Geotechnical Reconnaissance of the 2022 Southern Montana/ Yellowstone Floods

Flood Event: June 13-24, 2022

Flood locations: South Montana, Yellowstone Ntl. Park

Reconnaissance Visit: June 30 - July 4th, 2022

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GEER Association Report 079

Abstract

In June 2022, the southern part of Montana and the northern part of Yellowstone National Park experienced flooding along multiple watersheds, including the Yellowstone River. The flooding resulted from heavy snowmelt between June 10-13th, leading to record levels of river water elevation in most of the main tributaries to the Yellowstone River. Substantial damage occurred to residential, commercial, and transport infrastructure, however, no fatalities were reported. Estimated damages accumulate to approximately U.S. $29 million. The GEER reconnaissance effort, conducted between June 30th – July 4th, recorded geotechnical, geo-structural, and geomorphological observations of failures as well as successful mitigation of flood damage. In addition to traditional terrestrial photography and aerial imagery, the team collected (Light Detection Ranging (LIDAR) scanning, Structure for Motion (SfM) imagery, and Multispectral Imagery to establish point cloud models for case history analyses and post-reconnaissance failure analyses.

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Data Availability

- All photographs, Lidar data, SfM models are available through: https://doi.org/10.17603/ds2-m6zy-bv55
- Yellowstone National Park boundaries geospatial dataset is available online from Science Base at https://www.sciencebase.gov/catalog/item/4ffb3aebe4b0c15d5ce9fc0b.
- The watershed boundaries and stream centerlines were delineated from the Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) geospatial dataset using the Watershed Modeling System (WMS) software. The SRTM data are available online through https://www.earthdata.nasa.gov/.
- The USGS gauge locations geospatial dataset is available online from Science Base at https://www.sciencebase.gov/catalog/item/577445bee4b07657d1a991b6.
- Observed discharge and stage data are available from the National Water Information System (NWIS) at https://waterdata.usgs.gov/nwis.

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1 Introduction

1.0 Event Overview

During the month of June 2022, an anomalous rain event coupled with significant winter snowmelt in the Absaroka and Beartooth Mountain ranges of Montana and Wyoming produced an intense flood event that impacted the northern portion of Yellowstone National Park and numerous cities and communities to the north and east of the park. This event constituted the largest flood on record for this region, caused significant damage to infrastructure adjacent to the rivers and creeks and disrupted the lives of the thousands of residents in the region.

The Geotechnical Extreme Events Reconnaissance Association (GEER) deployed a team of volunteer researchers from multiple universities and consulting firms located around the country. Team members began arriving in the area on the evening of June 29, 2022 and left the area on July 4, 2022. At the time of the GEER reconnaissance, the National Park Service (NPS) was in contact with the GEER team but could not accommodate their request to gain access to the damaged areas inside of Yellowstone Park. GEER team members chartered a private flight to perform aerial surveillance of the damage inside the park but could not obtain terrestrial access for detailed observations and documentation of the damage. The GEER team continues to coordinate with professionals at NPS and other stakeholders and is planning to perform a Phase 2 reconnaissance that will document what remaining damage is still present among the ongoing accelerated reconstruction efforts within the park as well as outside of the park along the Yellowstone River.

This report presents a summarized analysis of geotechnical and geo-structural damage observed during the 2022 Southern Montana/Yellowstone flood event and concentrates on the observations collected in Southern Montana, focusing on flooded areas near the West and East entrance to the Yellowstone National Park.
Chapter 1 (the remainder of this chapter) will present a hydrological analysis of the flood events, followed by a summary of the GEER team's data collection efforts and methods (Chapter 2). All remaining chapters will present a summary of the team's respective field observations organized by river/creek (Chapter 3), and a summary the key observations and lessons learned from this extreme event (Chapter 4).

1.2 Watershed Description

Most of the areas in Yellowstone National Park drains to the Yellowstone River. There are several USGS river gauges in the park boundaries and in the downstream drainage area. Figure 1.1 presents a map of the park boundaries and the surrounding drainage area downstream. The park boundaries are outlined in red, selected USGS stream gauges are marked as orange dots, the delineated watershed boundary is outlined in black, and the delineated stream centerlines are marked with the light blue lines. Other rivers outside this delineated area are indicated with darker blue lines.

The delineated area represents the drainage area of the Yellowstone River which is approximately 11,000 square miles (mi^2). There are 27 USGS gauge locations marked that recorded hydrologic conditions in May and June of 2022. Most of these gauges are within the delineated region and some are in the surrounding area.

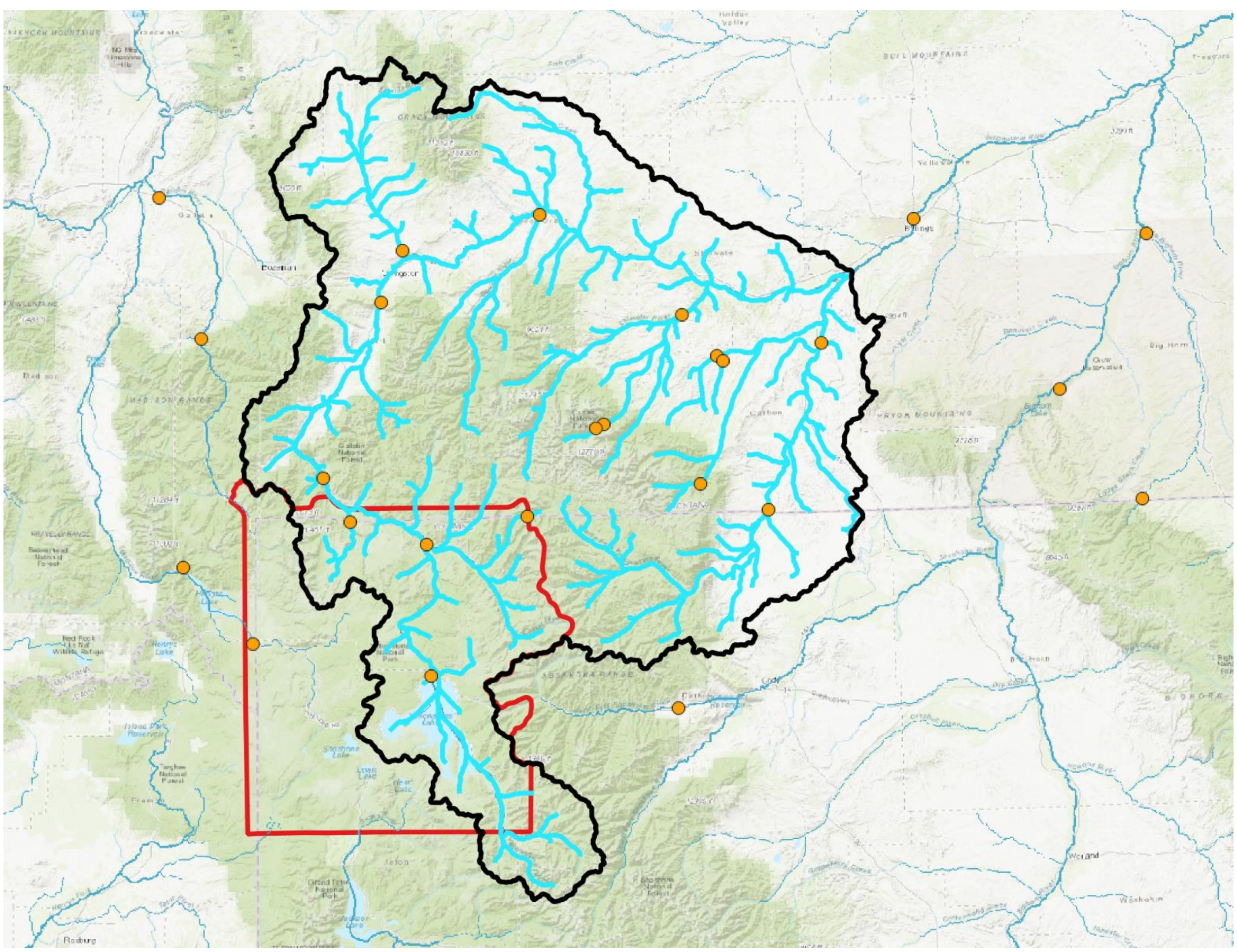


Figure 1.1: Map of Yellowstone Park boundaries (red), delineated hydrography, and USGS gauges (orange dots)

1.3 Flood Origin

In June of 2022 Yellowstone National Park experienced substantial floods triggered by consecutive rainfall and snowmelt events. These floods resulted in historically high-water levels that caused significant damage to the park infrastructure including roads, water and wastewater systems, power lines, and other facilities.

Beginning in late May and continuing through June, a band of tropical moisture, called an atmospheric river, brought several inches of rain/snow precipitation. This precipitation fell through much of northwestern Wyoming and south-central Montana (NASA 2022) and prolonged the period of high moisture culminating in extreme flooding beginning on June 11, 2022.

The rivers in and around Yellowstone usually experience higher flows during this time of the year driven by snow melt. In 2022, the snow melted somewhat more slowly than usual, resulting in a little more than typical amounts of snowmelt available during the anomalous May and June atmospheric river storms. Snowmelt and rainfall created heavy runoff and an extreme flooding. Imagery of the snowpack from the MODIS satellite is presented in Figure 1.2. The left panel imagery was captured on June 16, 2021 and the right panel on June 16, 2022. The 2022 imagery is greener which indicates more vegetation and soil moisture in addition to the larger white snowpack areas.

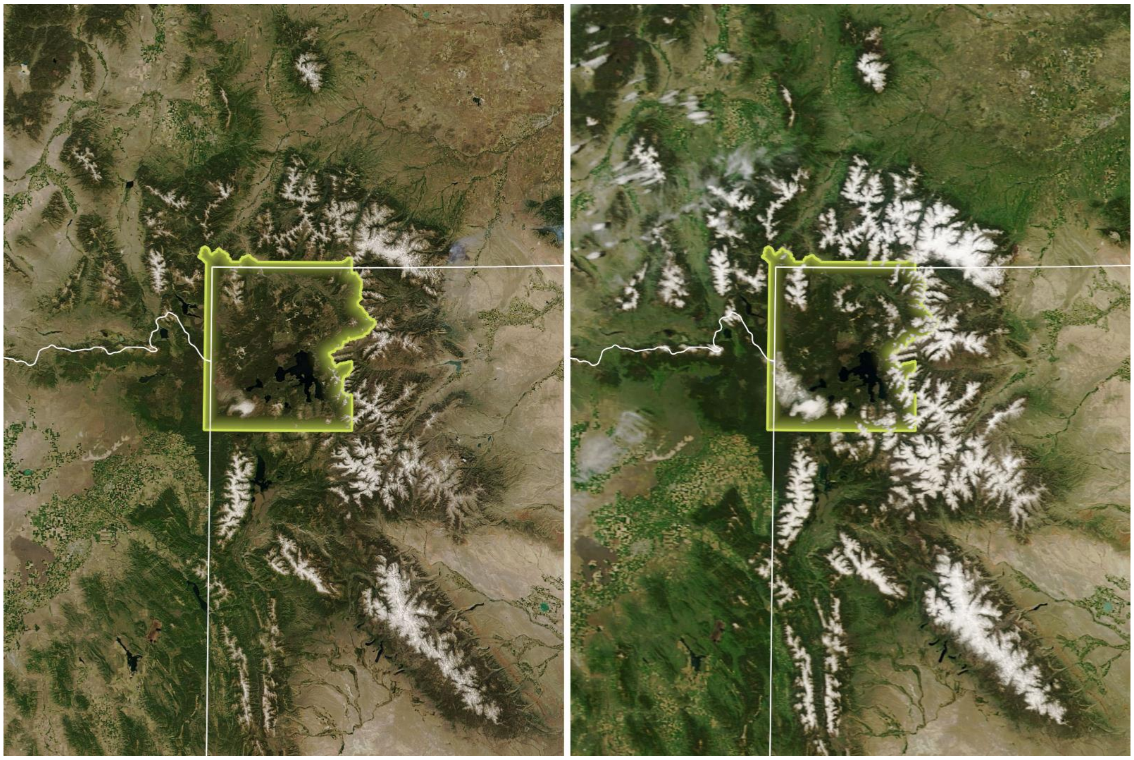


Figure 1.2: These images captured by the Moderate Resolution Imaging Spectrometer (MODIS) on June 16, 2021 (left panel) and June 16, 2022 (right panel) compares the snowpack one year apart (NASA 2022, accessed at https://earthobservatory.nasa.gov/images/150010/catastrophic-flooding-in-yellowstone)

While the Yellowstone Park area has been experiencing drought conditions (NIDIS 2022) precipitation was higher than normal beginning in April 2022. The increased precipitation resulted in a snowpack approaching the 30-year median by May. Figure 1.2 shows the large increase in the snowpack on June 16, 2021 (left panel) compared to June 16, 2022 (right panel). From June 10 to June 13, 2022, the Absaroka and Beartooth Mountain ranges received from 0.8 to 5 inches of precipitation, while at the same time there was between 2 and 5 inches of snowmelt at varying locations across the mountain ranges (NWS 2022a). This combined snowmelt and precipitation was equivalent to 4 to 9 inches of rainfall over a three-day period (NASA 2022). Because this occurred during a period of above-normal soil moisture and over such a short duration, much of that equivalent rainfall depth was available as runoff leading to significant discharge in the surrounding rivers.

Figure 1.3 shows soil moisture maps from May, approximately one month before the flood, for 2021 (left panel) and 2022 (right panel). These maps are based on NASA satellite imagery from the Crop Condition and Soil Moisture Analytics (Crop-CASMA) created using data from the Soil Moisture Active Passive (SMAP) mission and MODIS data for vegetation indices.

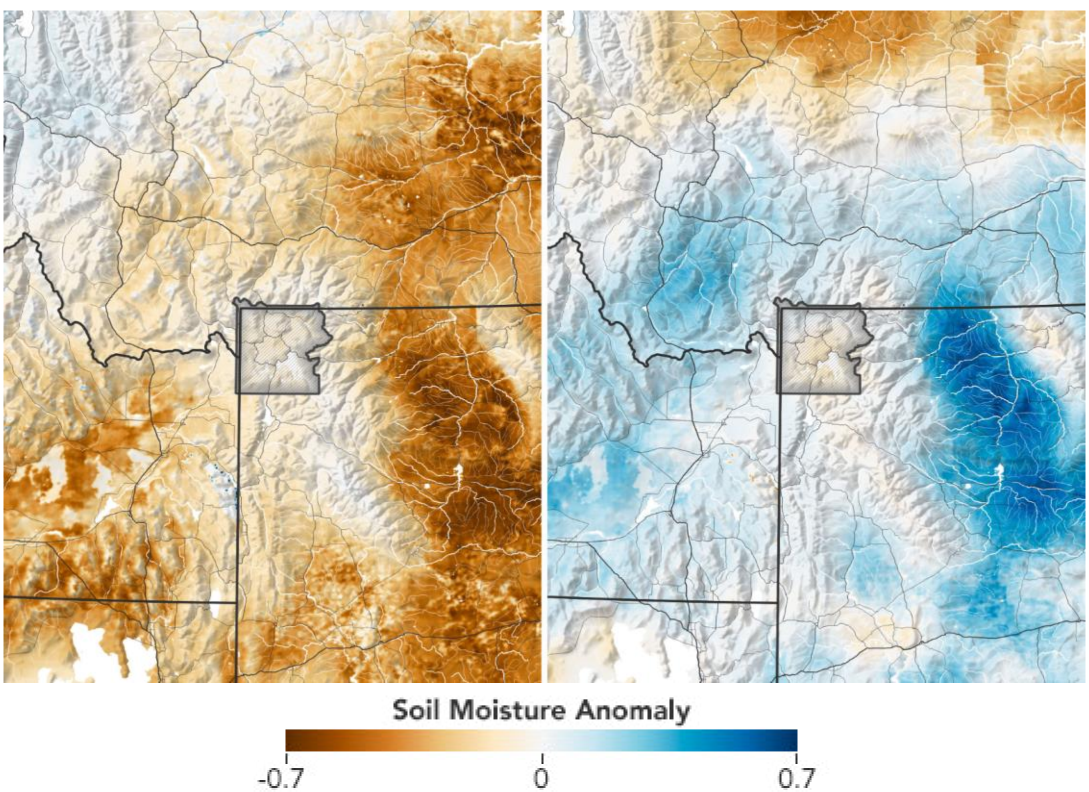


Figure 1.3: Soil moisture anomaly from May (about 1 month before the floods) for 2021 (left panel) and 2022 (right panel) showing the significant increase in soil moisture. (Image from NASA 2022)

Runoff created flood conditions in the Yellowstone, Stillwater, and Clarks Fork rivers and tributaries. Data from the National Weather Service (NWS 2022b) show a flood crest of 13.88 ft on June 13, 2022, at the Corwin Spring Gage on the Yellowstone River. This is 2.38 feet higher than the previous record of 11.50 feet set on June 14, 1918. These are flows of 49,400 cubic feet per second (cfs) and 32,200 cfs for the June 2022 and June 1918 events respectively, based on rating curve data from the USGS National Water Information System (USGS 2022).

1.4 Peak Flow Statistics

A summary of the 2022 peak flows recorded at relevant gauges is given in Table 1. The table lists the USGS gauge number, the peak flow and date and time when it occurred, the estimated return period of the peak flow using the Gumbel Type 1 extreme value distribution, the number of years of gauge records available that were used to estimate the return period, and the rank of the 2022 peak flow in the record of annual peak flows available for the gauge. Estimated return periods become more accurate as more years of gauge records become available so gauges with shorter periods of record may provide less meaningful return period estimates.

A peak flow rank of 1 means that the peak flow observed during the June 2022 floods were the largest ever recorded by that gauge. During the 2022 floods, several gauges recorded one of the largest, if not the single largest flows ever measured. Most gauges experienced peak flows on June 11 or at some point during the following week. A few gauges did not peak until later in the month. These summary data confirm that the floods that occurred during June were some of the largest ever recorded.

Table 1: Peak flow statistics for selected USGS gauges in the Yellowstone watershed during the May and June 2022 floods

Gauge Number	Peak Flow (cfs)	Peak Date	Return Period	Years Available	Peak Flow Rank
6214500	84,000	2022-06-15 09:30	809	34	1
6192500	55,200	2022-06-13 22:15	1000+	28	1
6191500	49,400	2022-06-13 13:45	1000+	32	1
6207500	23,900	2022-06-13 12:00	1000+	33	1
6205000	23,200	2022-06-13 12:30	1000+	33	1
6208500	21,900	2022-06-14 05:45	636	33	1
6188000	20,900	2022-06-13 07:30	565	34	1
6279940	11,900	2022-06-13 16:15	779	34	1

6200000	11,100	2022-06-13 18:38	876	29	1
6043500	8,980	2022-06-13 16:45	1000+	29	2
6052500	8,640	2022-06-14 10:30	771	29	2
6287000	7,230	2022-06-18 08:45	18	34	12
6043120	6,370	2022-06-13 15:15	991	4	1
6186500	5,270	2022-06-29 13:15	37	32	13
6038500	3,330	2022-06-15 00:00	557	29	4
6191000	2,980	2022-06-13 11:30	1000+	33	1
6037500	2,580	2022-06-13 15:00	501	29	3
6209500	2,570	2022-06-13 00:45	1000+	23	1
6294000	1,620	2022-06-02 03:15	8	29	8
6289000	1,360	2022-06-11 22:00	32	29	12
6187915	1,280	2022-06-11 22:30	832	24	2
6195600	1,230	2022-06-06 12:15	7	31	24
6204070	1,200	2022-06-19 11:20	167	16	3
6197800	1,090	2022-06-13 07:30	1000+	3	3
6204050	1,040	2022-06-19 10:00	116	18	3
6211000	703	2022-05-31 05:30	4	29	12
6211500	249	2022-05-31 01:45	3	18	10

Figure 1.4 presents a map of gauges with selected hydrographs included in Table 1. Figures 1.5 through Figure 1.11 show gauge data for these gauges from the list presented in Table 1. Each figure contains a top and bottom panel. The top panel shows a hydrograph of the gauge measurements from the middle of May through the end of June. The bottom panel is a scatter plot of the annual peak flows recorded for every year of gauge data available, including 2022. The horizontal red line on both panels marks the peak flow measured during the 2022 flooding.

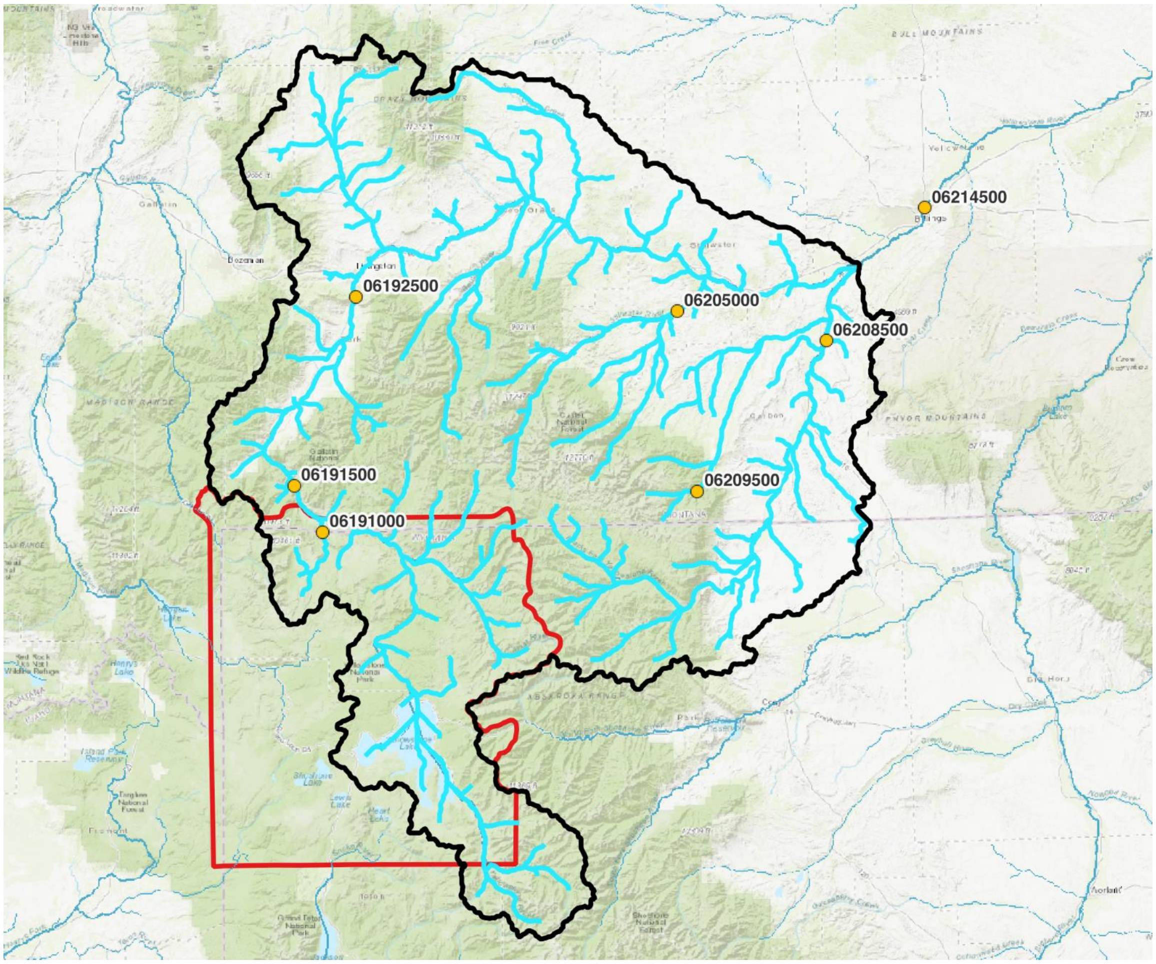


Figure 1.4: Map of selected gauges with hydrographs provided in this report

Figure 1.5 presents these graphs for USGS gauge 06214500 at Billings, MT which measured the largest peak flow on record. While the largest storm and floods began on June 11, the hydrographs show that the river had an increasing discharge beginning in mid-May. There are notable surges occurring following the storms on May 30, smaller storms in early June, and the largest surge following the storm beginning on June 11. After the peak on June 15, another smaller peak occurred on June 20. The peak from June 15 is the largest ever recorded but is of similar magnitude to the peak from 1997. Similar trends are visible in each of the other figures with different flow magnitudes and slightly different timing.

