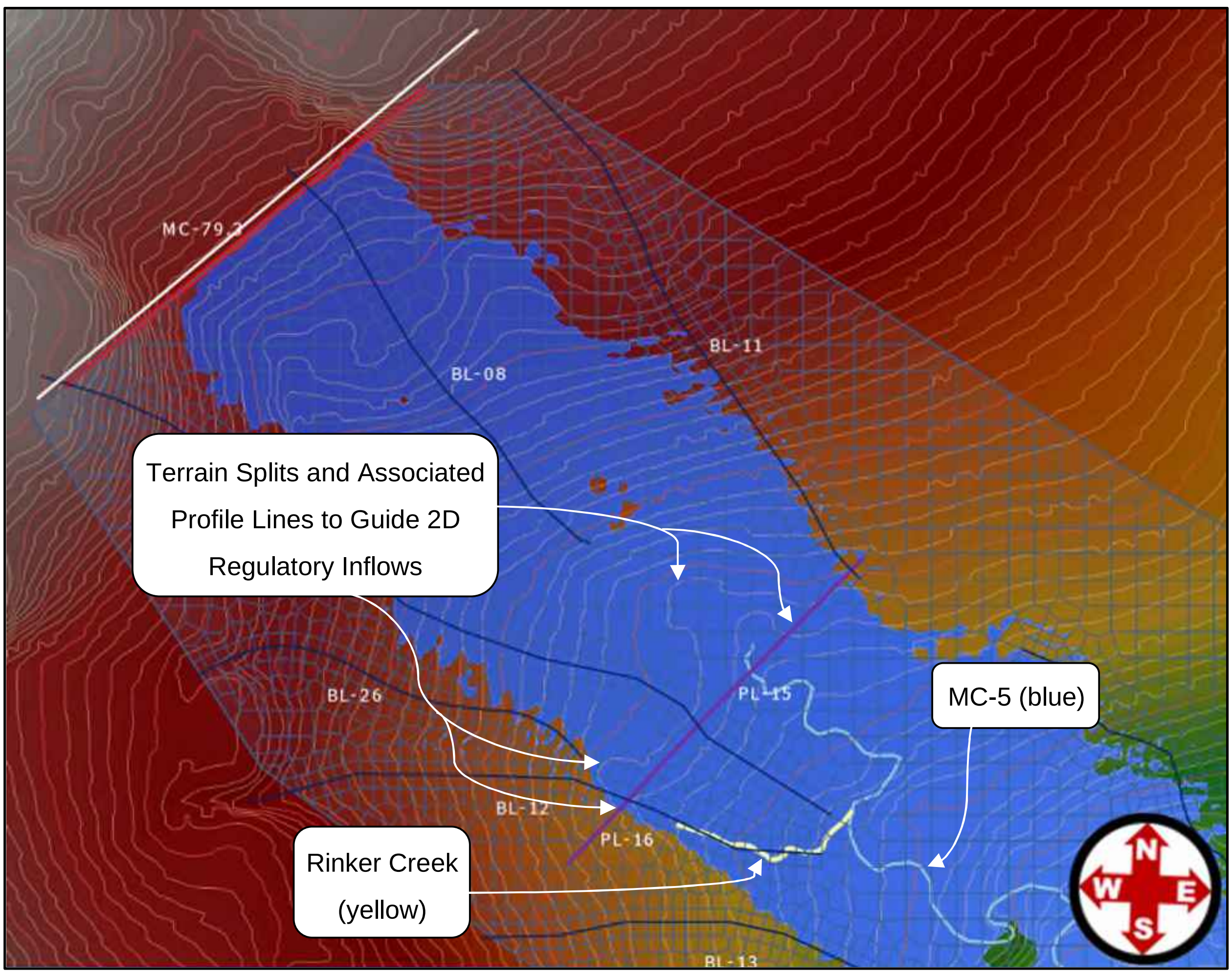

Figure 14: 2D 3DEP Model with 1% AC MC WSEL Inundating Rinker Creek

6.3.2 Shifting the Upstream End Location of Muddy Creek Reach 3

The original upstream extents of the MC-3 model ended at the MT Highway 220 (8th Lane NW) crossing over Muddy Creek. However, the MC-4 flooding extents represent significant split flow conditions near the MT Hwy 220 crossing. After determining the preliminary inundation boundaries from the 2D Regulatory model of MC-4, the upstream extent of the MC-3 model needed to be shifted further downstream to a more appropriate 1D/2D connection point. Figure 15 displays the adjusted extents of the MC-3 model to the more appropriate location.