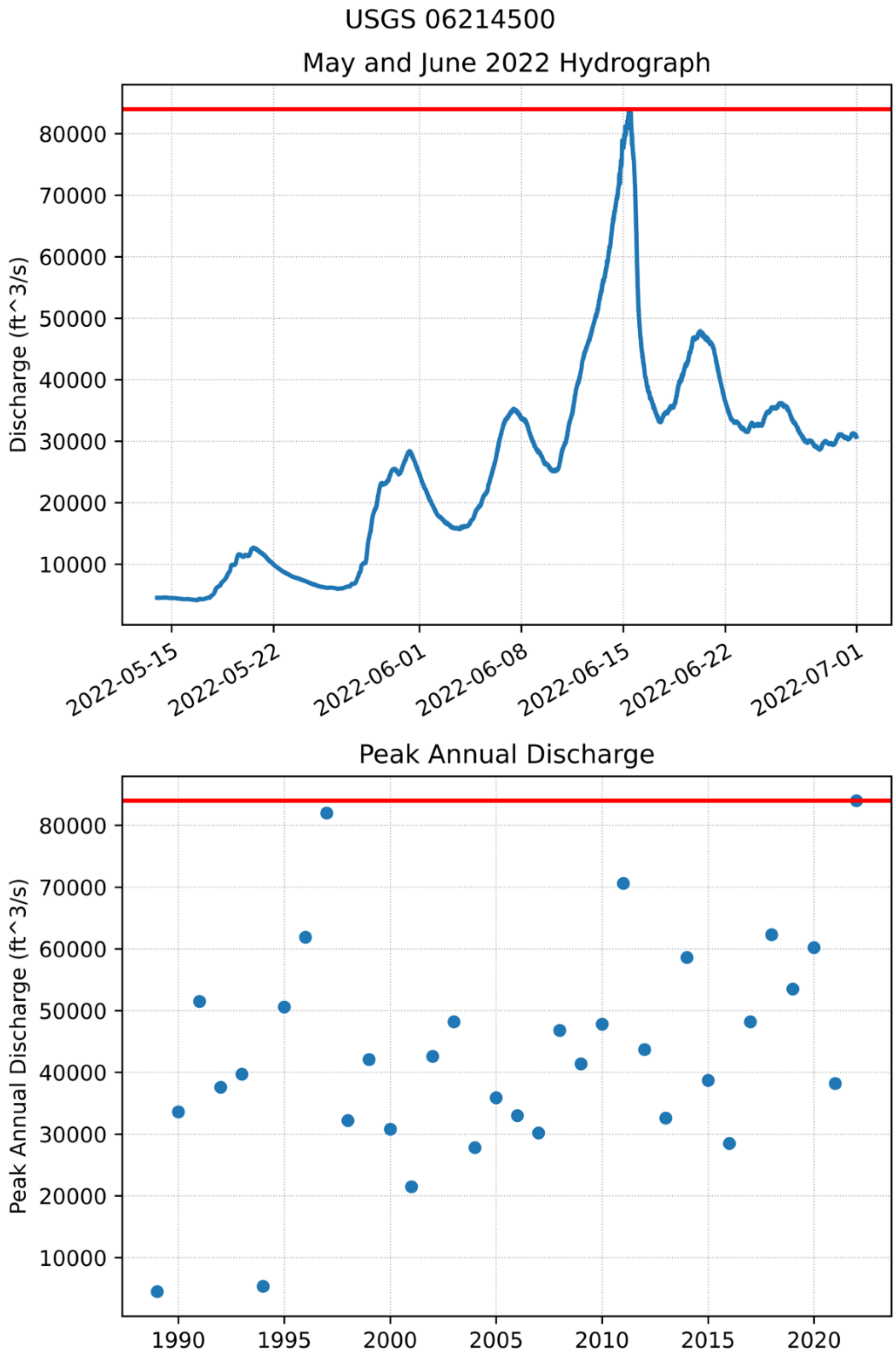


Figure 1.5: USGS Gauge 06214500 hydrograph on the Yellowstone River (near Billings) from the 2022 floods and a scatterplot of annual peak flows.

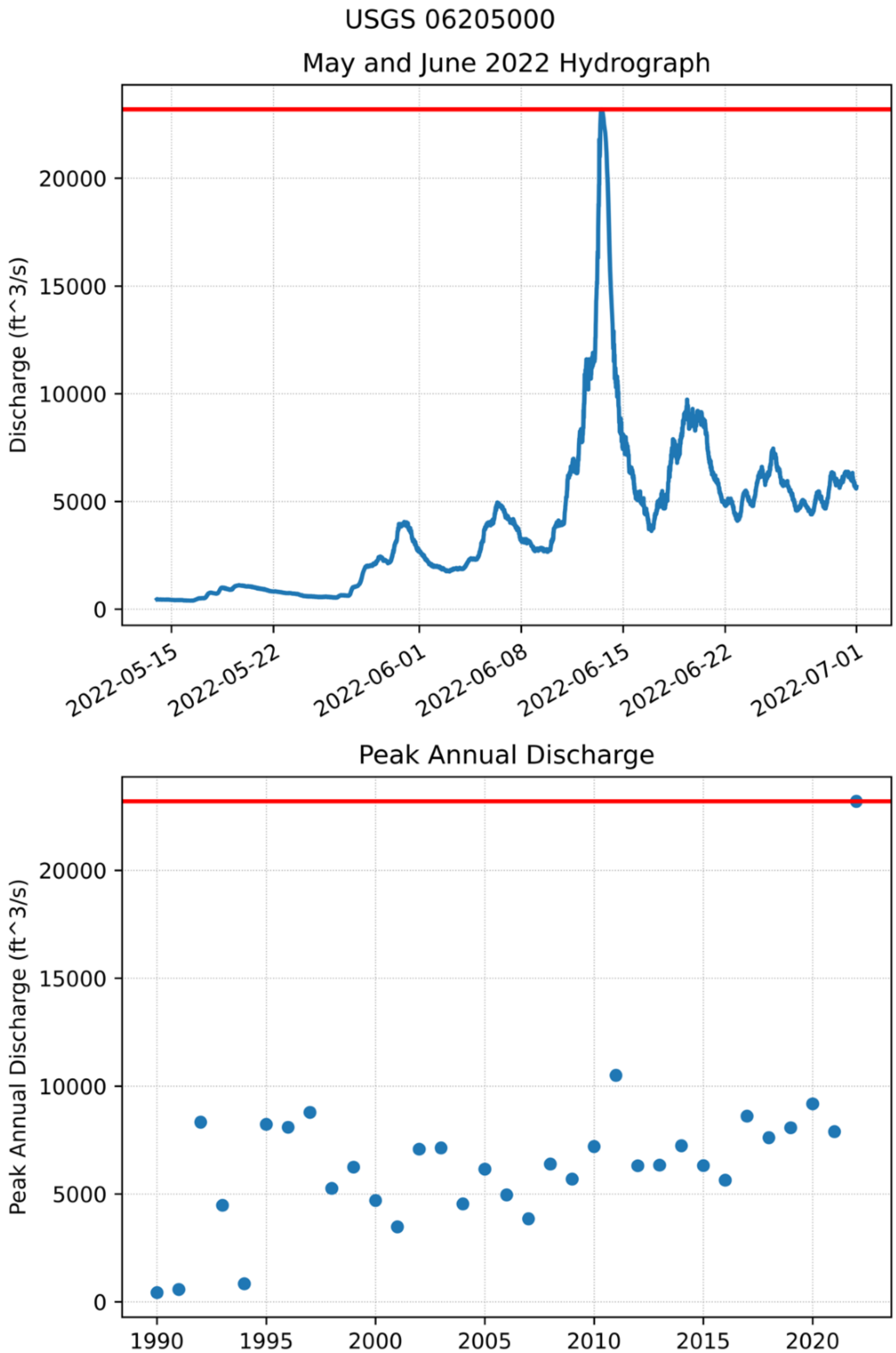


Figure 1.6: USGS Gauge 06205000 hydrograph on the Stillwater River (near Absarokee) from the 2022 floods and a scatterplot of annual peak flows.

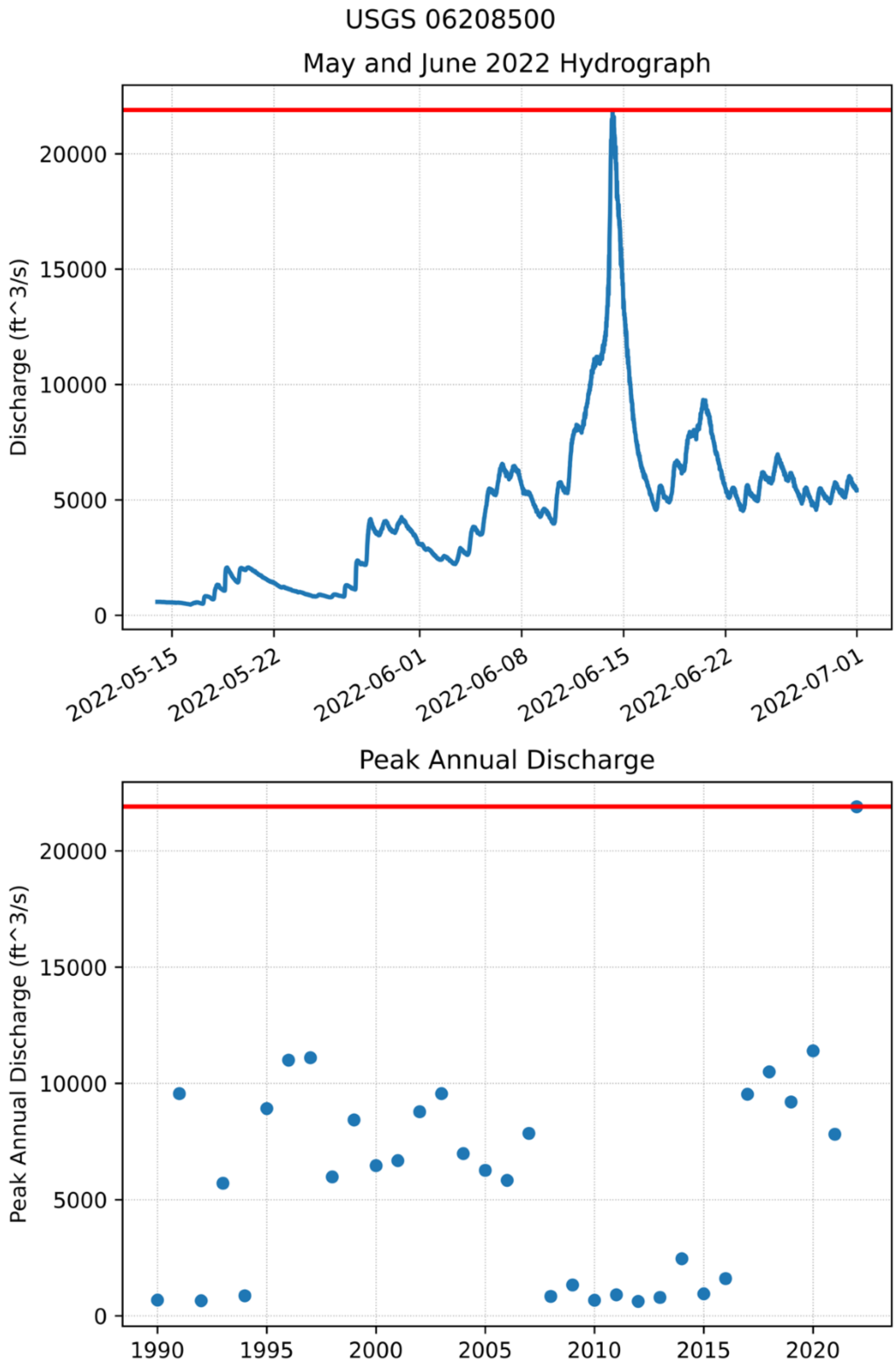


Figure 1.7: USGS Gauge 06208500 hydrograph on Clarks Fork of the Yellowstone River (near Bridger) from the 2022 floods and a scatterplot of annual peak flows.

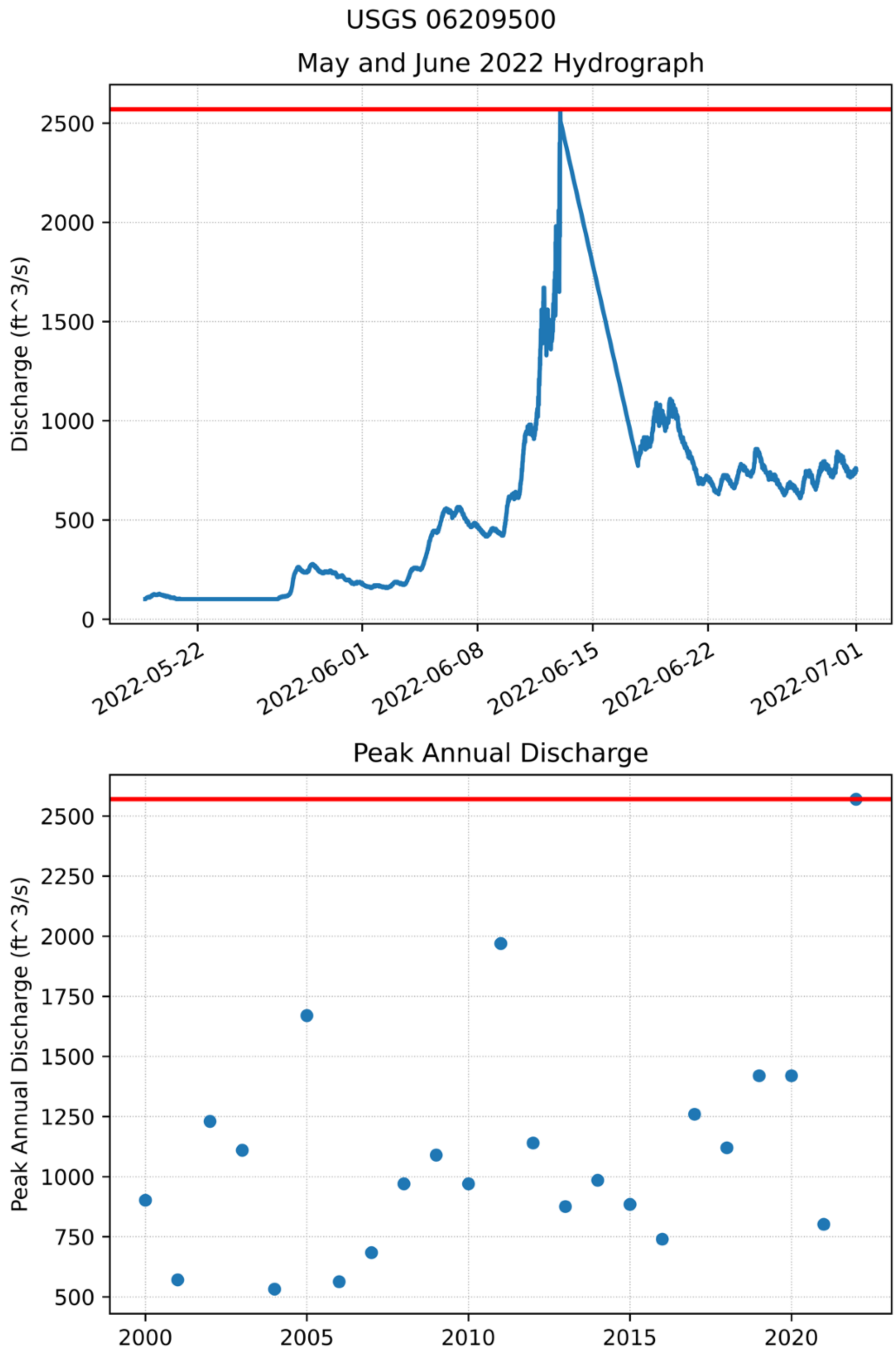


Figure 1.8: USGS Gauge 06209500 hydrograph on Rock Creek (near Red Lodge) from the 2022 floods and a scatterplot of annual peak flows.

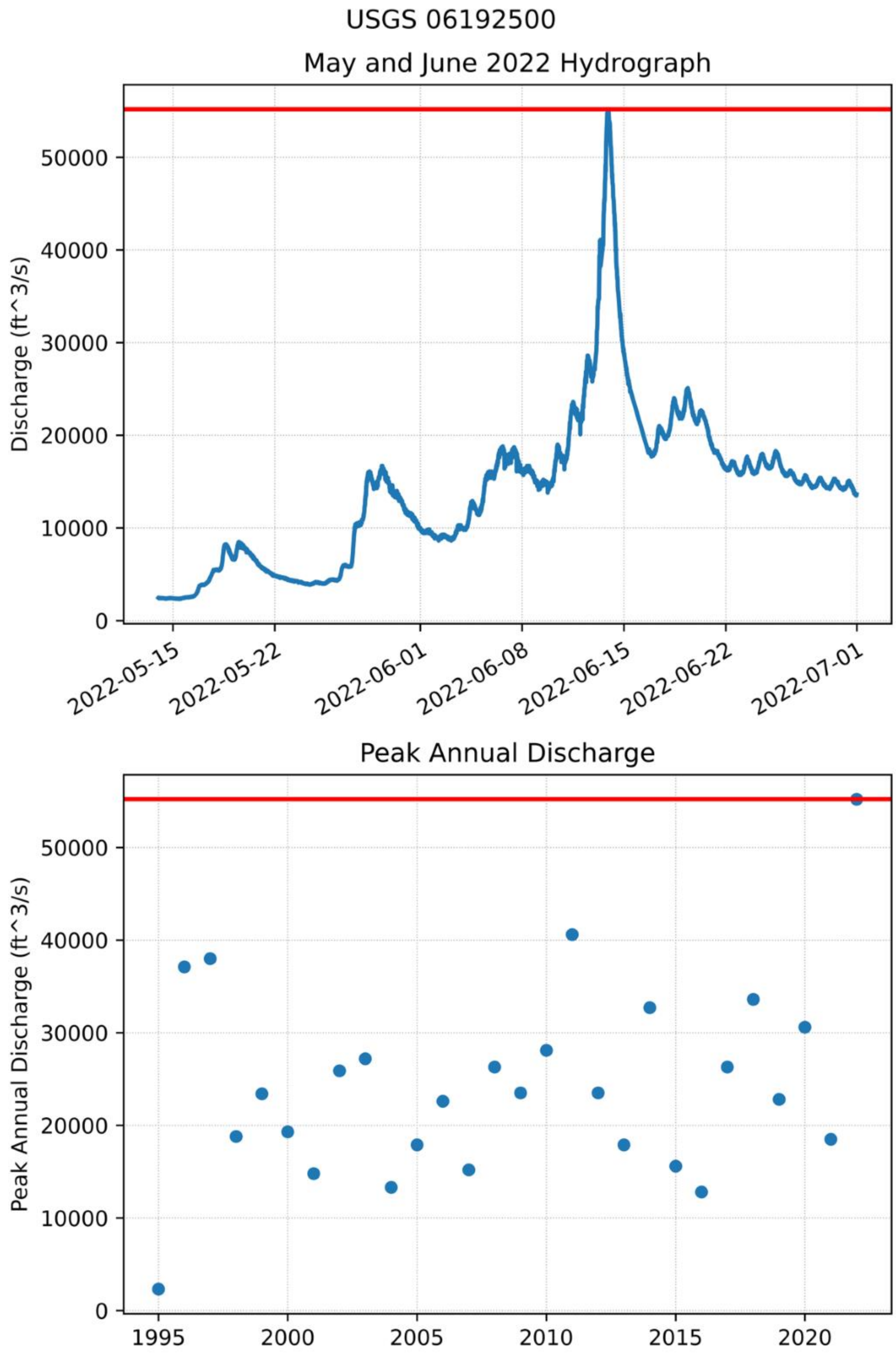


Figure 1.9: USGS Gauge 06192500 hydrograph on the Yellowstone River (near Livingston) from the 2022 floods and a scatterplot of annual peak flows.

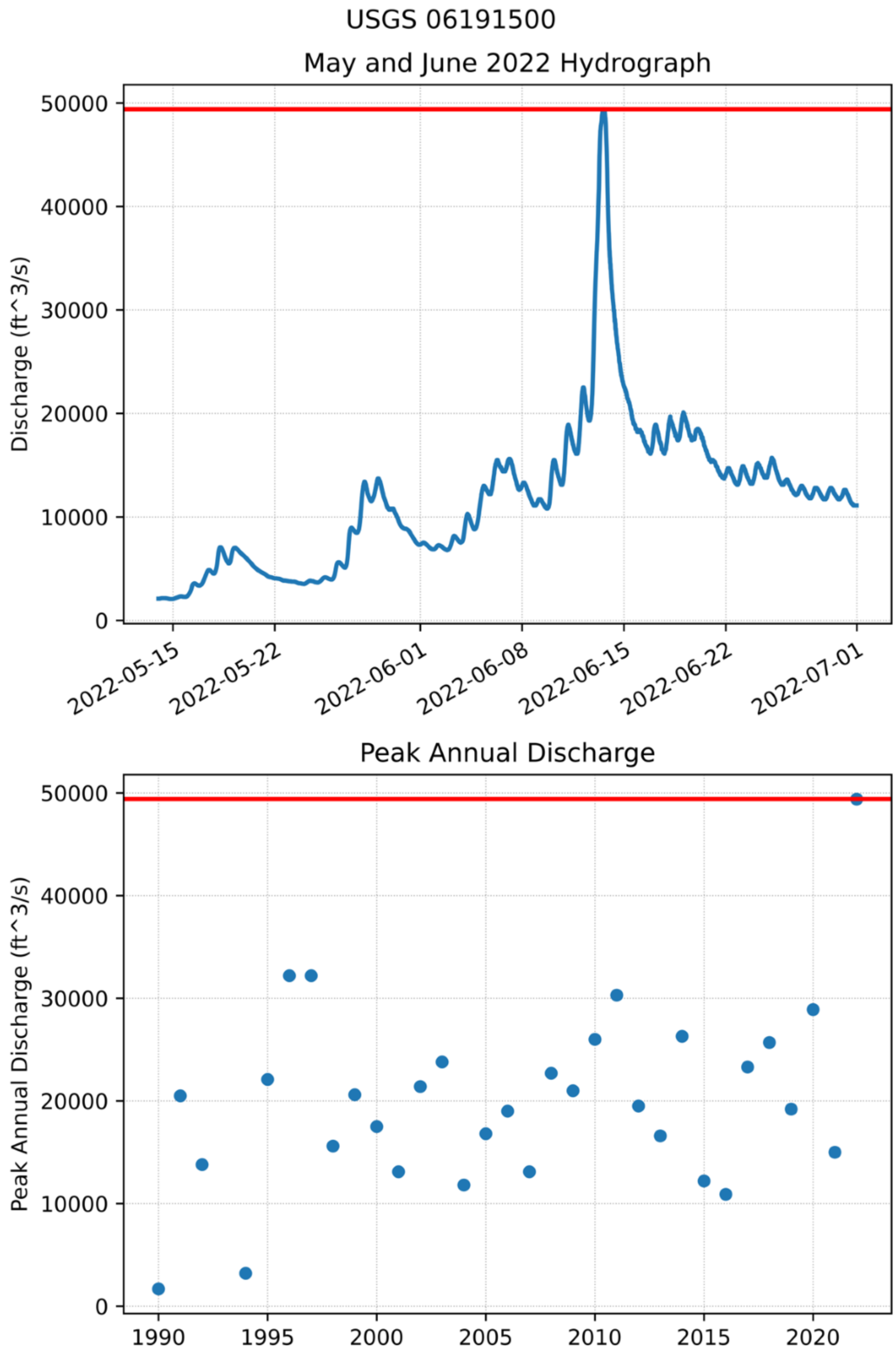


Figure 1.10: USGS Gauge 06191500 hydrograph on the Yellowstone River (near Gardiner) from the 2022 floods and a scatterplot of annual peak flows.

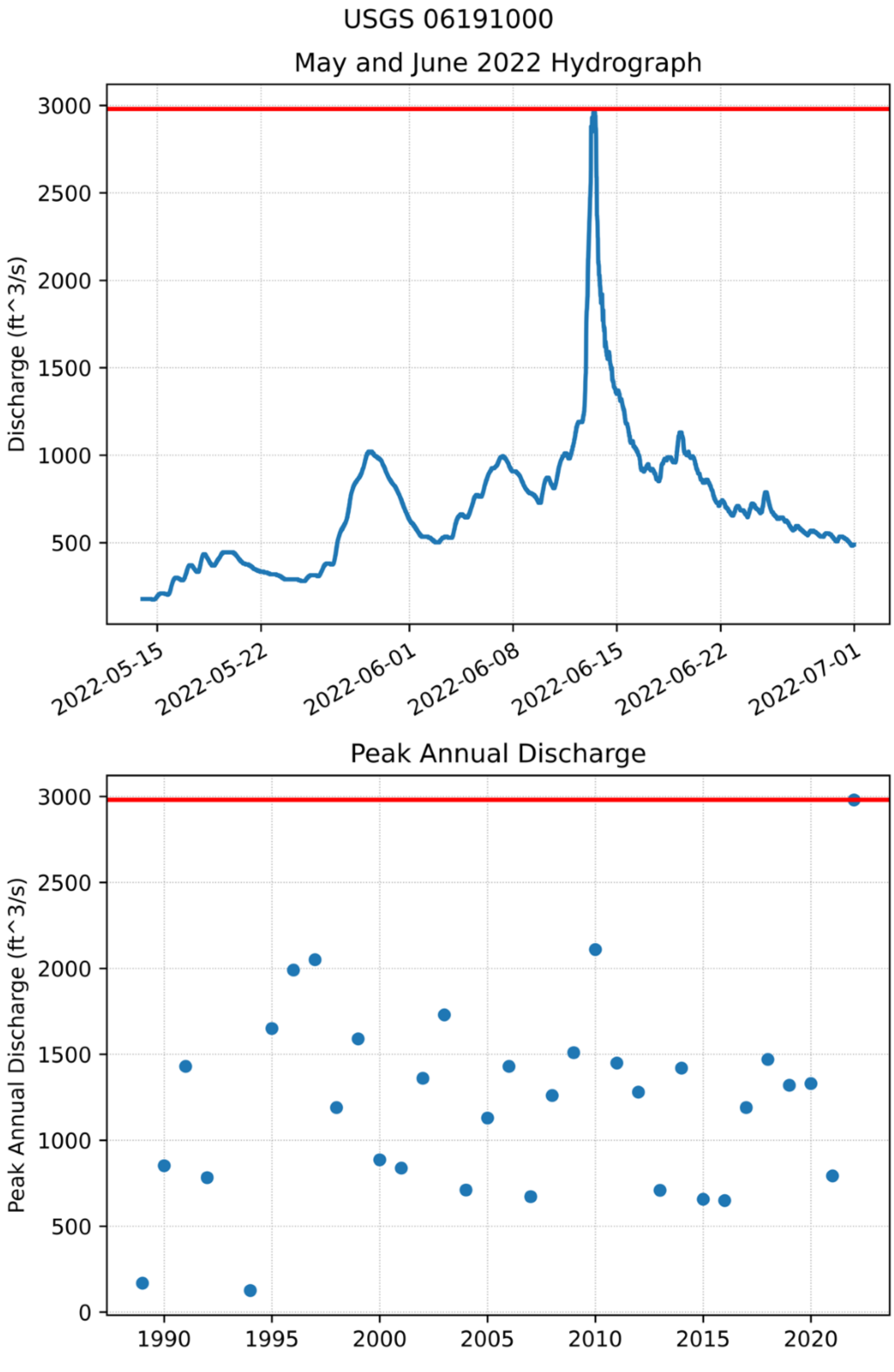


Figure 1.11: USGS Gauge 06191000 hydrograph on Gardiner Creek (near Mammoth) from the 2022 floods and a scatterplot of annual peak flows.

1.5 Geology

1.5.1. Geology near North-West Yellowstone

The geology of the north slope of the greater Yellowstone Area and the Beartooth Mountain Range Massif is critical to understanding infrastructure damage in the flooded regions of Southern Montana. Most damage near bridges and highways visited by the GEER team were located on soil sites. The majority of the canyons through which the rivers and creeks flow (i.e., the Yellowstone River and its tributaries as well as the Rock Creek river and its tributaries) are glacial valleys or have a significant history of glaciation. This has resulted in generally U-shaped valleys with thick terraces of rounded gravels, cobbles and boulders in a largely sand matrix that the current channels incise. When rivers cut through rock, the rock may be Archean igneous and metamorphic formations closer to the Massif and younger Missisippian to Cretatous limestones, shales and sandstones. Frequent young igneous formations abound due to the area being near Yellowstone Caldera.

Alluvium in the canyons and river valleys is generally holocene, while glacial deposits are generally pleistocene with a few areas of more recent holocene activity. Alluvium is often in terrace deposits. Terrace deposits often include clasts and calcite cements. Terrace deposits may be several hundred feet thick, as are moraines and glacial outwash. Clasts, gravels, cobbles and boulders in the alluvium are mainly granitic igneous rocks, granitic gneiss, schist, volcanic rocks, and quartzite, with lesser amounts of limestone and sandstone.

Livingston sits north of the foothills on an alluvial plain bordered by Holocene pediment gravel deposits, with a ridge of Andesitic siltstone and sandstone with beds of tuff and bentonite to the south, separating Livingston from the Paradise Valley through which the Yellowstone River flows north out of the Park. Carters Bridge, which sits at the north end of the Paradise Valley and most of the paradise valley north of Carbella, is situated in midst of glacial outwash deposits and alluvial terraces.

South of Carbella, the Yellowstone River passes through a constricted gorge, the Yellowstone River Gorge. This gorge is where the river has cut through an east-west salient of Archean schist and gneiss. This rock is highly deformed and includes minor quartz beds (Lopez and Reiten, 2003). From Gardiner to the Yellowstone River Gorge, the Yellowstone River flows through alluvial terraces, basaltic rockslide deposits and frequent mass-wasting landslides. Gardiner itself sits on a complex of alluvial and glacial terraces intermixed with lava flows, travertine, and basaltic rockslides. The Yellowstone River in Gardiner cuts through the alluvial and glacial terraces, with the lava flows and rockslide deposits up on the hillsides. Overall, the Paradise Valley and most of the Gardiner area (to the south of the Gorge) is a complex of alluvial terrace deposits, glacial terraces, glacial outwash, and Andesite vent facies, sills, flows and breccias (Lopez and Reiten, 2003)

1.5.2. The Geology of North-East Yellowstone

Terrace deposits dominate the landscape in and around the town of Red Lodge, on Rock Creek. Areas with scour and bridge damage in the town of Red Lodge are primarily alluvium of the youngest alluvial terrace. Some mine tailings have been placed in and around town, generally along the east side of Rock Creek. Some small, mapped landslides on the east side of Rock Creek intersperse with the tailings through the town in the areas visited by the GEER team. An outcrop of the Tongue River member of the Fort Union formation runs along or above the east side of Rock Creek through the area visited by the GEER team and separates the youngest terrace deposits from older terrace deposits on the bluffs above town. This member of the Fort Union formation is medium-grained sandstone interbedded with brownish-gray carbonaceous shale and siltstone and coal beds (Lopez 2005).

The bottom of Rock Creek Canyon through which Rock Creek cuts consists of glacial till. This Pleistocene aged till that includes unsorted clay is dominated by cobble to boulder-size material transported and deposited by glaciers. Clasts are predominantly Archean metamorphic gneiss with lesser amounts of quartzite, igneous rocks, dolomite, and limestone (Lopez 2005). The mountains the GEER team visited along Rock Creek Canyon are primarily Archean gneiss. There are minor alluvial fans that have developed in the recent Holocene in Rock Creek Canyon from minor side drainages. These minor alluvial fans include layers of silt, clay, and fine sands. Clays are derived from the parent gneiss of the surrounding mountains.

The town of Nye and the Mountain View Mine complex are in the foothills of the Beartooth Mountains on the Stillwater River. GEER team sites along the Stillwater River in the foothills are a mix of glacial till and moraine and alluvial terraces tight against the Stillwater Complex, composed of zones of Archean anorthosite, gabbro, norlite, bronzitite, and peridotite. The moraines and terraces are thick in the steeply dipping canyon valleys of the foothills, as the rock dips at approximately 50 degrees below the infill sediments of these glaciated canyons (Geraghty 2013).

The foothills to the Beartooth Mountain Massif extend north towards the Yellowstone River Plain. Between the foothills and the Yellowstone River Plain are wide areas of hills and open valleys through which Rock Creek, East and West Rosebud Creeks, the Stillwater River, and Clarks Fork flow as they head north from the Beartooth Mountains to the Yellowstone River. Communities visited by the GEER team such as Roscoe, Fishtail, Beehive, Fromberg, and Absorokee sit on these tributaries in this hilly transition zone between the foothills and the Yellowstone River plain to the north. These hills are younger sedimentary rocks compared to the mountains and foothills being Cretaceous to early Paleocene. Mostly composed of the Fort Union Formation, Judith River Formation, Hell Creek Formation, and the Sliderock Mountain Formation (igneous), the hills are cut by the north flowing tributaries. The valleys of the tributaries are infilled with terrace deposits, with areas of exposed Bearpaw Shale. These various sedimentary formations are typically mudstone, sandstone and shale with coal beds. These are fossil rich formations, brittle and easily eroded. The Sliderock Mountain Formation is mostly andesite breccia (Geraghty 2013).

Boulders within glacial moraines, tills and alluvial terraces throughout the area impacted by the floods are rounded and range up to 3-m in diameter. Boulders 0.5 to 1-m diameter are common in these deposits. Some areas, such as along the Yellowstone River in the Gardiner area and the Paradise Valley have smaller maximum boulder sizes in deposits, and more cobbles. Other areas, such as Roscoe, Red Lodge, and Nye have larger maximum boulder sizes. The exception to the rounded boulders are in the Yellowstone River Gorge south of Carbella in the Paradise Valley. Boulders in this area are recently broken from the parent rock and are blocky to angular. Maximum boulder size in the Yellowstone River Gorge south of Carbella is 5-m. The large distance from glacial till deposits and observed boulder impacts to bridges in areas such as the Beehive Bridge on the Stillwater River show that fluid velocities in the flood event carried boulders distances of up to two kilometers.

1.6 Flood Impact Overview

Several towns near the State border of Montana and Wyoming, just north of Yellowstone National Park were isolated by the floods. These include the town of Gardiner in the Northwest of Yellowstone National Park (NW Park Entrance) and Cooke City in the Northeast of the Yellowstone National Park (NE Entrance) (Figure 1.12). The floods washed out roads and bridges, destroyed many homes (Figure 1.13) and caused flood-damage to hundreds more. Red Lodge, Montana, lost bridges and historic downtown businesses through flooding of Rock Creek. In the northern part of the park, the Gardner River flows through a canyon, which concentrated the flood waters causing the river to cut a new course. This washed out the road between Gardiner and Yellowstone Park Headquarters at Mammoth. Figure 1.12 shows an example of a channel change that washed-out part of the road at the northwest entrance. In narrow areas, the large flows caused the rivers to cut into the banks and change the location of the river center lines.

Figure 1.12: The Northeast Entrance Road washout near Trout Lake Trailhead showing the new river course in the canyon after the flood. (Yellowstone National Park 2022)

Figure 1.13: Park employee housing being washed downstream by the Yellowstone River. (Yellowstone National Park 2022)

2. Data Collection

Reconnaissance data were collected through unmanned aerial vehicle (UAV) and terrestrial photography, terrestrial light detection and ranging (LiDAR) scans, multispectral photography, UAV-derived structure-from-motion models, satellite imagery, on-site measurements (manual), material sample collection (shovel & bags), and on-site interviews. The documentation included geotechnical and structural damage, water levels (taken at visible watermarks) on buildings, general information on flood progression and water level rise, infrastructure damage, riverbed erosion and sediment redeposition, scour, utility network performance, and first response information.

Tables 2.1 - 2.3 provide a summary of data collected through the technologies described above, along with the location, GPS coordinates and an image preview of the data.

LiDAR scans were performed at nine locations, primarily in and around Red Lodge, MT Gardiner, MT, and at the Beehive bridge along the Stillwater River, MT. LiDAR is an optical remote-sensing technique that uses laser light to densely sample the surface of the earth, producing highly accurate 3D measurements. LiDAR scans were collected using a 2-km range Maptek I-Site LR3 long-range scanner. Point clouds were processed using the Maptek Point Studio software. Additional cleaning and processing of point cloud files were done in the open-source software CloudCompare. Additional LiDAR scans were obtained using a ground-based Leica RTC 360 medium-range laser scanner and processed using Cyclone 360 (proprietary software for Leica scanners).

Aerial multispectral imaging was performed at the 9th Street Bridge in Red Lodge site and the Yellowstone River Gorge site below Gardiner. Multispectral images were collected using a MicaSense Altum-PT multispectral and thermal camera which was either mounted on a UAV or used as hand-held application. A DJI P4 multispectral imaging camera was also used with a Phantom 4 UAV. Images were manually processed in Python using MicaSense multispectral image processing libraries. Hand-held multispectral imagery was taken in the town of Red Lodge along Haggin Ave S and Broadway Ave S. streets.

UAV imagery was collected both through double-gridded autopilot missions and manual image collection to document flood damage. Drone images were collected using DJI Mavic2, Mavic Pro, Inspire2, Matrice, and Phantom multi-spectral drones. Three-dimensional SfM models were created using ContextCapture by Bentley.

Table 2: Overview of Lidar Scans during the reconnaissance visit (obtained with Maptek LR3)

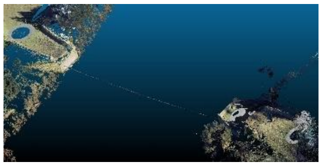
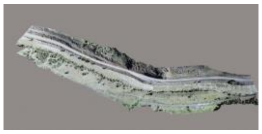
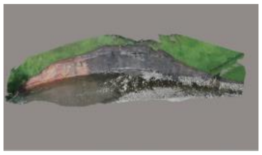
Type of Structure	Location (City/Country)	GPS coordinates	Photo
Gardiner Montana Utility Lines (Pipeline Crossing)	Gardiner, MT	45.0330, -110.7122	
Gardiner, Confluence Gardner and Yellowstone River	Gardiner, MT	45.0298, -110.7003	
Gardiner: HWY 89 House erosion	HW 89, SW Montana	45.0355, -110.7205	
Carbella Bridge (Tom Miner Bridge)	HW 89, SW Montana	45.2041, -110.9016	
Cinnabar Bridge	HW 89, SW Montana	45.1116, -110.7939	
9th St. Rock Creek Bridge	Red Lodge, MT	45.1889, -109.2431	
Broadway, Park/ 19th street intersection, Red Lodge	Red Lodge, MT	45.1801, -109.2463	

Table 3: Overview of UAV-based SFM models during the reconnaissance visit

Type of Site/Structure	Location (City/State)	GPS coordinates	Photo	HTML Link
Beartooth Highway/ Rock Creek Scour Scarp	South of Red Lodge, MT	45.0692°N 108.3896°W		Link Here
Rock Creek Bridge Collapse	South of Red Lodge, MT	45.0861°N 109.3308°W		Link Here
Nye Road / Stillwater River Scour Scarp	Southwest of Nye, MT (next to Stillwater Mine)	45.3933°N 109.8711°W		Link Here
Yellowstone River in North Gardiner	Gardiner, MT	45.0336°N 110.7144°W		Link Here
Rockfall north of Gardiner	North of Gardiner, MT	45.1724°N 110.8750°W		Link Here
Flooded Portion of Red Lodge	Red Lodge, MT	45.1822°N 109.2445°W		Link Here

9th Street Scarp	Red Lodge, MT	45.1897°N 109.2415°W		Link Here
9th Street Bridge Collapse and Scarp	Red Lodge, MT	45.1890°N 109.2433°W		Link Here
Flooded Area in Roscoe, MT	Roscoe, MT	45.3510°N 109.4956°W		Link Here
Double Bridge Washout in Fishtail, MT	Fishtail, MT	45.4805° N, 109.454° W		
Adjacent Railroad and Highway Bridges	Livingston, MT	45.6750°N 110.5368°W		Link Here
Cinnabar Bridge	Cinnabar, MT	45.1118°N 110.7925°W		Link Here

Beehive Bridge	North of Nye, MT	45.50333°N -109.6524°W		
Carter Bridge	Livingston, MT	45.5969°N 110.5674°W		
HW 308 Bridge	Red Lodge, MT	45.1740°N 109.2500°W		
Yankee Jim Picnic Area	Gardiner, MT	45.1682°N 110.8550°W		

3. Field Damage - Summary of Key Observations

3.1. Observations along the Yellowstone River in the Paradise Valley

Figure 3.1 shows a map with specific locations at which damage was observed and documented along the Yellowstone River between Gardiner and Livingston Montana, known regionally as the Paradise Valley. From Yellowstone Lake, through Gardiner, and to Livingston, the Yellowstone River flows north. In Livingston, the river takes a bend and turns east and flows through the Yellowstone River Valley towards Billings, Montana and eventually merges with the Missouri River.

As the GEER team traveled from Billings Montana up-river, very high water and debris were observed on the river, but little to no visible damage. Once the river enters Livingston, the river flows through a wide, flat, plain. The channel is frequently braided with ample room for the river to migrate, as infrastructure is sited and designed to allow the river to move with few restrictions. On the Yellowstone River Plain, large bridges have several spans over the river bottoms so that the river can move, erode, and deposit sediments well away from abutments. However, south of Livingston the river is more constricted, with shorter bridges and restrictions to the river due to the narrower geography of the Paradise Valley. Therefore, damage frequency and magnitude increased in the upstream direction. While the Yellowstone River caused little to no damage in Livingston, noticeable erosion, large-scale sediment redeposition, damage to bridge and foundation infrastructure as well as damage to utility networks and residential housing increased as the team traveled south through the Paradise Valley and approached the town of Gardiner. A map with specific sites exhibiting noticeable flood impacts are depicted in Figure 3.1.