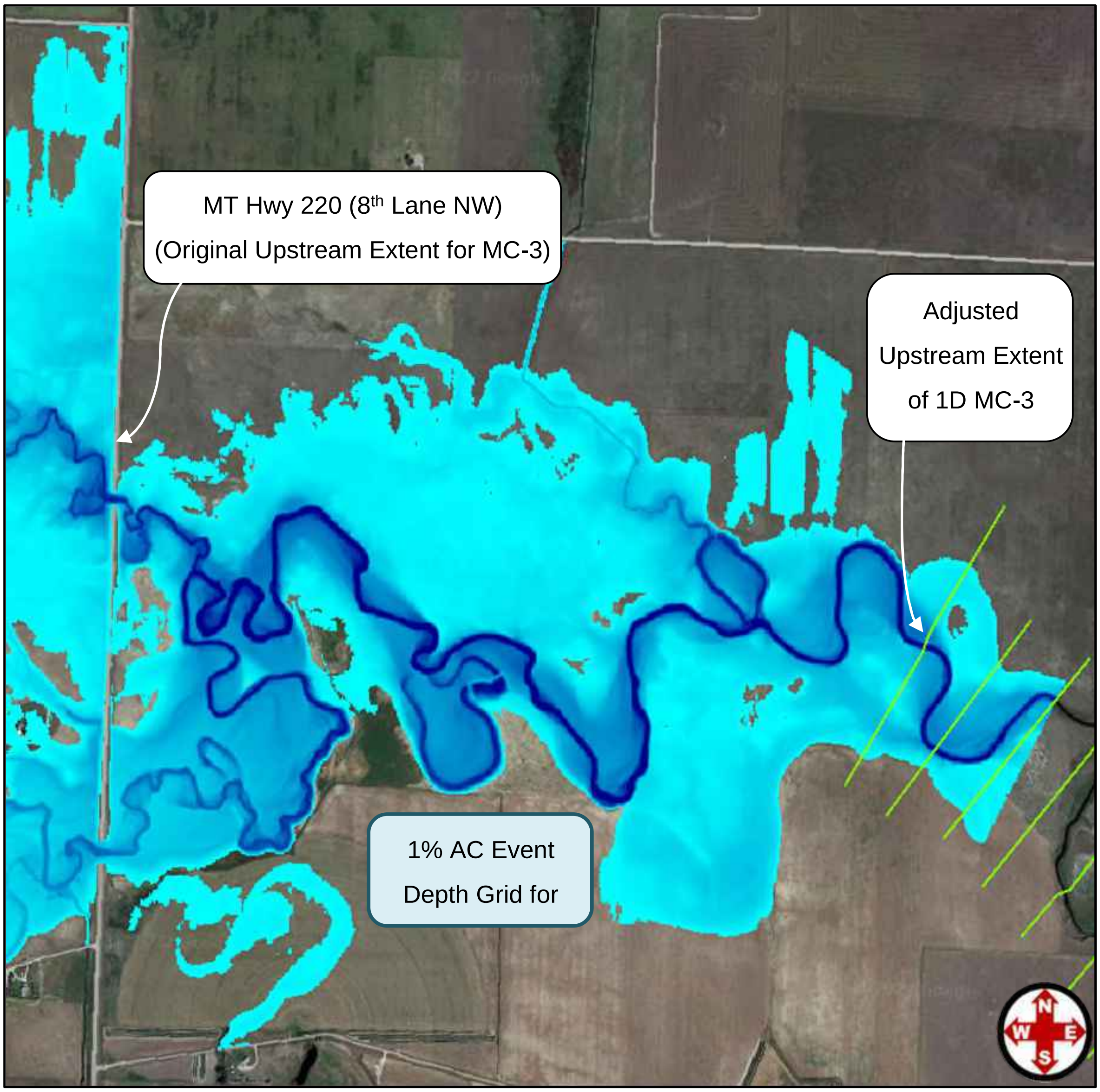

Figure 15: Upstream Extents of MC-3

6.3.3 Containing Shallow Flooding Extents along Farmers Coulee Reach FC-2

The preliminary one-dimensional modeling of Farmers Coulee reach FC-2 indicated expansive shallow flooding through the complex topography to the west of Farmers Coulee. The modeling for this area was therefore transformed into a 2D Regulatory model given the complex hydraulic conditions. Figure 16 also highlights other modeling intricacies associated with FC-2—namely the closed check structure and an area of expansive ponding which will be eliminated through a Limit of Study line during the product development stage. The check structure is modeled as closed based on field observations of this structure in June 2021. Shallower flows are directed around this closed structure in the 2D model. Figure 17 is a photo of this structure from the field review.