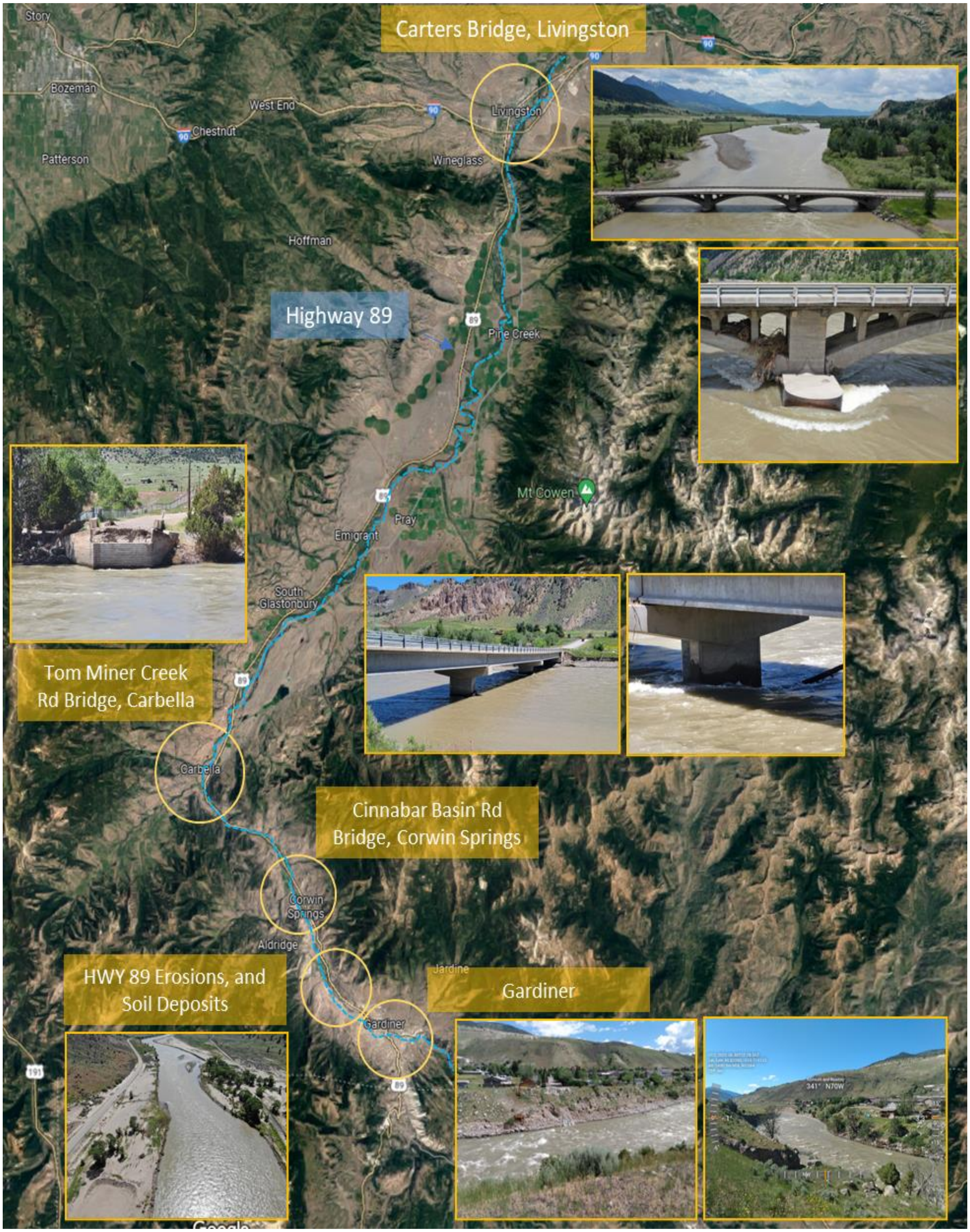


Figure 3.1: Locations with major flood related observations

3.1.1. Livingston Area

Livingston is a historic train town founded in the late 1880s and is considered the "Original Gateway City to Yellowstone National Park". It is located an hour's drive north of Yellowstone National Park, and right along the Yellowstone River, encompassing an area of 5.17 sq. miles and approximately 8000 inhabitants. Livingston is part of the wide, flat Yellowstone River Plain between Livingston and Billings. The GEER team visited four bridges in the Livingston area (Figure 3.2 - 3.3). All four bridges remained structurally intact, and overall minimal damage was observed in the Livingston area.

3.1.1.1 Bridge at 9th Street Island Drive

Figure 3.2 depicts the bridge at 9th street drive across the Yellowstone River. The bridge is a two-span reinforced concrete bridge; embankment slopes were stabilized with rocks. This bridge (marked for inspection by authorities) did not show any visible damage. Unlike other bridges upstream with saw boulders armoring the abutments and approaches washed away by the flood, flow velocities had dropped by the time the floods reached this bridge and boulder armoring was not affected or compromised. A new gravel bar was deposited at the bridge, with "dirty" silty and sandy sediments intermixed with the gravels, again indicating lower fluid velocities by the time the river reached this location, after several km of flat grades in the channel and a wider channel compared to other bridges in the Paradise Valley.

Figure 3.2: Bridge @ 9th street/Yellowstone during GEER visit. An extra span allows for the river to move between the banks and erode and deposit sediments freely. Note the new gravel bar deposited from the recent floods. Also note the "dirty" nature of the bar, indicating flow velocities were low enough for finer sediments to deposit at this bridge in the flood. (45.64970166034406, -110.56177707651814).

3.1.1.2 HWY 90 Bridge at Island Park

The HWY90 Bridge at Island Park (Figure 3.3.) was structurally stable and showed no signs of damage. The surrounding embankments were overtopped, and debris (sediments and tree logs) were deposited along various areas around the bridge. This is a large steel bridge, with 3-m freeboard above the typical spring river water surface elevation. It is an elongated bridge, with extra spans across the river bottoms. These extra spans allow for some riverbed migration with immediate impact on the bridge.

Figure 3.3: HWY 90 crossing of the Yellowstone River. Of particular interest are spans over dry river bottoms, which allow the river to migrate within the floodplain (45.64447387617702, -110.56115186026274).

3.1.1.3. I-90 Business Route and Adjacent Railroad Bridges

I-90 Business Route is the main business artery through Livingston and provides business access to I-90. It therefore has significant economic importance to Livingston and the residents there. A four-span bridge (45.6749 N, 110.5368 W) crosses the Yellowstone River on the I-90 Business Route. An adjacent two-span truss railway bridge constructed in the 1890s is located approximately 58 m to the north of the highway bridge. An image of the bridges is shown in Figure 3.4. These bridges are located at narrow river sections, and thus are considered the most at-risk from flooding.

Figure 3.4: I-90 Business Route Bridge (bottom) and Railway Truss Bridge (top) over the Yellowstone River in Livingston (45.6749 N 110.5368 W)

No noticeable damage to the highway bridge was observed by MDT inspectors following the flood event. However, those inspectors began noticing approximately one week after the flood that the concrete bent supporting the railway bridge was spalling severely on the southern side of the bridge, potentially placing the highway bridge at risk if the railway bridge were to collapse. At the date of this report, GEER has not been updated on the status of these bridges. SfM imagery was taken of this bridge and is stored at the DesignSafe Data Deposit.

3.1.1.4. Carter’s Bridge

Carters Bridge is located three miles south of Livingston on US Highway 89 and one mile east on Secondary 540 (Figures 3.5, 3.6) at the north end of the Paradise Valley. Just to the north of the bridge (downstream) is a tight pass through a range of small mountains that separate the Yellowstone River Plain from the Paradise Valley. The GEER team did not observe any significant flood damage in the pass between the Valley and Livingston, as the river passes through a series of boulder fields and exposed bedrock in the pass, highly resistant to scour and erosion, with no bridges. However, due to the more erodible soils at Carter’s Bridge, damage and changes to the channel were both observed at the bridge. Although the river is relatively wide at Carter’s Bridge, the channel grade steepens, and flow velocities climb at this location due to the nearby cut through the mountains immediately to the North.

Being the northernmost bridge of the Paradise Valley, Carter’s Bridge is essential for community travel. Residents reported Carter’s bridge to be closed for inspection for one day, and immediately reopened. Google maps still showed the bridge as closed during the time of the team’s visit; however, an on-site inspection by the team members concluded with no signs of apparent damage to the bridge. Flow patterns suggested the presence of a scour hole at the western bridge pier. Flow velocity was well above 1 m/s at the western-central section of the river upstream of the bridge, while flow velocities were visibly slower on the eastern side, likely associated with the presence of a large gravel bank. Upstream of the bridge, local fishermen reported that a large scour hole existed around the eastern bridge pier but filled up about 5-6 years ago. The GEER team recorded SfM data around the bridge and flow patterns around the bridge piers. Figure 3.7 shows a photograph of the bridge pier suggesting a scour hole to be present near the left-hand pier in down-stream direction. A stronger current around the bridge pier is visible. Figure 3.8 shows an aerial photograph around the bridge in upstream direction. Figure 3.9 shows large sediment deposits along the riverbank of the Yellowstone River, abutment scour predominantly on the western bank, and debris still stuck to the bridge structure. Less abutment scour was observed on the eastern upstream abutment; however, some erosion upstream of the boulder-size deposits protected the abutment.

Figure 3.5: Location of Carters bridge and surroundings (source: google maps satellite image)

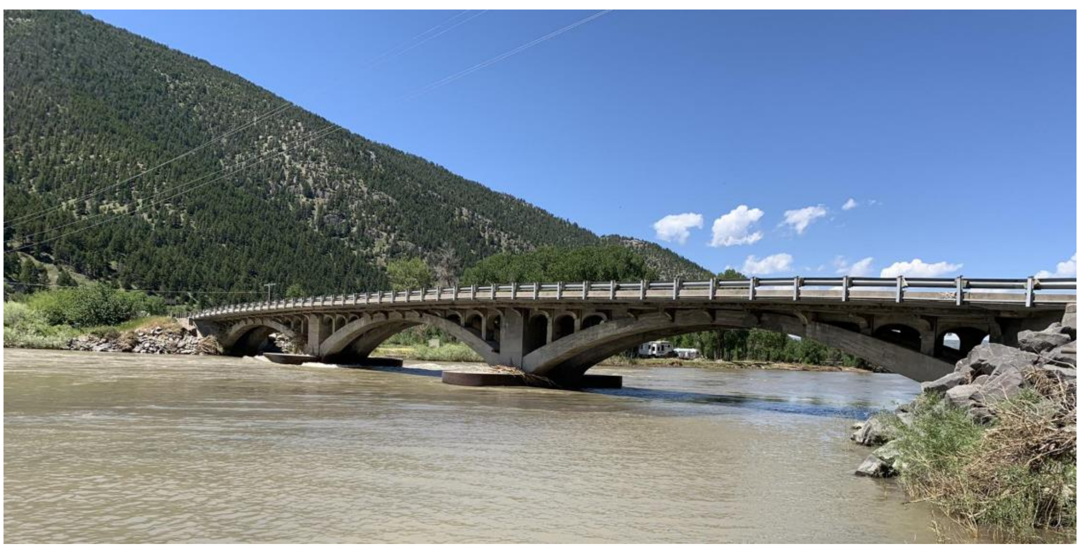


Figure 3.6: Downstream view of Carters bridge across the Yellowstone River (45.597185482878835, -110.56725528055462)

Figure 3.7: Downstream view of Yellowstone River and change in flow. Damage to the middle pier from scour erosion and subsequent slope instability can also be seen. (45.597005176806064, -110.56656540935629)

Figure 3.8: UAV aerial view of Carter bridge from downstream direction (45.59757057191095, -110.56653085768644)

Figure 3.9: Large Sediment Deposit and abutment armoring slope instability damage around the Carter bridge, downstream (45.59693187817401, -110.56611409046789)

3.1.2. Carbella Area: Carbella Bridge (Tom Miner Basin Road Bridge)

The Carbella Bridge (also known as the Tom Miner Road Bridge) was built in 1918 and spanned the Yellowstone River, connecting US-89 with Carbella and Miner, as shown in Figure 3.10. This bridge is just north of the Yellowstone River Gorge and is a key cross-river linkage in the Paradise Valley. This 175-foot truss bridge washed away during the flooding event. The bridge was lifted from the abutments and washed downstream. Unlike other damaged bridges documented by the GEER team, which experienced significant abutment damages with lesser damage to bents and superstructure, this bridge had relatively little abutment damage and bents were washed away. This was one of the few truss bridges on the river and tributaries, and logjam flotsam pressures against the superstructure may have played a major role in the damage. Photos of the bridge prior to flooding are shown in Figure 3.11. Satellite images of the bridge and Yellowstone River prior to flooding (September 6, 2021) and following the flood event (June 15, 2022) are shown in Figure 3.12. The elevated water level (and color change due to sediment load) can be seen in the image taken following the flood. Figure 3.13 shows video footage captured by onsite viewers documenting the extent of the floods and the disappearance of the bridge.

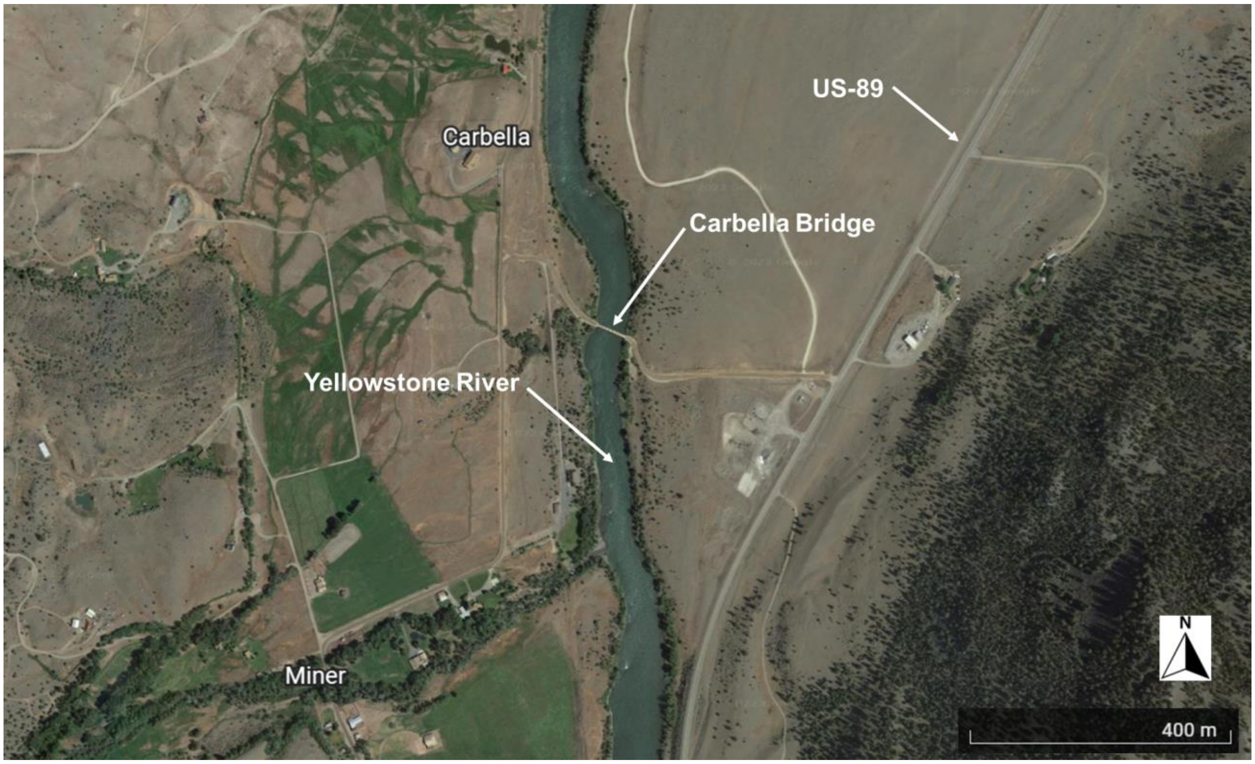


Figure 3.10: Google Earth Image (image taken in June 2022 and provided by Maxar Technologies) of southeastern parts of Carbella area - including Yellowstone River, Carbella Bridge, and US-89 (all labeled with white arrows).

Figure 3.11: Images of Carbella Bridge (Photos by John A. Jackson, Accessed through: https://bridgehunter.com/mt/park/L3430100003001/)

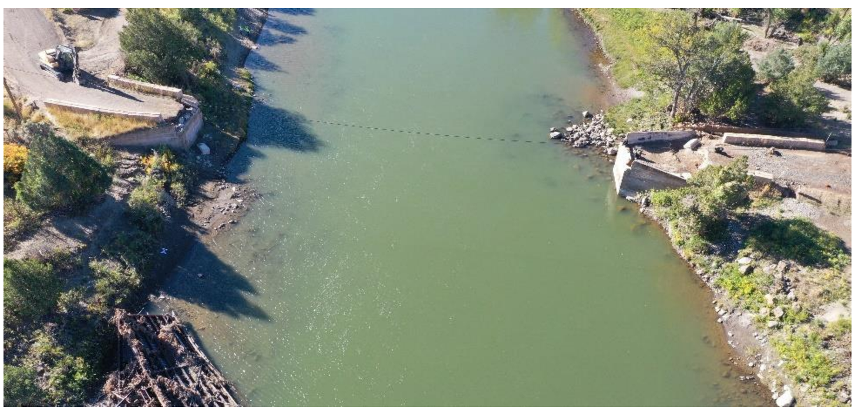


Figure 3.12: Top and Center: Satellites Images of Tom Miner Bridge in Carbella, Montana, from (a) pre-flood - September 6, 2021 and (b) post-flood - June 15, 2022. Source: CNBC/Maxar Technologies via Reuters, accessed through: https://www.cnbc.com/2022/06/16/yellowstone-flood-satellite-photos-show-devastation.html, Bottom: Aerial Photo of the bridge abutments taken by the GEER team during the reconnaissance visit

Figure 3.13: Video footage showing bridge flowing down the river, Source: Billings Gazette, accessed through: https://www.youtube.com/watch?v=REAIicH5pX4.

Figures 3.14 and 3.15 show the bridge abutments at the time of the team's visit (June 30th, 2022). Both abutments suffered damage along the wingwalls, and within the onramp area. The west abutment (Figure 3.15) had significant erosion of soils on the onramp behind the abutment wall (indicating overtopping – which was consistent with observed high water level indicators surrounding the bridge). Several feet of fill material (gravelly fill) behind the wall was washed out and fines deposited as flood waters receded. Additionally, flow patterns in the river indicated a suspected scour hole near the upstream side of the west abutment. The east abutment (Figure 3.14) suffered less damage and did not show significant erosion of onramp soils.

Figure 3.14: Remaining bridge abutments of the Carbella bridge at the time of the team's visit.

Figure 3.15: Photographs of remaining Carbella bridge abutments

Figure 3.16 shows remaining elements of the superstructure truss in the Yellowstone riverbed. Just downstream of the bridge. According to video footage provided online, the truss was lifted of its bearings, rotated, and followed the river in downstream direction. The majority of the center piece remained connected.

Figure 3.16: Bride deck pieces of the Carbella bridge in the Yellowstone River

3.1.3. Cinnabar Basin Rd Bridge

The Cinnabar Basin Rd bridge crosses the Yellowstone River at N45°6’41.51” W110°47’34.73” downstream of Gardiner, MT in the Paradise Valley south of Carbella Bridge and north of the Yellowstone River Gorge (Fig. 3.1). The bridge did not exhibit any signs of structural damage, but the GEER team observed significant erosion of riverbanks near the bridge and signs of significant scour with noticeable asymmetry across the river regarding the different piles and abutments. The bridge is named for Cinnabar exposures in the hills to the west of the bridge. No Cinnabar is in the soil or rock at or near the bridge itself.

Figure 3.17 shows two satellite images well before the flood (2014 and 2019). No recent satellite image was available at this time. The images suggest a river width of ~ 84 m along the upstream bridge deck. About 170 m upstream of the bridge, the river width was 93 m in 2014 and decreased to 70 m in 2019 due to the evolution or emergence of a gravelly shoal near the southwest riverbank. Erosion appeared already visible between 2014 and 2019 along the upstream northeastern riverbank starting most noticeably from where the shoal is constraining the river.

Figure 3.17: Cinnabar Basin Rd Bridge crossing the Yellowstone River downstream of the town of Gardiner, MT, in Google Earth images from July 2014 (left) and September 2019 (right).

The GEER team visited the Cinnabar Basin Rd bridge on June 30, 2022. Observations were documented via photos (with some being presented in the following). Furthermore, Lidar scans, aerial images for structure from motion, and soil samples were obtained for further analysis. At the time of the visit, a team from the Montana USGS was collecting flow velocity measurements. The USGS team members reported cross-river flow asymmetry. This was also qualitatively visible from turbulence appearing more significant at the northeastern (NE) bridge pier (Fig. 3.18 left second pier, also visible in Figure 3.18 right) versus the southwestern (SW) bridge pier (Fig. 3.18 left). Turbulence appeared also enhanced between the NE bridge pier and the NE abutment, and significant erosion was visible upstream of the NE abutment (Fig. 3.19).

Figure 3.18: Cinnabar Basin Rd bridge, Gardiner, MT. Left: image taken from the SW upstream riverbank of the bridge. Right) image taken from the NE upstream riverbank of the NE segment of the bridge (45.11185551, -110.7926037).

Figure 3.19: Washed out abutment support around the Cinnabar Basin Rd bridge (45.1115243, -110.79229245).

The SW downstream riverbank was characterized by a sharp erosion scarp on the downstream side of the bridge (Fig. 3.20 left). The scarp revealed clear layering of sandy to gravelly and cobbly materials. A sediment sample was collected. The SW upstream riverbank was subjected to sediment deposition. Sand deposits were clearly visible (Fig. 3.20) with small scarping, possibly related to different flood stages, and with clear evolution of parallel ripples suggesting flows parallel and possibly slightly onshore to the river flow. Deposits reached about 10 m and more from the current water edge inland, despite a significant elevation increase from the water edge.

Figure 3.20: Left: Erosion scarp at the SW downstream riverbank of the bridge; Right: Sand deposition with ripple formation on the SW upstream riverbank of the bridge (45.11118928, -110.79336519).

The NE upstream riverbank was subject to significant erosion within the same section already identified in 2019 and to some degree in 2014 (Fig. 3.17). However, the river eroded more soil away during this event. For example, the distance from picnic tables clearly visible in the satellite images from 2014 to 2019 to the water edge decreased from 23 m to 9 m (please note that this may be related to water level changes and to erosion), but during the GEER team visit the distance to the tables was in locations further reduced to ~ 5 m (Fig. 3.21 right). The erosion scarp revealed a sand layer on top of a gravelly-cobbly layer with varying thickness of both layers along the scarp. In some sections, gravel almost dominated the entire scarp wall and vice versa (Fig. 3.21 center).

The SW downstream riverbank eroded noticeably (Fig. 3.20 and Fig. 3.22 left), while the NE downstream riverbank was subjected to significant flooding (as reported by local observers), but experienced limited erosion (Fig. 3.22 right).

Overall, the team observed significant asymmetry of erosion, as well as turbulence around bridge elements across the river. The bridge is centered in a ~ 2500 m long approximately straight section of the river with even limited meandering beyond this section. The only significant river constraining and bending element in this river section is the gravelly shoal that is located adjacent to the SW upstream riverbank approximately 250 upstream of the bridge. It may be hypothesized that this shoal has a significant influence on flow and the observed diagonal riverbank erosion pattern, pronounced scour at the NE bridge elements, and deposition on the SW upstream riverbank. The shoal has clearly evolved over years (Fig. 3.21).

Figure 3.21: NE upstream riverbank being subject to significant erosion (45.1115243, -110.79229245).

Figure 3.22: Left: SW downstream riverbank with noticeable erosion particularly starting about 120 m downstream of the bridge. Right: NE downstream riverbank with only limited and localized erosion (45.11194786, -110.79351977)

Lidar scans and structure from motion modeling as well as video and photo recordings (e.g., Figure 3.23) from unmanned aerial vehicle flights were performed of the Cinnabar Basin Rd bridge section of the Yellowstone River. Furthermore, multispectral aerial imaging was carried out.

Figure 3.23: Top: UAV Image of erosion sourrounding the Cinnabar basin onramp, Bottom: Aerial photo of Cinnabar bridge at the time of the team's visit (45.11185551, -110.7926037)

3.1.4. Riverbank erosion and sediment redeposition: Yellowstone River between Carbella and Gardiner

Riverbank erosion including the development of sharp vertical erosion scarps as well as larger slope failures were observed in multiple locations along the Yellowstone River in the Paradise Valley between Carbella and Gardiner. These erosion events occurred in differing geologies and landforms, but no bridges are located on this stretch of the river. Although the majority of this river section is open glacial valley composed of glacial and alluvial terraces, the river passes through a 2-km long gorge through an east-west rocky hill salient that crosses the valley. Erosion occurred where riverbanks were less than 0.5-m in height. In addition significant overland flow resulted in thick sediment deposits over several square meters in area. Debris from homes washed away in Gardiner was resting in tree branches 3 to 4-meters above the bank in the gorge. Sediments on the highway pavement and water marks on the rock faces in the gorge above the pavement give additional data on the maximum water surface. Thus, there is evidence that the maximum water surface at several locations along the river showed water was 1-m or more above the highway pavement and approximately 4-m above the water surface at the time of the GEER visit. Figure 3.13 shows two views of the Yellowstone River Gorge and significant scour that occurred all through the gorge.

Figure 3.24: The Yellowstone River Gorge. Significant scour all through the gorge, with peak water surfaces up to 1-m above the pavement of the highway (45.17018368, -110.86630538).

The Yellowstone River Gorge differs from other areas visited by the GEER team in several ways. In this area the boulders lining the slopes are angular, and recently derived from the parent rock outcrops above the river rather than rounded glaciated boulders. Boulders are the majority of the geomaterial lining the river, with boulders ranging from 0.5 to 4-m diameter forming a rock armoring that would be similar to an engineered system. Little to no vegetation sits down by the river except at the ends of the gorge (where ovens and refrigerators from Gardiner ended in trees). However, the grade of the channel is steep and the width is constricted, forming conditions for extremely high flow velocities. GEER team members flew the gorge with UAVs and collected both conventional and multispectral image data (Figure 3.25).

Figure 3.25: Rock Erosion along Highway 89 near Sphinx-Creek and Yellowstone River confluence (45.17018368, -110.86630538)

Some rockfall occurred at the outcrops in the gorge according to local, county and state officials. However, these were cleaned up by the time the GEER team arrived on site, being critical for evacuation of tourists from Gardiner when the floodwaters subsided. Some blocks remained in the roadside drainage ditch, measuring 1-m or less. It was unclear where on the outcrop faces that the blocks came from, being highly weathered. It was reported to the GEER team that these rockfalls were not caused by the floods, but by heavy rains that immediately preceded the flooding.

The over-steepened slopes in the gorge after the floods are primed for slope instability. A special study area, shown in Figure 3.26, in the gorge was delineated by the GEER team to examine the possibility for slope instability. Figure 3.15 shows a view from the highway of newly exposed soils on these over-steepened slopes. The light brown color in the figure is the newly exposed material. The thickness of the newly exposed material varied from 1 to 3-m. While no failures had occurred of the slopes at the time of the GEER visit, large tension cracks were observed and documented by the GEER team. Figure 3.16 shows some of these tension cracks. Tension cracks were measured at 3 to 40-cm wide (generally 15-cm), and 10-cm to 2-m deep (generally 1-m). Much of the area in the tension crack zone is heavily vegetated, and it is likely that root reinforcement is adding sufficient tensile strength to prevent failure. Indeed, Figure 3.26 shows that trees are holding the slope together.

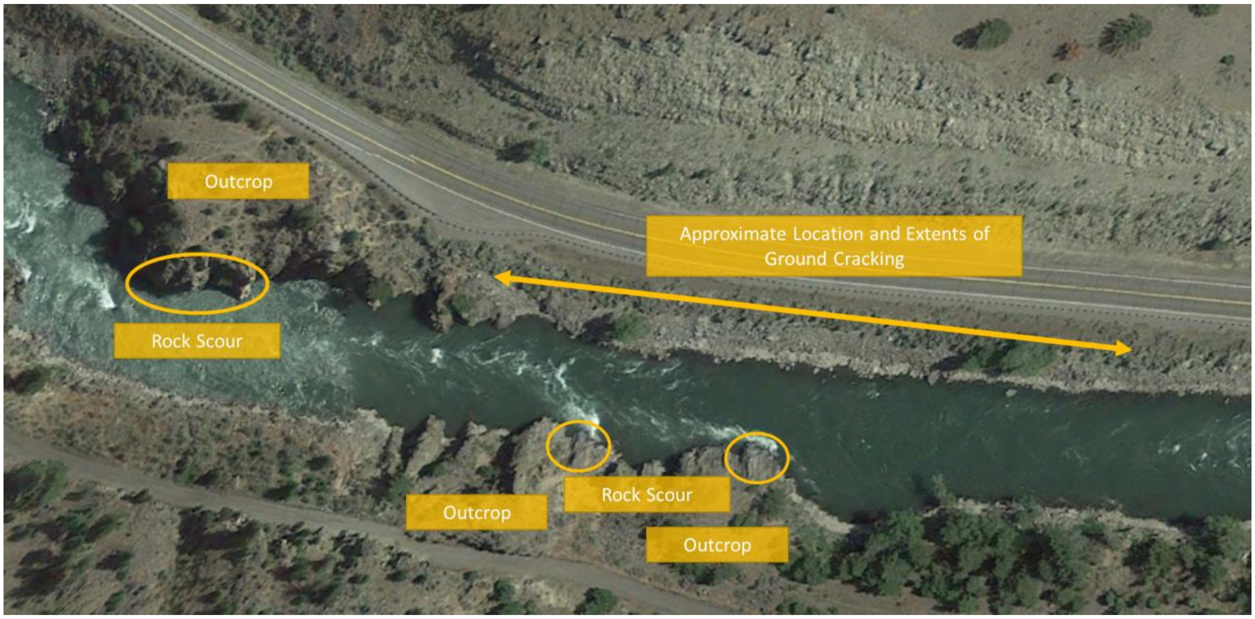


Figure 3.26: Area of special study by the GEER team in the Yellowstone River Gorge (45.17657N, -110.88198E).

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Figure 3.27: Newly exposed soil in the Yellowstone River Gorge, 1-m to 3-m high forming over-steepened slopes. (45.17657N, -110.88198E)

In addition to soil erosion, rock erosion occurred in the Yellowstone River Gorge. Figure 3.29 shows newly exposed rock after large blocks have been removed by floodwaters and impacts of boulders. Removed rock sizes are estimated to be 0.3-m to 1.5-m in size based on rock fracture patterns on outcrops that were inundated in the flood. These rock blocks are only lightly weathered, with fractures accessible to the GEER team being tight, with little to no infill.

Figure 3.28: Tension cracks documented by the GEER team.

Figure 3.29: Rock scour occurrence in the Yellowstone River Gorge. Lighter colored rock is newly exposed.

Sediment deposits upstream of the Yellowstone River Gorge were imaged via UAV by the GEER team, and hand measurements of the sediments suggested thicknesses of up to 0.5m. Figures 3.30 and 3.31 depict a large stretch of sedimentation south of the gorge. Figure 3.32 shows the cracks in the sediment deposits which allowed the team to estimate the depth of the sediment thickness. Using a tape measure, the thickness at the location depicted in Figure 3.32 was approximated as 38 cm (15 inches), (Figure 3.32, bottom right).

Figure 3.30. Sediments deposited from flooding at the top (upstream end) of the Yellowstone River Gorge (45.1676340, -110.8532592).

Figure 3.31: Alternative view of the sediment deposits in former grass flats. The thicket of willows and cottonwood trees along the river were host to debris and trash left by flood waters in the branches (45.1676340, -110.8532592).

Figure 3.32: Sediment Deposit along Highway 89 near 45.1672386, -110.8499935, suggesting deposits with thickness >15 inches.

South of the sediment area shown in Figures 3.30 through 3.32, the bank of the river is elevated 2 to 7-m above the river, and significant erosion occurred at nearly every outside bend of the river. Too numerous to document in good detail individually, Figure 3.33

shows a selection of these erosion events. The glacial moraine and alluvial terraces in the Paradise Valley are thick and boulder rich and overlay fan deposits and tills. Some of the lithology exposed by erosion were these deeper fans and tills, but the majority of the scour is in the upper moraine and terrace deposits. Several of these erosion events triggered slope stability failures. Slide volumes were on the order of 4,000 cubic meters. Locations with slides are typically composed of soils with significant amounts of gravels and boulders, while areas in which erosion did not trigger slope failures are in glaciated sandy to silty materials. These glaciated materials are very dense and act as if lightly cemented (i.e., till). Banks in this stretch of the river are only lightly vegetated and have no vegetation armoring. Boulder lining to the channels in place before the flood were largely removed by floodwaters. Gravel bars and large gravel beds developed in the flooding on the subsequent bend after scour events. Some of these gravel beds are estimated to be on the order of 4,500 cubic meters of material.

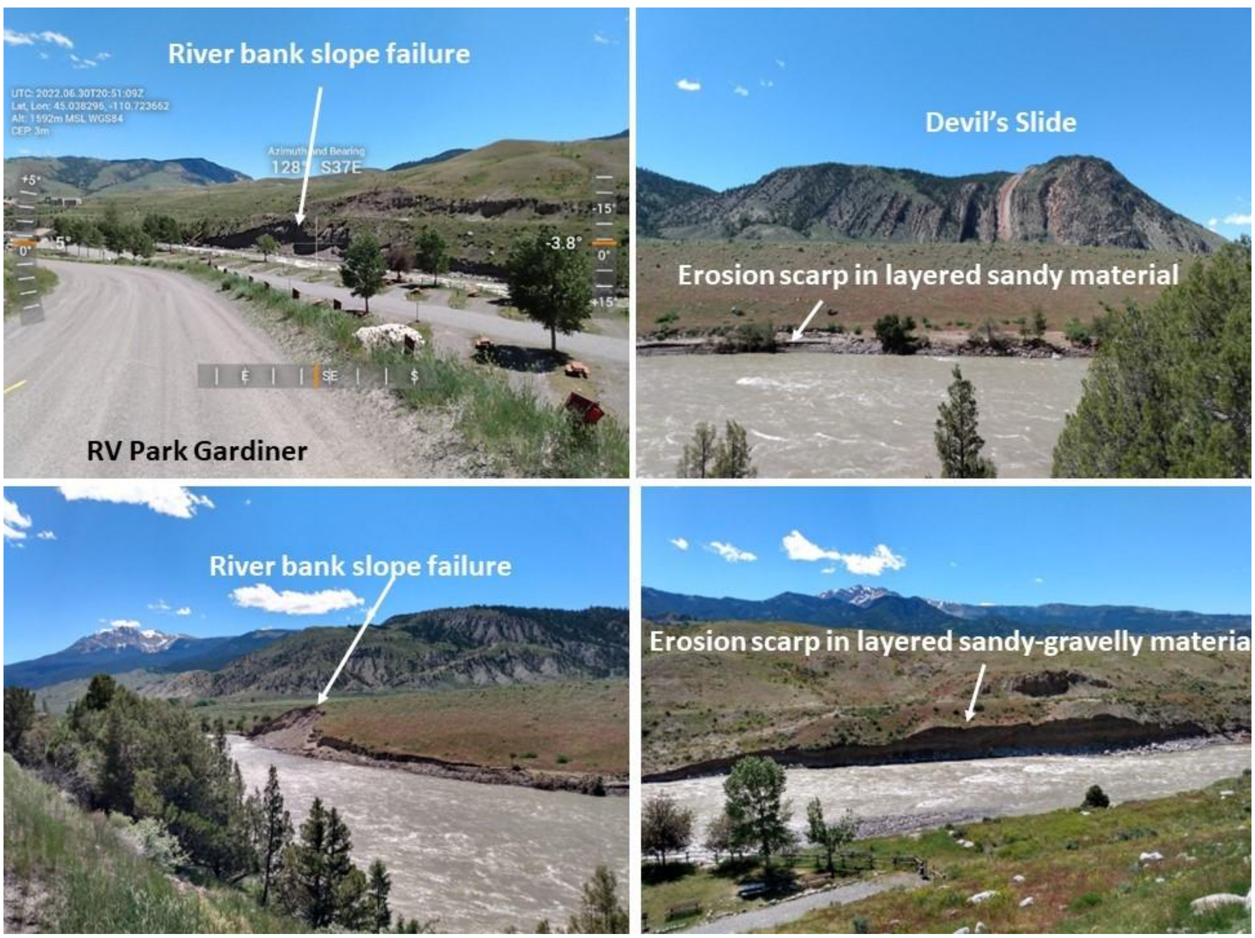

Figure 3.33: Selected photos showing erosion along the Yellowstone River between Gardiner, MT, and the Yellowstone River Gorge in glacial moraines and alluvial terraces (45.0941353, -110.7816088)

3.1.5. Gardiner

The town of Gardiner, Montana is located at the junction of the Gardner and the Yellowstone Rivers. It has historically been referenced as early as 1805 and was officially founded in 1880. Park Street fringes Yellowstone National Park. Gardiner has a population of approximately 833 and counts about 30,000 visitors in typical summers (Gardiner Chamber of Commerce and CVB, 2019).

GEER team members met with Dennis McIntosh, President of the Greater Gardiner Community Council and Director of Facilities and Sustainability for Yellowstone Forever. Mr. McIntosh provided general information about the town of Gardiner, its relationship with the Yellowstone National Park, and showed some specific areas of concern to the GEER team members. Those areas of concern for the community discussed and visited were: 1) the Gardner River and Yellowstone River confluence where Mr. McIntosh pointed out significant changes in geomorphology and associated steep slopes in the vicinity of multiple buildings, 2) the Yellowstone River bridge (built in 1930, rehabilitated in 1975 and 2019-2020), 3) sewer and water pipes crossing the Yellowstone River downstream of the Yellowstone River bridge of which the water pipe was severely damaged and the sewage pipe was still functional but in unknown condition at the time of the visit, and 4) the building failure at 123 US-89. The GEER team members visited and collected perishable data at most of the sites listed. More details are provided in the following sections.

3.1.5.1 Yellowstone River - Gardner River confluence

The Gardner River is flowing into the Yellowstone River upstream of the Yellowstone River bridge at N45°1’48.47” W110°41’56.60” (Fig. 3.34). A comparison of satellite images (available from Google Earth) between July 2014 and June 2022 (under receding flood levels) reveals significant changes in geomorphology: A breach of the southwestern corner of the confluence, deposits of coarse gravel to boulder size materials on the same side, a sharp erosion edge and removal of vegetation can be observed on the southeastern corner of the confluence. The Gardner River width just before the confluence varied from 6.5 m to 24.3 m (Fig. 3.35). While this immediate data collection does not allow the GEER team to ascertain which and how much of the change in geomorphology is related to the flood event versus other events in the eight years between the satellite images, Dennis McIntosh confirmed significant geomorphological change from the 2022 flood event.

The hydraulic conditions of both rivers during the flood event are shown through two USGS gauges, USGS 06191000 measuring the Gardner River near Mammoth, YNP, and USGS 06192500 measuring the Yellowstone River near Livingston, MT. It should be noted that both locations are not in the direct vicinity of Gardiner but represent nearby gages reflecting the conditions of the rivers. The Gardner River reached discharge rates of ~ 85 m^3/s and water levels of 1.74 m (from typical water levels around 1 m at this location and season) and the Yellowstone River reached ~ 1700 m^3/s and water levels of ~ 3.5 m (typically < 2 m) (Fig. 3.36).

The GEER team visited the Gardner-Yellowstone Rivers confluence on July 3, 2022. The Gardner River had clearly decreased from the observed width in June 2022 and appears possibly even further constrained by coarse deposits and sharp erosion scarps on the eastern Gardner Riverbank in the vicinity of the confluence (Fig. 3.35). The significantly steeper western Gardner Riverbank with buildings on top of the slope experienced toe erosion associated with being the outer river meander where stronger flows would be expected. This toe erosion likely led to the slope failure that is clearly visible in Fig. 3.37 and still appeared unstable to the team at the time of the visit. The breach on the western confluence corner visible in Figs. 3.35 (left) through 3.39 had evolved to a shoal of wide grain size distribution reaching from some fines to cobbles. Samples were retrieved and are currently undergoing testing.

Figure 3.34: Google Earth Image (image taken in June 2022 and provided by Maxar Technologies) of southeastern parts of Gardiner including the Gardner River - Yellowstone River confluence, the Yellowstone National Park North Entrance, and the Yellowstone River bridge (all labeled with white arrows).

Figure 3.35: Google Earth Images from July 2014 (left) and from June 2022 during receding flooding (right) showing a significant change in width of the Gardner River, breaching of the southwestern side of the confluence, deposits of coarse sediments, and a sharp erosion edge and removal of vegetation on the southeastern corner of the confluence. (Images by Maxar Technologies)

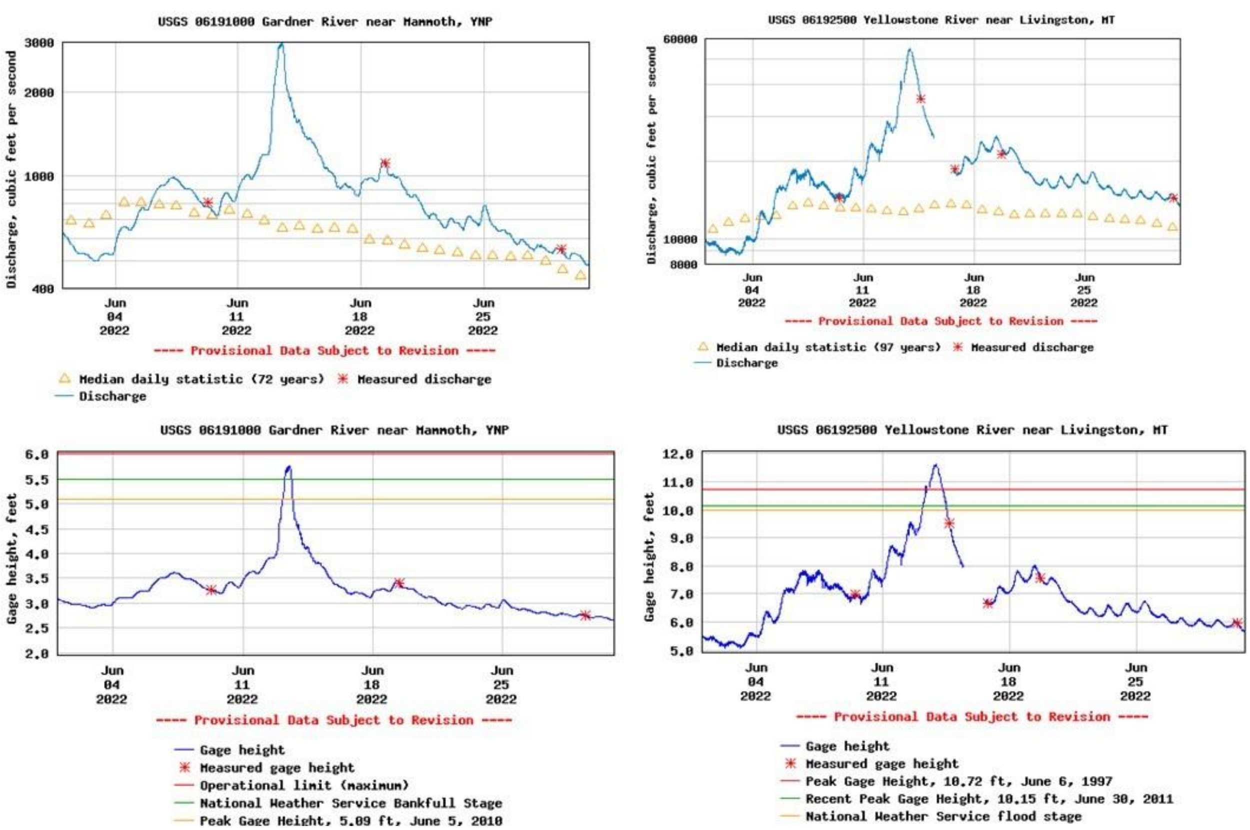

Figure 3.36: USGS gage readings for June 2022 from the Gardner River near Mammoth, YNP (gage #06191000; left) and from the Yellowstone River near Livingston, MT (gage #06192500).

Figure 3.37 shows the view from the confluence towards the Yellowstone River Bridge. The GEER team had planned to collect data near the foundations of the bridge. However, an approaching storm and time restrictions did not allow a closer inspection at this time.

Figure 3.37: Photos taken during the GEER team visit on July 3, 2022. Top left) Slope failure at the western bank of the Gardner River just upstream of the confluence and direct vicinity of building on top of the slope; top right) Gardner River and erosion scarp on the eastern bank just upstream of the confluence; bottom left) different erosion scarp formations on the eastern side of the Gardner Riverbank approaching the confluence; bottom right) confluence during the GEER team visit (45.0298548, -110.7001440).

Figure 3.38: Photo of sandy to cobbly sediments on the western confluence corner shoal.

Figure 3.39: View from the confluence towards Yellowstone River Bridge.

Lidar measurements were conducted in addition to photos and soil sampling. Figure 3.40 shows the lidar imagery taken of the Gardner River and Yellowstone River Confluence in Gardiner.