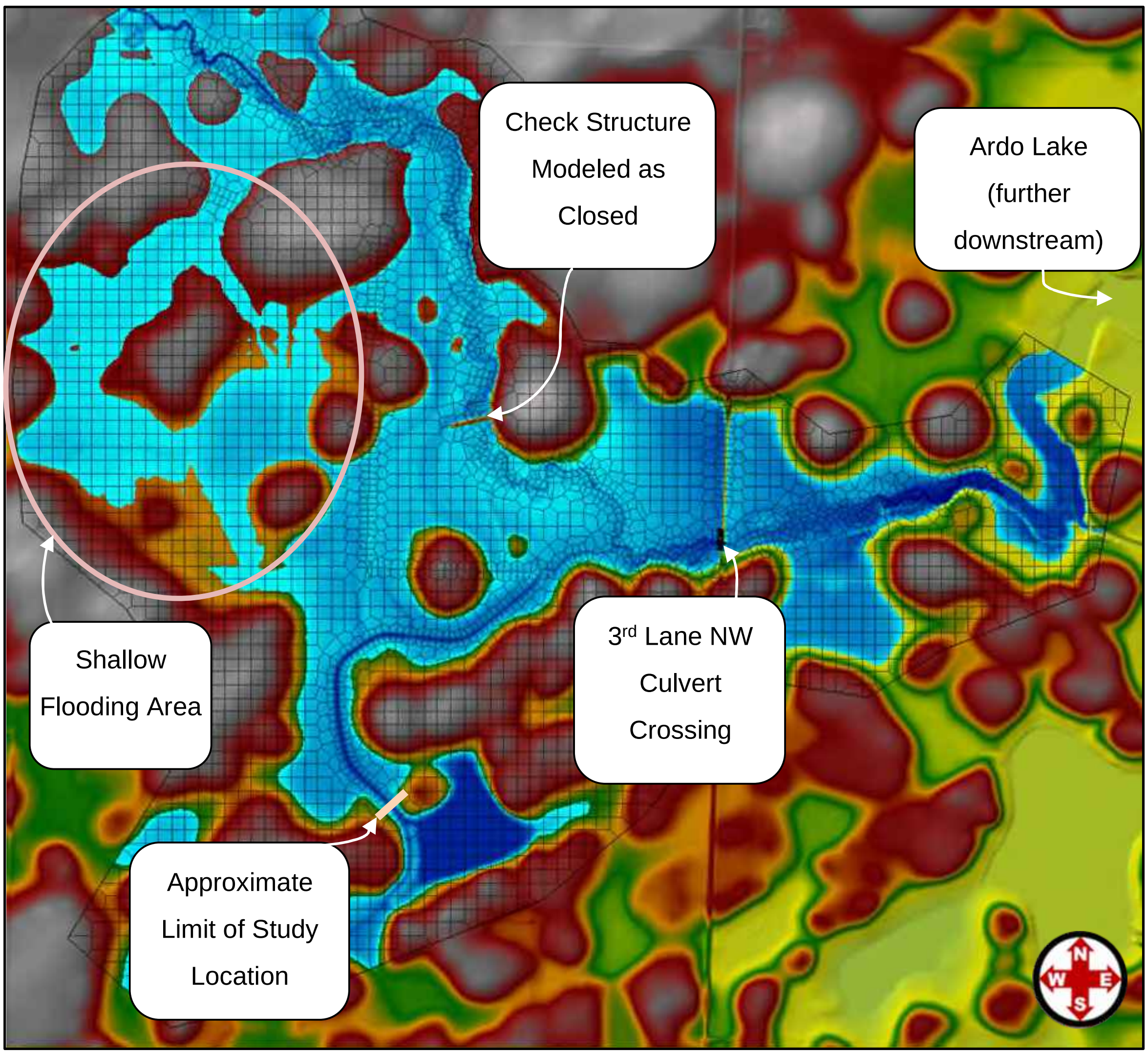

Figure 16: Highlighting Model Intricacies of FC-2

Figure 17: Closed Check Structure on Foster Creek Reach FC-2

7.0 FLOODWAYS

No floodways have been computed along Deep Creek, Muddy Creek or their tributaries. Since there are no floodway computations for this study, the hydraulic data package will not contain any floodway analysis simulations, floodway data tables, or spatial files associated with floodway delineations.

8.0 FLOODPLAIN MAPPING

8.1 HYDRAULIC MAPPING LIMITATIONS

Hydraulic model mapping outputs have limitations that are corrected during the Floodplain Mapping Task. Some of these limitations include diverging water surfaces, backwater adjustments, roadways and structures overtopping and cascading water surfaces.

Diverging water surfaces can occur where there is a split flow but is not significant enough to be incorporated into the model. These splits represent small flows or are modeled as ineffective.

When the main/modeled channel water surface elevation drops faster than the water surface of the split flow, split flow flood hazards can be missed in the mapping.
The hydraulic modeling outputs can underpredict or overpredict the water surface boundary for backwater zones. Backwater adjustments are made by replacing the sloped water surface from the hydraulic model outputs with a boundary that represents a constant water surface.

Roadways and Structures which exhibit minor overtopping or a large water surface elevation differential between the upstream and downstream cross sections are often not accurately mapped in the raw hydraulic outputs. Since roadways may need to be used as emergency routes, it is important to accurately map roadway overtopping.

8.2 Non-Levee Features Modeling and Mapping

It has been standard practice in the state of Montana to extend cross sections through non-levee features in the Hydraulic Modeling Task with the intent to map the backside in the Floodplain Mapping Task (DNRC, 2021). A draft memo describing the suggested approaches for modeling and mapping was issued in May 2021 and is included in Appendix A. For this study the first approach was used which states:

> *"First Approach – Simply extend the BFEs from the stream side to the landward side. This approach is appropriate where the flow areas on the landside of the levee would not be significant and would not significantly reduce the BFE. Examples of this approach include when the area behind the embankment is very small and/or primarily ineffective flow area, or a populated area where the ground is not significantly lower than the with levee BFE and you have a lot of obstructions to the flow. Engineering judgment should be used to determine when this approach is appropriate." (Memo Page 3)*

It is also stated that cross sections are not truncated to high points of non-levee features.

> *"It is also recommended that they not truncate the cross section at the non-levee feature in either the model or the floodplain mapping files." (Memo Page 4)*

9.0 QUALITY REVIEW

DOWL has developed an internal QA/QC process for review of the Hydraulic Data and Floodplain Mapping tasks for floodplain studies. This includes detailed checklists, an independent review by another water resources engineer, as well as review by a senior engineer. The details of this review are provided in Appendix D.

10.0 FLOOD INSURANCE STUDY PRODUCTS

The only Flood Insurance Study products included as part of this Hydraulic Data Capture are flood profiles for the 1D regulatory modeled reaches. Flood profiles were developed using RASPLOT Version 3.0 (FEMA, 2015a) (FEMA, 2015b). This software extracts the results from the HEC-RAS analysis and creates databases for each modeled stream. RASPLOT uses information entered on the plot extents and labels to create and export the flood profiles to Drawing Exchange Format (DXF) files. The resulting profiles were reviewed and edited as necessary for better placement of labels and then exported to PDF files (FEMA, 2020).

11.0 REFERENCES

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Appendix A: Technical Reports

Appendix B: Working Maps

Appendix C: Flood Profiles

Appendix D: Model Review

Appendix E: HEC-RAS Model Documentation

Appendix F: HEC-RAS Model Outputs

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