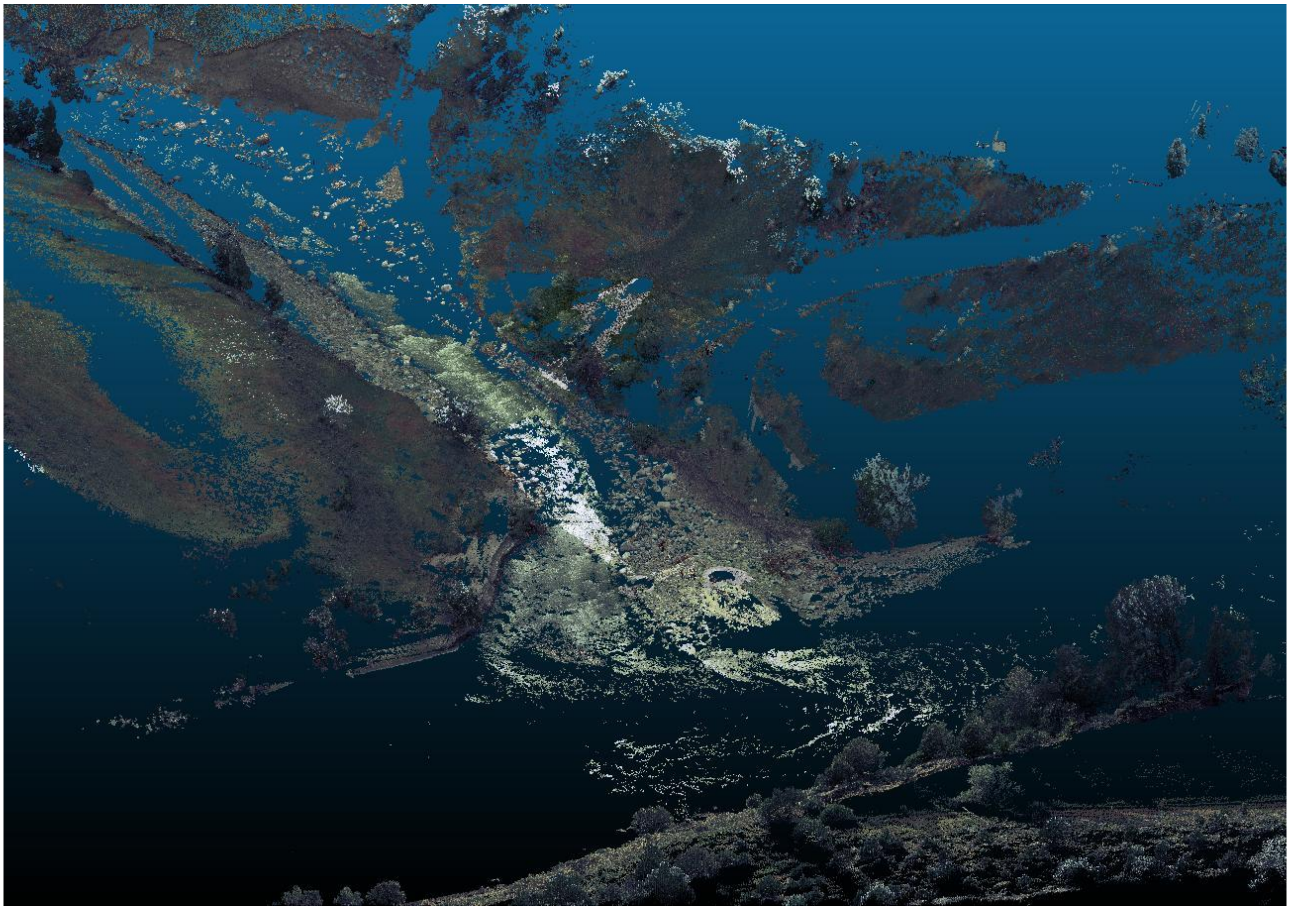

Figure 3.40: Lidar model of Yellowstone – Gardner River Confluence in Gardiner, MT

3.1.5.2. Yellowstone River pipeline crossing

Mr. McIntosh informed the GEER team of a concern regarding utilities pipeline crossings of the Yellowstone River. Downstream of the Yellowstone River bridge and upstream of the riverbank failure that led to a building being swept away, historically three pipes crossed the Yellowstone River (Fig. 3.40): two freshwater pipes and one sewer pipe crossing the river at N45°1’59.46” W110°42’47.60”. Those pipes service the town of Gardiner, but also service communities in the Yellowstone National Park. To the best understanding of the GEER team members, one of the freshwater pipes was damaged during a previous event, the other one was damaged during the 2022 flood event, and the sewer pipe remained functional. However, it represents a concern to the community after partial exposure during the flood event and unknown current condition.

Figure 3.41: Google Earth image (by Maxar Technologies) from September 2019 showing Gardiner, MT, highlighting (white arrows) the Yellowstone River Bridge in the East, the pipeline crossing location and pump station, and the buildings that were swept away during the 2022 flood event.

Figure 3.42 shows the location of the pipeline crossing in July 2014, September 2019, and June 2022 with the latter showing receding flood conditions from the 2022 event. The river width, being here directly related to water level and possibly to a minor degree to erosion, measured below the white arrow with the “pipeline crossing” label about 44 m in July 2014 and 40 m during September 2019, but increased to 55 m in the image from June 2022. Similarly, the distance between the white boulder materials separating the dead-end road from the riverbank slope to the northern river edge decreased from 25 m in the image from September 2019 to 12 m in the image from June 2022.

Figure 3.42: Zoom on the pipeline crossing areas using Google Earth images (provided by Maxar Technologies) from July 2014, September 2019, and June 2022.

The GEER team visited the pipeline crossing site on July 3, 2022. Photos are shown in Fig. 4.43. Riverbank slope failures at- and around the pipeline crossing location were observed. This led to exposure of the buried pipes, according to Mr. McIntosh, and concrete was poured on the emerged and exposed parts of the pipe. The concrete stabilization was visible to the GEER team (Fig. 3.43). At that time, no information was available about the state of the submerged parts of the sewer pipe. Erosion exposed coarse gravel and boulder materials at the riverbank toe and sandy materials with clear slope failure scarps above the coarse material.

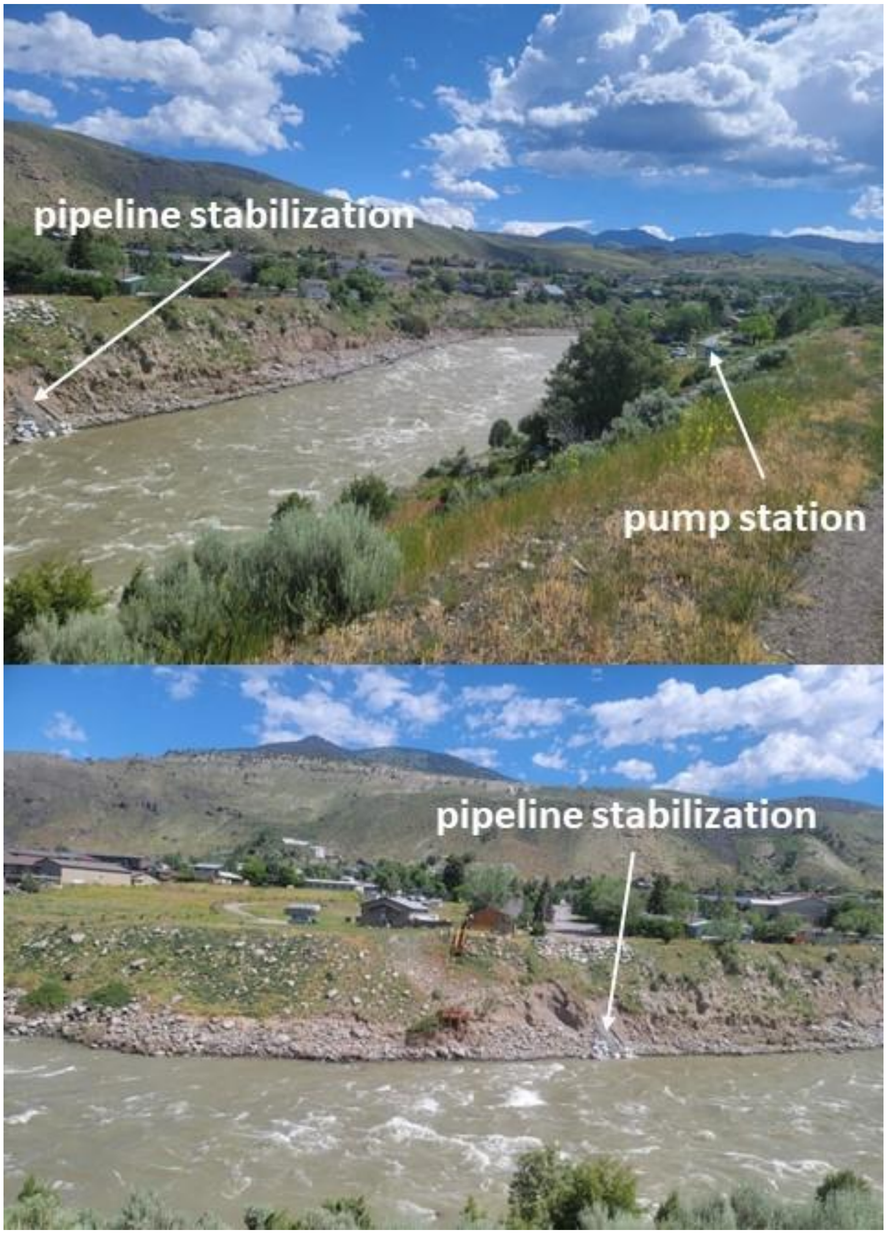

Figure 3.43: Photos taken by the GEER team on July 2, 2022 of the pipeline Yellowstone River crossing section.

The GEER team scanned the exposed pipeline section and the surrounding slope failures and erosion using lidar from the southern riverbank (where also the images in Fig. 3.43 were taken). Figure 3.44 shows the lidar image of the pipeline. At the time of report writing, the condition of the sewer pipe was still unclear in the submerged sections. Planning for an inspection were ongoing.

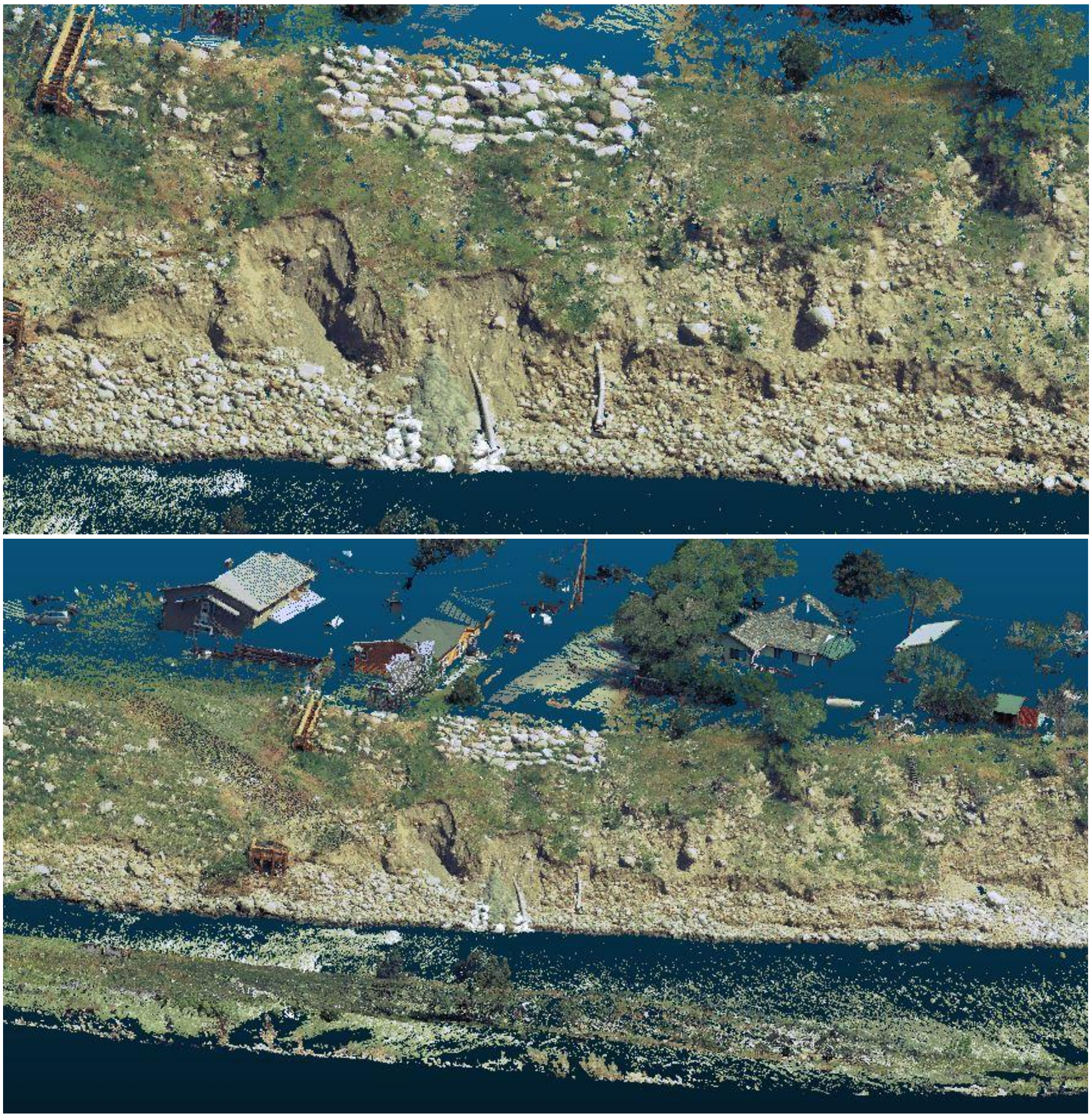

Figure 3.44: Lidar scan of Pipeline crossing

3.1.5.3. 123 North US-89 Building Failure

One of the major infrastructure damages in Gardiner during the flood in June 2022 was the washing away of the building at an address of 123 North US-89, Gardiner, MT located between the Yellowstone RV Park (west of the building failure) and the Elk River Gallery Lodge (east of the building failure) on the northern riverbank (N45°2’12.26”, W110°43’11.02”). Satellite images of this river section from July 2014, September 2019, and June 2022 (during receding flood), as available on Google Earth, are shown in Fig. 3.45. The 2014 and 2019 images suggest a distance of ~ 25 m between the larger house and the northern riverbank and a river width of ~ 44 m. It should be noted that variations are likely mostly resulting from water level variations as well as geospatial accuracy of the image. At the receding flood stage of the image from June 2022, the image suggests a river width of 102 m at the same location with both buildings gone and a shoal developed near the southern riverbank (Fig. 3.45). With the currently available information, it cannot be determined whether the shoal evolved under the flood of June 2022 conditions or earlier.

Figure 3.46 shows a sequence of failure obtained from publicly available video footage. It shows that soil eroded initially under the smaller upstream located building which eventually failed first. The second larger building experienced similarly continuous erosion of soil underneath it (what became the new riverbank), until the building eventually tilted forward, rotates into the river, and is being swept away. Building debris floated miles down the river with items found near the Yankee Jim Canyon about 25 km downstream.

Figure 3.45: Google Earth images (provided by Maxar Technologies) from the Yellowstone River section where two buildings (marked by white arrow) were lost at 123 US-89, Gardiner, MT (N45°2'12.26", W110°43'11.02") from July 2014, September 2019, and during the receding flood in June 2022.

Figure 3.46: Image sequence obtained from videos available on YouTube (https://www.youtube.com/watch?v=3Q0fpeObMT4; https://www.youtube.com/watch?v=GrtV0asee2I) of building failures at 123 US-89 in Gardiner, MT.

The GEER team visited the southern riverbank of this site on July 3, 2022. Representative images are shown in Fig. 3.47. The image shows remaining pipes sticking out of the soil where the buildings were located. A sharp erosion scarp composed of gravelly to cobbly materials near the toe with sand above it is apparent. Upstream of the building locations, a significant erosion and riverbank slope failure scarp is visible. This scarp is located across (northern riverbank) of a gravelly shoal near the southern riverbank. If the shoal would have existed prior to the flooding or would have evolved during early stages of flooding, it may be hypothesized that enhanced erosion at the location where the more significant slope failure scarp is visible would have occurred from flow being directed stronger against the northern riverbank from the contraction of flow resulting from the presence of the shoal. It can further be hypothesized that this significant toe erosion led to the riverbank slope failure observed and subsequent significant erosion of the northern riverbank immediately downstream of the riverbank slope failure, and eventually at the location of the buildings. The original river morphology showing some slight northern bend right and river narrowing right at the location of the failed buildings (see Figure 3.46) would have enhanced the hypothesized process of subsequent failures. The presence of sandy material enabled the rapid erosion of the riverbanks. In addition to the photo documentation performed at this location, Lidar Scans were collected on July 3, 2022. At the locations of the building (i.e., pipes), the sand layer appears thicker, i.e., the bank appears composed of more sand than gravel.

Figure 3.47: Annotated photos by the GEER team obtained on July 3, 2022. Top) Northern riverbank scene of failure: erosion scarp, remaining pipes, and the related location of a RV park building. Left) Erosion scarp composed of gravelly to cobbly materials at the riverbank toe and sandy materials above it.. Right) Gravelly to sandy shoal across the river from the location where the significant erosion scarp starts upstream. (45.0368767, -110.7218001)

3.1.6. Yellowstone River overflight

On Jul 1, 2022, representatives of the GEER team chartered a Chessna propeller plane from Northern Aviation, a local charter company, to gain an overview of damages along the Yellowstone River and in the northern parts of the Yellowstone National Park stretching from Livingston to Mammoth Springs and Cooke City. The flight track is depicted in Fig. 3.48. In this chapter, selected photos and commentary pertinent to observations of river morphodynamics and infrastructure will be presented.

The Yellowstone River features in sections strong meandering, island and shoal development (Fig. 3.49).

Figure 3.48: Flight path of GEER overflight on Jul 1, 2022.

Figure 3.49: Aerial images of the Yellowstone River in Bozeman showing significant meandering (top) and island and shoal evolution (bottom) in sections (45.640485 -110.564269).

Figure 3.50 shows a Google Earth image from June 2021 and an aerial photo taken on July 1, 2022 of a roadway and railroad bridge pair in Livingston, MT (N45°40'33.73", W110°32'30.30"). The bridges are clearly funneling the river, decreasing the river width from ~ 180 m about 100 m upstream of the roadway bridge to a river width of ~112 m at the roadway bridge to ~70 m at the railway bridge. This represents a significant contraction of flow, leading to increased flow velocities and likelihood for erosion and scour. The aerial image clearly shows the development of a horseshoe vortex in front of the railway bridge pier and turbulence near both abutments. While no damage was visible, significant scour must be expected, and the arrangement of the bridges related to river geomorphology represents a clear risk.

River meanders evolve through erosion at the outer meander riverbank and deposition on the inner meander riverbank. This behavior is exacerbated by strong flow events. Figure. 2.4.4 shows outer meander riverbank erosion displayed in an unvegetated steep erosion scarp fringing the river. A housing development is located along the downstream half of the outer meander riverbank which was less affected by erosion during this event; however, risk during future floods should be assessed and possibly mitigated through riverbank enforcement. The GEER team did not visit the site on ground, and thus, cannot determine if bank enforcement is already in place and may have contributed to limited erosion right near the residential buildings.

Figure 3. 50: Roadway and railway bridge pair in Livingston, MT, (N45°40’33.73”, W110°32’30.30”). Left: Google Earth image from June 201; Right: Aerial photo taken on July 1, 2022.

Figure 3.51: Erosion scarp visible at the outer meander riverbank at N45°26’33.24” W110°37’10.81”.

Figure 3.52 shows aerial images of the Yellowstone River crossing bridge south of South Glastonbury (N45°15'14.77" W110°51'10.81"). Satellite images suggest that the northern bridge abutment has been reinforced with riprap for years, i.e., likely representing a point of concern regarding scour and erosion. The aerial photographs suggest that riprap and a section of the bridge deck were renewed after the June 2022 flood, likely in response to damages from erosion around the abutment and overwash over the northern end of the bridge. The GEER team has no data prior to the repair efforts.

Figure 3.52: Bridge south of South Glastonbury (N45°15'14.77" W110°51'10.81") with apparent repair work of riprap and bridge deck at the northern abutment.

Sandy flood deposits were found particularly downstream of Gardiner, MT in the Carbella area. Examples showing deposits fringing the river and in inner meanders are displayed in Fig. 3.53. Additionally, driftwood deposits were specifically found on river shoals and at meanders (Fig. 3.54).

Riverbank erosion was recurrently observed in most river sections often associated with sandy steep riverbanks, and/or meandering (Fig. 3.55).

Figure 3.53: Sandy flood deposits in the Carbella area (N45°10’27.40” W110°51’28.24”).

Figure 3.54: Driftwood deposits on river island (45.139680, -110.811759).

Figure 3.55: Examples of erosion observations along the Yellowstone River (various locations).

The flight path separated from the Yellowstone River following the Gardner River towards Mammoth Hot Springs. Severe damages were reported for the road following the Gardner River. Coming from the North, damages were observed starting at approximately N45°1’1.44” W110°41’37.77” near Gardner Canyon. The following sequence (Fig. 3.56) of images represents satellite images available from Google Earth of this river section reaching down to N45°0’14.58” W110°41’30.41” collected in June 2022 during receding water levels post flood. It can be seen that the severe road damages are associated with outer meander erosion (scenes 1-4) and combines impacts of outer meander erosion and slope failures (scene 5). Flood deposits in the inner meanders are visible particularly in scene 3. Before 2014 and after images also suggest an increase of river meandering over the years approaching the flood and possibly during the flood. A more detailed study on river morphology would be needed to draw more detailed conclusions in this matter.

Figure 3.56: Google Earth imagery along the Gardner River starting near Gardner Canyon (1) and following the road to the South showing significant road damages from erosion and slope failures (from scene 1 at N45°1’1.44” W110°41’37.77” to scene 5 at N45°0’14.58” W110°41’30.41”).

Figures 3.57 and 3.58 show aerial images taken during the overflight on July 1, 2022. Water levels are clearly lower and construction equipment was on site. However, road damages were still severe and cut communities off.

Figure 3.57: Aerial images of road damages along the Gardner River between Gardiner and Mammoth Hot Springs taken on Jul 1, 2022.

Figure 3.58: Aerial images of road failures, erosion, and slope failures near the Gardner River (Top left photo: 45.005255, -110.691759, Top right photo: 45.023285, -110.698620, Bottom photo: 45.016004, -110.692658)

Slope failures at steep riverbanks represented a major characteristic of the area. Fig. 3.59 represents an example of a scene with historic but also recent slope failures in this case most recently exposed within an outer meander of the Yellowstone River.

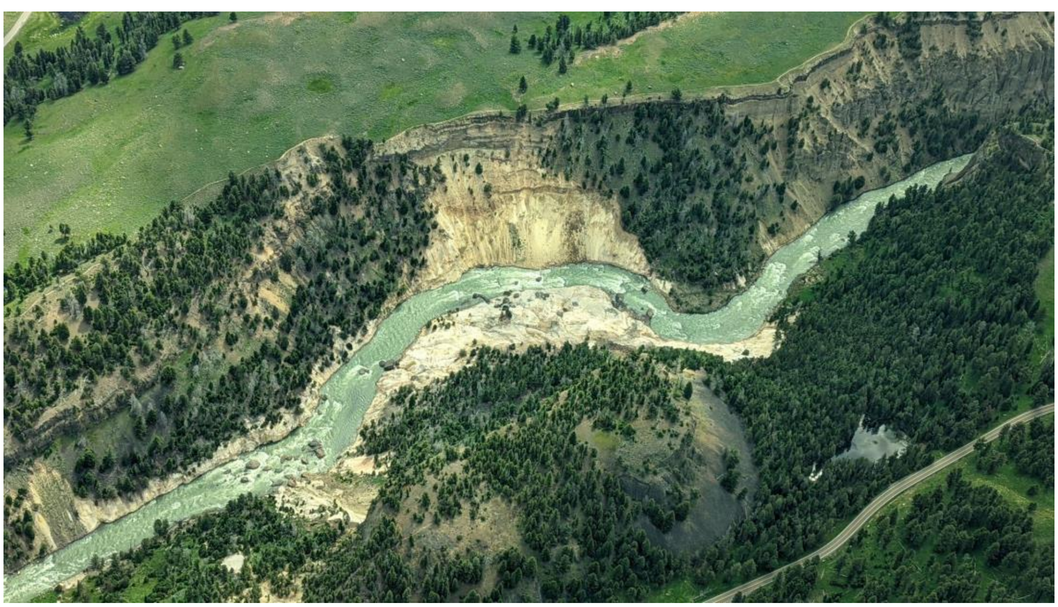

Figure 3.59: Over-steepened riverbank at the Yellowstone River with most recent slope failure in an outer meander (44.908112, -110.394739).

Meandering represents a major characteristic of the rivers of the area also affecting infrastructure where meandering occurs in the direct vicinity of infrastructure. The following aerial images represent examples of the extent of meandering and river braiding in the area of interest (Fig. 3.60). In locations, it appeared as if meanders were starting to developed during the flood event, in locations threatening but not damaging infrastructure in this event (Fig. 3.61).

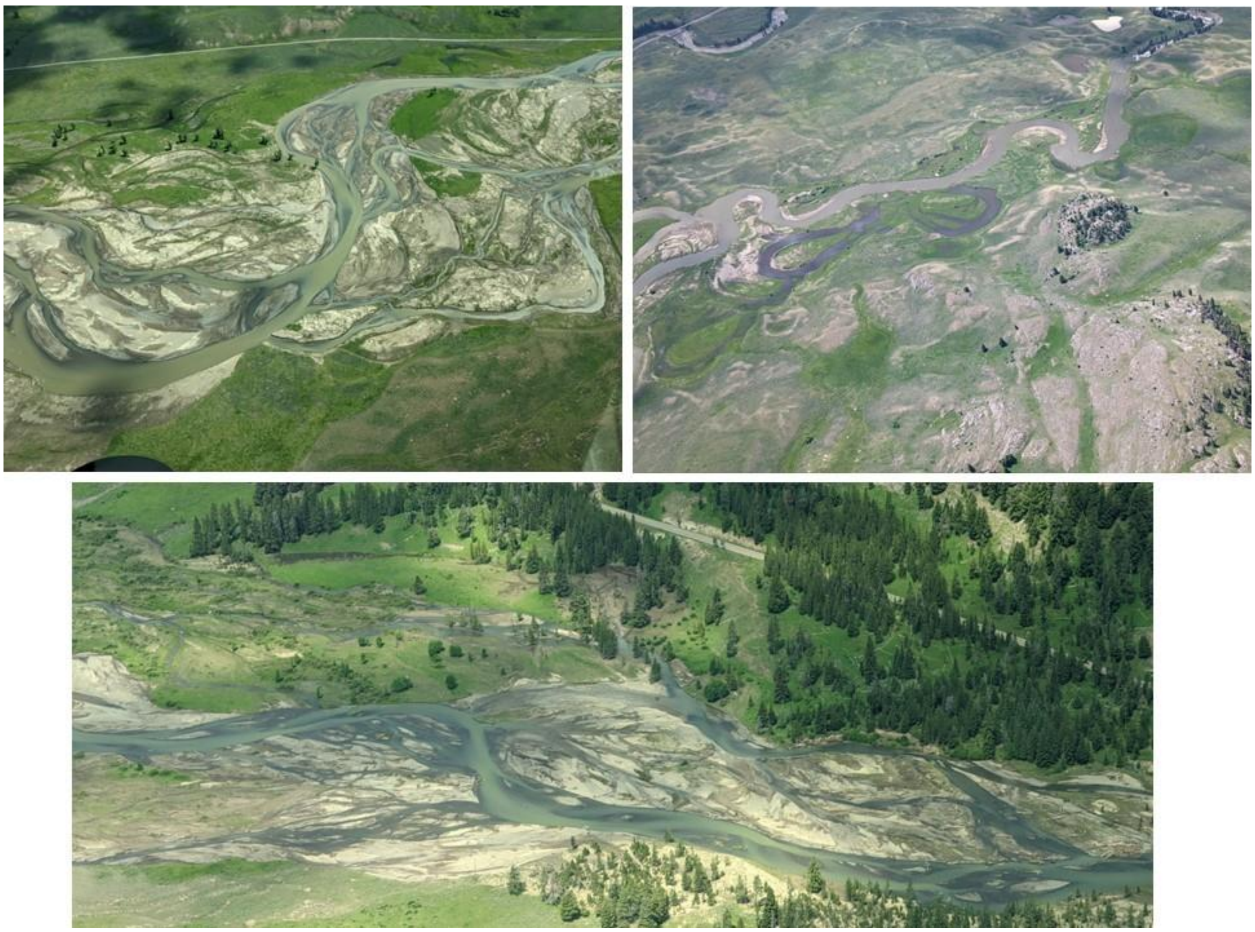

Figure 3.60: River braiding and meandering including abandoned channels and meanders in the Lamar Valley (44.86798694, -110.1910517).

The GEER team overflight enabled a quick screening along the Yellowstone and Gardner Rivers, as well as some other rivers such as the Lamar River in the area. It also enabled access to areas of road damage that were inaccessible at the time of the reconnaissance measurements. While detailed documentation was difficult from the air, it provided a good overview of key features and observations in this area. In addition to the RGB imagery, multispectral imagery was taken of most of the scenes. The data is currently still in processing.

Figure 3.61: Initial meandering of the river approaching road sections (44.953619, -110.074767).

3.2. Observations Along the Northeast and East Slope Tributaries (Nye to Fromberg)

Although much of the damage documented by the GEER team occurred along the Yellowstone River north and south of Gardiner, MT, additional high-damage areas were located along the tributaries of the Yellowstone River coming out of the Northeast and East Slopes of the Beartooth Massif in the area of Nye to Red Lodge, MT. Several rivers and large creeks drain the Northeast and Eastern parts of the Massif. These major tributaries of the Yellowstone River include (from west to east) the Stillwater River, West Rosebud Creek, East Rosebud Creek, Rock Creek, and Clarks Fork of the Yellowstone River. Figure 3.62 shows these tributaries. Figure 3.63 shows the towns built aside these tributaries, and areas visited by the GEER team on the Northeast and East Slopes of the Beartooth Massif.

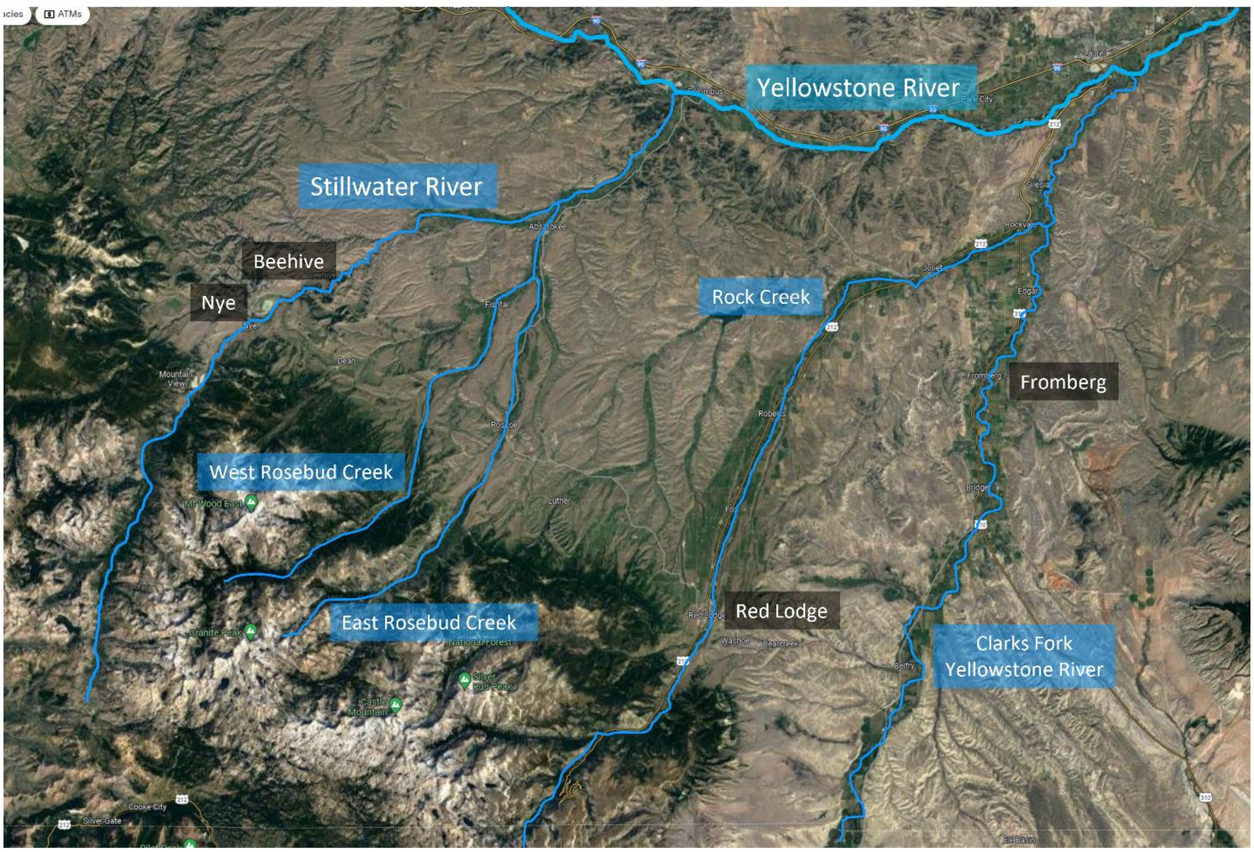

Figure 3.62: Major tributaries to the Yellowstone West Area in Southern Montana

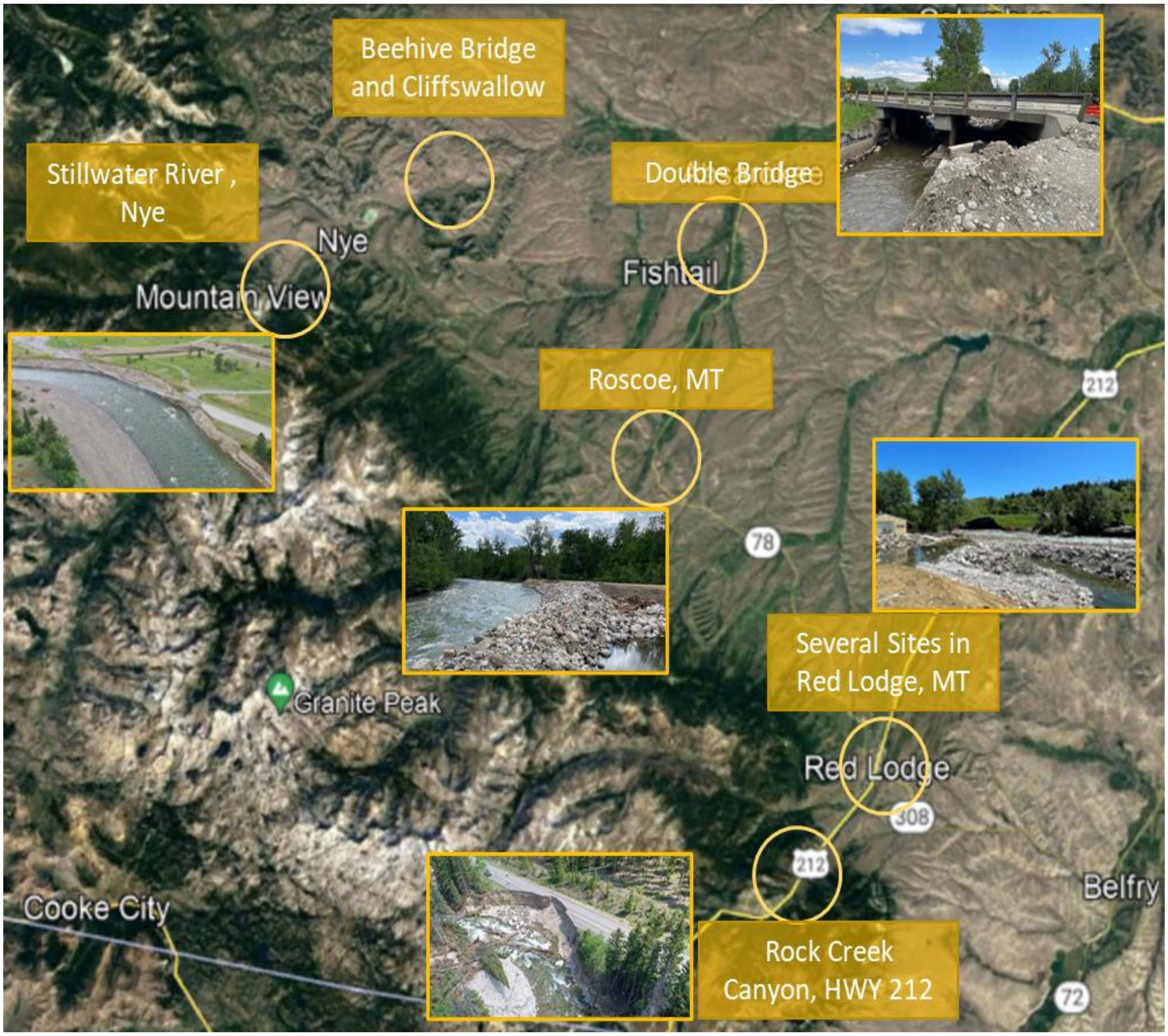

Figure 3.63: Overview of general areas visited by the GEER Team along the Northeast Slope Tributaries (Stillwater River, East and West Rosebud Creeks, Rock Creek, and Clarks Fork).

Although significant flood damage occurred along Clarks Fork in the towns of Fromburg, Clark, Belfry, and Bridger, the flat slope of the Clarks Fork canyon and valley, combined with the wide, open nature of this canyon and downstream valley, produced very little scour, erosion, or bridge damage. More than 300 homes were flooded in Bridger alone according to conversations with local authorities by the GEER team (personal communication). However, with little geotechnical damage along the Clarks Fork drainage, GEER efforts focused on the other 4 tributaries to the Yellowstone River between Red Lodge and Nye. The GEER team did visit Fromburg, Bridger and Belfy and noted the lack of geotechnical damage in these towns.

Other notable tributaries, such as the Boulder River, which lays between Gardiner and Nye, were not visited by the GEER team. These rivers and creeks were not identified by locals as having notable bridge damage or loss of structures. However, conversations with locals do indicate that large erosion sites were recorded on the Boulder River and smaller creeks between Nye and Gardiner. Locals indicate that erosion along these tributaries is similar to what was observed on the Stillwater River and East and West Rosebud Creeks.

3.2.1 Beartooth Highway (Montana Highway 212)

Montana Highway 212, known to motorcycle, backpacking, and mountaineering enthusiasts around the world as the Beartooth Highway, runs adjacent to Rock Creek south of the city of Red Lodge, MT. Rock Creek flows from Glacier Lake south into Wyoming before turning north back into Montana. It flows through the town of Red Lodge before entering the Clarks Fork of the Yellowstone River (Figure 3.62).

Due to excessive snow and adverse winter conditions, the Beartooth Highway is closed from Mid-September to May. The Beartooth Highway pass near the border to Wyoming is characterized by unpredictable weather conditions and steep terrain, making the undertaking, maintenance, and safe operations of Beartooth Highway extremely challenging (Montana Gov, 2022). It climbs to 10,947 feet above sea level and has a total length of 68.72 miles, most of which are characterized by hundreds of switchbacks or its vicinity next to the Rock Creek.

The Beartooth Pass that leads to Cooke City, MT and Cody, WY, was not visited by the GEER team due to inaccessibility: a number of severe washouts up-canyon beyond 45.1377 N and 109.2826 W (shown in Figure 3.64) made this road inaccessible. Damage points along Highway 212 are shown in Figure 3.64 and are described in downstream sequence hereafter.

MDT engineers reported that a total of six scour scarps damaged the hillside and the overlying roadway of the Beartooth Highway during the July 2022 flood. Four of these damage areas were inaccessible to the GEER team, two damage sites are documented hereafter. The MDT also reported that the remainder of the Beartooth Highway performed quite well during the flood. Of particular initial concern immediately following the flood was a portion of switchbacks along the highway approximately 21km southwest of Red Lodge. These switchbacks were severely damaged by a series of mudslides in June 2005, and were subsequently engineered and repaired. Although GEER could not observe the switchbacks, MDT reported that their inspectors had observed and reported negligible damage from the 2022 flood.

Although the GEER team did not see any damage locations prior to the flood, a general trend between site with erosion and sites without erosion was observed along the Rock Creek banks. When considering the length of the bank with erosion versus without, less than about 25% of the bank along Rock Creek experienced any observable erosion. The remaining 75% that did not experience any observable erosion had one key characteristic: vegetation armoring. No matter the size of the boulder on the bank, steepness of the channel grade, width of the channel, or other factors, the common key to non-erosion observations was vegetation armoring. This can be supported based on GEER team's observations of the following characteristics: a) several species of trees are co-located with a healthy mix of shrubs, grasses and forbs; b) roots of larger anchor trees have sinkers (vertical roots) out away from the dripline of the foliage; c) stand thickness is not at an unhealthy thickness, with sufficient room between trees for water to pass and underbrush to develop; d) underbrush includes more native species with deeper root systems; and e) behind the bank soils are carbon-rich with noticeable mycorrhizae populations. These characteristics are explicit and beneficial combinations of flood protection, as many trees have been carried away by bank erosion, and banks with only grasses were observed to have erosion in many cases as well. Soils in the areas of erosion sites did not include noticeable carbon stores or mycorrhizae. Areas that included more invasive or imported grass species tended to suffer more scour unless a heavy rhizomal turf mat had developed. Exposed roots of trees carried away in flood waters showed few signs of sinkers, and in many cases no signs of sinkers. Stands with overly thick trees and brush were more likely to erode in the quick inventory of the GEER team.

Figure 3.64: Google Map of Beartooth Highway (Montana Highway 212) south of Red Lodge, MT (45.1377 N 109.2826 W)

Figure 3.65 shows an example of vegetation armoring along Rock Creek (and is typical of all of the other tributaries to the Yellowstone River visited by the GEER team). It is notable that areas with vegetation armoring in many cases experienced overland flow, and sediments left by flooding were prominent, as shown in Figure 3.66.

Figure 3.65: Example of vegetative armoring along Rock Creek for non-scour case history. Several species of trees, shrubs, grasses and forbs have interfingered with cobbles and gravels.

Figure 3.66: Sediments left from overland flow along Rock Creek in areas without scour from vegetation armoring. Note tree spacing is more dense than pre-1900s stands, but not overly thick.

3.2.1.1. Large Erosions along Beartooth Highway (45.0691 N 109.3896 W)

The most southern accessible damage site along Rock Creek is shown in Figure 3.64 and 3.67. Significant erosion occurred along the creek at 45.0691 N 109.3896 W. At the time of the GEER Reconnaissance, reconstruction efforts were already well underway along the Beartooth Highway. Construction crews had closed access to the highway approximately 4.8 km (3 mi) south of Red Lodge. The GEER team was given access to observe the remaining two existing erosion scarps where Rock Creek had either partially or completely eroded the hillside and roadway on the highway. MDT informed us that a total of six such scarps existed along the highway and were in various stages of being repaired. We were not allowed access to document the other four scarps further upstream to the south of the road closure. The largest of the two documented scarps is shown in Figure 3.67. A 3D model of this scarp was developed using SFM and UAV images.

Figure 3.67: Large scour scarp along the Beartooth Highway south of Red Lodge (45.0691 N 109.3896 W)

3.2.1.2. Highway 212 Bridge over Rock Creek (45.0867 N 109.3665 W)

The Highway 212 Bridge over Rock Creek (45.0867 N 109.3665 W) survived the flooding but experienced massive scour to the abutments as well as boulder impacts to the pile foundations exposed by the scour within the main channel. This bridge is shown in Figure 3.68. The bridge is a 3-span bridge with two bents that straddle the channel of Rock Creek. Between these bents and the abutments were a slope and bench armored with boulders to protect the abutments from potential scour. Figure 3.68 (bottom) shows the scour damage beneath the bridge as well as a boulder (approximately 1.5 meter in diameter) that has impacted a pile/column. Note that the pile/column was spared significant damage by a tree trunk that absorbed the boulder impact and likely aided in the survival of the bridge. Pre-flood, the slope from the bench under the bridge touched the piles but has scoured away. Also shown is approximately 3-m by 5-m soil loss.

Figure 3.68: Highway 212 Bridge over Rock Creek (45.0867 N 109.3665 W). Boulder is circled in Yellow.

3.2.1.3. Bridge damage at Westminster Spire Church Camp (45.0859 N 109.3508 W)

While the tall and rigid Highway 212 bridge (Fig. 3.68) survived due in part to the elevation above the creek and significant freeboard during the flood, the Westminster Spire Church Camp bridge (45.0859 N 109.3508 W) shown in Figure 3.69 experienced more damage. This bridge was built and owned by a private entity to traverse Rock Creek and provide access to a summer camp. This bridge showed signs of overtopping during the flood and severe damage to the western abutment of the bridge, which was completely scoured behind the foundation. Very little erosion was observed upstream or downstream of this bridge due to heavy root armoring and reinforcing of the banks from the dense forest of fir, spruce, pine, and Aspen. Although this bridge is wood, with timber piles, its abutment was partially protected by the vegetation armoring of the bank. Figure 3.69 shows the undamaged wing-walls of this bridge that slowed scour processes and forced water to overtop instead. These abutments and co-located vegetation armoring may have played a significant role in why this bridge survived while similar bridges less than a mile downstream washed out. The scour gap shown in Figure 3.69 (bottom) is 1-m wide and 2-m deep.

Figure 3.69: Imagery showing damage behind the abutment at the Westminster Church Camp Bridge near Highway 212 South of Red Lodge (45.0859 N 109.3508 W).

3.2.1.4. Large erosion along Beartooth Highway (45.0866 N 109.3470 W)

A larger erosion event than the one documented above was observed by the GEER team and is shown in Figures 3.70 and 3.71. This erosion occurred just below the Westminster camp and coincided with a bend of the Rock Creek River. At the time of the team's visit, this damage had been repaired and the road was fully accessible. Figure 3.70 shows aerial imagery of the repaired erosion damage, Figure 3.71 includes the Rock Creek River upstream and downstream from the eroded area. Tree debris and deposits are noticeable in both directions; however, much larger deposits are visible upstream.

Figure 3.70: A repaired scarp on the Beartooth Highway south of Red Lodge (45.0866 N 109.3470 W)

Figure 3.71: Imagery showing upstream (left) and downstream (right) from the repaired scarp on the Beartooth Highway south of Red Lodge (45.0866 N 109.3470 W)

3.2.1.5. Washed-out bridge at USGS gauge station (45.086N 109.330826W)

Downstream of the Westminster Church Camp Bridge was a washed-out bridge at the location of the Rock Creek USGS Gauge Station (45.086N 109.330826W). Figure 3.72 shows the former bridge site. This case history is a complete washout of a bridge, with no remains onsite for inspection. The cuts due to soil erosion are up to 2-m deep at the locations of the former abutments. This road is an access to a campground that was evacuated by small dirt tracks running along the south and east of the creek to the nearest ranch. It is speculated that the bridge was built by the Civilian Conservation Corps prior to World War II. There was no evidence of the former abutments or any pile foundations when the GEER team visited. The lack of any visible signs of deep foundations indicates that the bridge was likely on shallow foundations, with minimal wing-walls protecting the abutments. Pavements and electrical cables are the only remnant of the bridge.

The GEER team was able to collect soil and sediment samples at this bridge for further analysis. This bridge washout is anomalous in that a) the bridge was not on a bend in the creek, b) the channel is wide, and c) the grade in the channel is flat in this area. These would lead to lower fluid velocities. However, it does not appear that the bridge was elevated. Little freeboard coupled with GEER team observations that vegetation armoring of the banks is virtually non-existent in this area, and shallow foundations add up to a potentially hazardous scenario.

Figure 3.72: Washed out bridge at USGS Gauge Station on Rock Creek (45.086N 109.330826W).

3.2.1.6. Washed-out bridge at a Cabin Ranch (45.12065N 109.2966W)

Approximately 1-mile downstream of the USGS Gauge Station bridge failure is another washout case history. This washed-out bridge was built by private landowners for accessing a Cabin Ranch. Figure 3.73 shows the missing bridge, which was built on a bend, and at a constricted channel location with a steep channel grade. In this case, it appears that the bridge builders narrowed the channel by several meters to decrease the bridge length. The wing-walls were small, and not set back deeply into the bank. Although vegetation armoring of the bank upstream and downstream of the bridge were excellent, the bridge was not significantly elevated. The combination of low freeboard, a constricted channel in a high-velocity part of the river, and poor wing walls likely resulted in the complete washout of the bridge, with only remnants of the south wing walls still evident at the time of the GEER team visit. Erosion cuts at this bridge were at least 1-m deep and likely washed up to 2m of riverbank soil away (perpendicular to the river flow). GEER team members were impressed by the ferocity of Rock Creek at this location. Despite the damage to the bridge, there was little to no erosion observed several hundred meters upstream or downstream, indicating that vegetation armoring in the area was robust and reinforcing the notion that more intensive wing-walls and scour mitigations at the bridge itself could have prevented this washout from occurring.

Figure 3.73: Washed out bridge at Cabin Ranch. Note the size of boulders that were behind the wing-walls at this bridge (45.12065N 109.2966W).

3.2.2. Red Lodge, MT

Red Lodge is known as the Gateway to Yellowstone National Park and the starting point of the famous Beartooth Highway (HWY 212). Located at an elevation of 5,568ft above sea level, Red Lodge spans an area of 2.71 sq miles and has a population of 2257 people (City of Red Lodge, 2022).

The city of Red Lodge, Montana was flooded by the Rock Creek during the June flooding event. The flooded zone of Red Lodge is highlighted in Figure 3.74 and begins at the 19th Street/Park Avenue bridge (right corner of yellow outlined area), where a significant portion of the creek eroded the riverbank behind the bridge abutment and created a channel to Broadway Avenue/MT-212 and through the city, which is the city's main transportation artery. Moving north (see Figure 3.74), the city between Main Street and the creek were inundated beneath at least one meter of water according to eye-witness accounts.

Figure 3.74: 3D model image depicting the observed flood zone in Red Lodge, Montana

3.2.2.1. Damage to Residents and Infrastructure in Red Lodge

Figure 3.75 depicts flood damage in Red Lodge during, and immediately following the flood and provides an idea of the magnitude and extent of the damage observed in this historical town.

Throughout the flooded area, the GEER team observed sediment deposits with cobble diameters reaching approximately 0.2 meter. The sediment deposit thickness in some locations exceeded 50 cm. Lidar scans were obtained of some of these areas for additional detailed study. Eye-witness accounts from locals described hearing/feeling the "grinding and the intense vibrations from massive boulders being rolled along like small marbles in the creek bed." These boulders in the creek bed, once visible with receding floodwaters, approached 1 meter in diameter based on visual estimates from the GEER team.

Figure 3.75: Damage in Red Lodge, MT. Source: https://billingsgazette.com/news/local/photos-extreme-flooding-devastates-red-lodge-and-the-surrounding-region/collection_d3f7e430-eb63-11ec-b484-7bd00158f809.html#26; Photo source of bottom left photo: Source: https://www.ypradio.org/regional-news/2022-06-20/red-lodge-area-continues-recovery-following-last-weeks-flooding, credit: Sandra Haisler

Figures 3.76 – 3.78 depicts a residence located at the intersection of Broadway Ave S (HWY 212) and 19th Street/Park Avenue during and after the flood event. The building was located within 50ft to the Rock Creek River and was inundated with floodwater and debris but remained structurally stable (Figure 3.78).

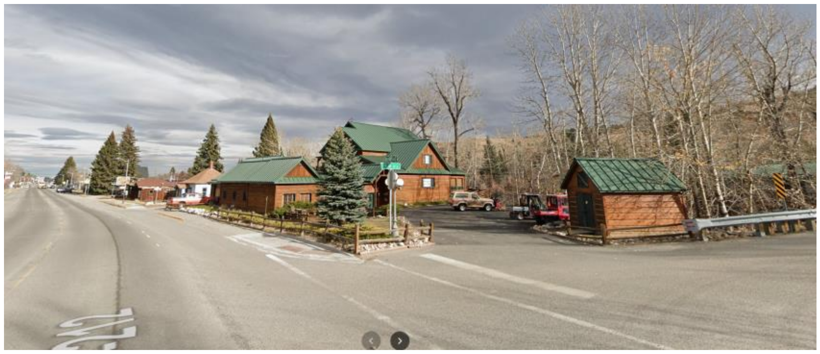

Figure 3.76 Residential Structure at Broadway/19th Street W, before the flood (45.179494, -109.246217). Photo Source: Google Street View

Figure 3.77: Residential Structure at Broadway/19th Street W, during the flood, Photo Source: https://billingsgazette.com/news/local/photos-extreme-flooding-devastates-red-lodge-and-the-surrounding-region/collection_d3f7e430-eb63-11ec-b484-7bd00158f809.html#26

Figure 3.78: Residential Structure at Broadway/19th Street W, at the time of the GEER team visit (45.179494, -109.246217)

At the same intersection, scour damage nearby the 19th street bridge, and all along the Broadway Avenue Sidewalk was visible (Figure 3.79). Even though the slopes were stabilized with heavy boulder rip rap, severe damage was observed, which led to closure of the sidewalk and damage to buried utility lines. Figure 3.80 (left) depicts sediment in the town of Red Lodge, some of which have been naturally deposited, and some of which have been moved around by clean-up work following the flood. Large cobbles are visible in the deposit. In Figure 3.80 (right), substantial riverbank erosion is visible with cuts of about 1m.

Figure 3. 79: Collapsed sidewalk along Broadway Ave S due to scour damage. The sidewalk was located along an outside bend of the creek (45.1784 N 109.2468 W).

Figure 3.80: Sediment deposits greater than 1 meter in thickness. Cobbles are visible in the deposits (45.1802 N 109.2466 W), and erosion along Rock Creek River near Broadway Ave S.

Just north of the collapsed 9th Street bridge and just south of the critical electrical transmission station, GEER team members observed a very large erosion scarp in the hillside (45.1897 N 109.2415 W). This scarp is approximately 11.5 meters in height and clearly shows several sediment layers. The top photograph shows the flooded area around the scarp (shown in the top photo to the right).

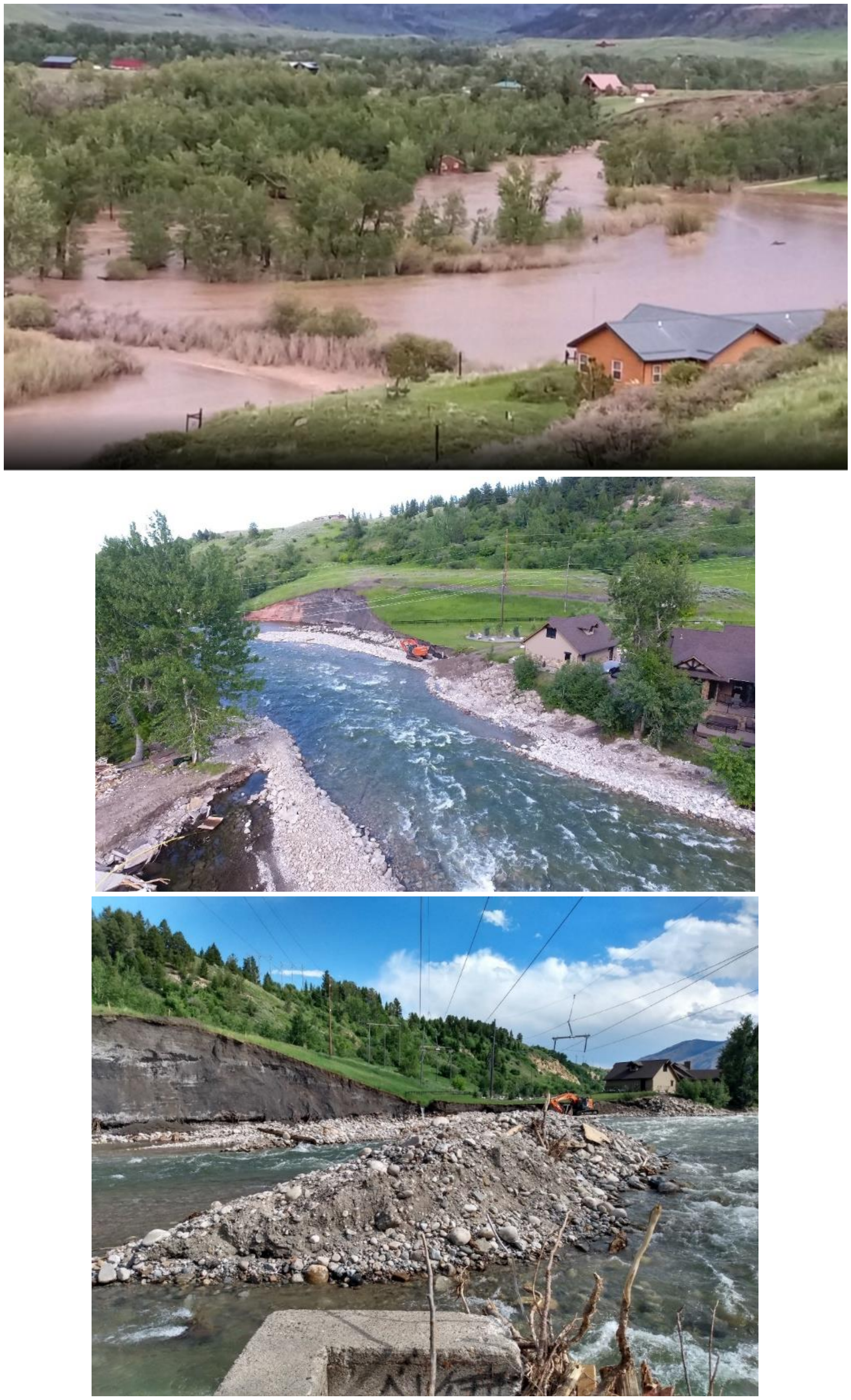

Figure 3.81: Large hillside erosion near 9th street and Rock Creek intersection (45.1897 N 109.2415 W); top photo obtained from https://www.ktvq.com/news/gianforte-declares-statewide-disaster

Lidar, SfM, UAV and on-ground imagery was collected at the site. Figure 3.82 shows a panoramic photograph along with the SfM model taken of the hillside erosion.

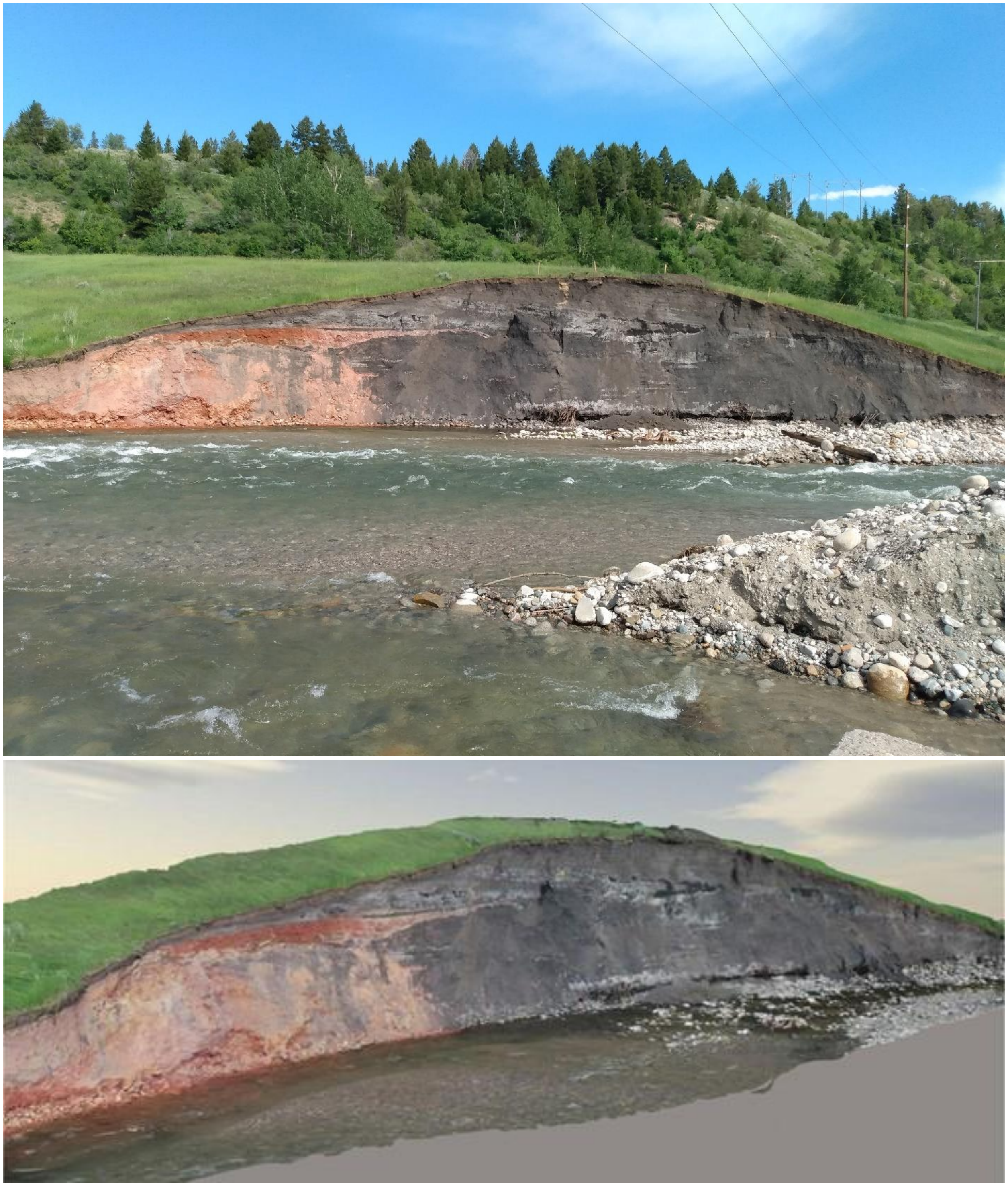

Figure 3.82: Photographs and SfM model of the 11.5-meter-high scour scarp exposed by the June flood along Rock Creek (9th street intersection, 45.1897 N 109.2415 W)

Near this specific location (i.e., the hill side erosion and the washed-out 9th Street bridge), damage was observed to residential structures, and major sediment deposits were visible along all roadways and backyards in the neighborhood. Figure 3.83 shows a "before" photograph of the residential home at 219 9th St E, in Red Lodge; a distance of at least 50-60 feet is visible in the left photo, showing a google street view from November 2021. The photograph on the right was taken by the GEER team, suggested that the river eroded the entire lawn in front of the house.
Figure 3.84 shows substantial erosion along the riverbank of the Rock Creek River and shows the steep cuts along the riverbank.

Figure 3.83: Before and after images of a residential home along the Rock Creek River (45.1886855, -109.2433483)

Figure 3.84: Erosion cuts and washouts along the Rock Creek River leaving substantial damage and support loss to a residential home

3.2.2.2 Bridge damage in Red Lodge

The GEER team observed several bridges that were either damaged or destroyed crossing Rock Creek south of Red Lodge. Most of the bridges provided access to campgrounds or private properties. Community Members from Red Lodge informed the GEER team that ownership of many of these bridges was being disputed at the time of our visit. County personnel stated that many of the bridges had been present for many years, and their level of engineering design was unknown. Figure 3.85 presents five bridges in Red Lodge, which were mapped and inspected by the GEER team.

Figure 3.85: Map of Red Lodge (google maps) showing flooded area and bridges across Rock Creek

Bridges that were engineered (e.g., the Montana Highway 308 bridge in Red Lodge, shown in Figure 3.86) performed well in the flood. These bridges generally featured well armored abutments (either with wing walls or other boulder armoring) and sufficient steel or reinforced concrete deep foundations.

Figure 3.86: UAV image of the Montana Highway 308 bridge in Red Lodge (45.1739 N 109.2500 W)

The performance of the various observed bridges varied considerably, ranging from excellent performance (e.g., the Montana Highway 308 bridge in Red Lodge) to total collapse (e.g., the 9th Street/Kainu Avenue bridge in Red Lodge). Some bridges that were significantly damaged but did not collapse provided valuable insight into progresses and damage sequences. However, important to note beyond the performance of the actual bridge structures, is the influence of the bridges on neighboring structures. For example, the Montana Highway 308 bridge performed well and survived the flood event, but the design of the bridge itself constrains the creek channel to a smaller width than what might occur naturally. Due to the constrained channel width, the creek is unable to effectively contain the flow and water was forced to flow over the bridge abutments which likely induced more damage immediately downstream of the bridge.

The bridge at the intersection of 19th Street/Park Avenue and Broadway Ave S (HWY 212) in Red Lodge (45.1791 N 109.2465 W) experienced limited damage. An image of the scoured and subsequently repaired abutment, as well as a screenshot of the 3D SfM model from UAV imagery of the bridge are shown in Figure 3.87. Rock Creek flooded the bank of the creek at the western abutment of the bridge. Eyewitnesses indicated that the water had ripped off the wing walls of the abutment (seen in Figure 3.85) and scoured away the soil behind the abutment within a matter of a few minutes. Additionally, these eyewitnesses reported watching a full-size pine tree get stripped through the railing of the bridge, stripping all the branches from the trunk by the force of the water. Incredibly, the bridge did not collapse. City and county work crews rapidly placed new fill at the abutment (shown in the figure) and re-armored the abutment with angular boulders. The location of the bridge is less favorable since the bridge abutment sits directly on the outer radius of a bend in the river where velocities are highest and hydrodynamic loads on the bridge abutment increased.

Figure 3.87: Imagery of the 19th Street/Park Avenue bridge in Red Lodge. Top image shows the eroded and repaired abutment; bottom image is a screenshot from the 3D UAV SfM model (45.1791 N 109.2465 W)

The bridge at 13th street performed exceptionally well. Based on the team's conversation and visit with the County Commissioner, this bridge experienced no damage and continued to serve as the remaining access point to cross the Rock Creek River to obtain access to the Eastern parts of Red Lodge. Figure 3.88 shows a before image obtained from Google Street view, and Figure 3.89 shows an aerial image obtained through our UAV documentation of the entire city of Red Lodge. The combination of a relatively straight river flow at this location and the straight passage through the bridge, combined with sturdy armoring through natural trees and vegetation around the bridge and its abutments, might have contributed to its successful bridge performance during the flood. In addition, the Rock Creek River likely expanded its flow outside the river channel at this point (water was taking its course through the streets of Red Lodge near this location) which helped reduce the velocity and debris impact at this bridge.

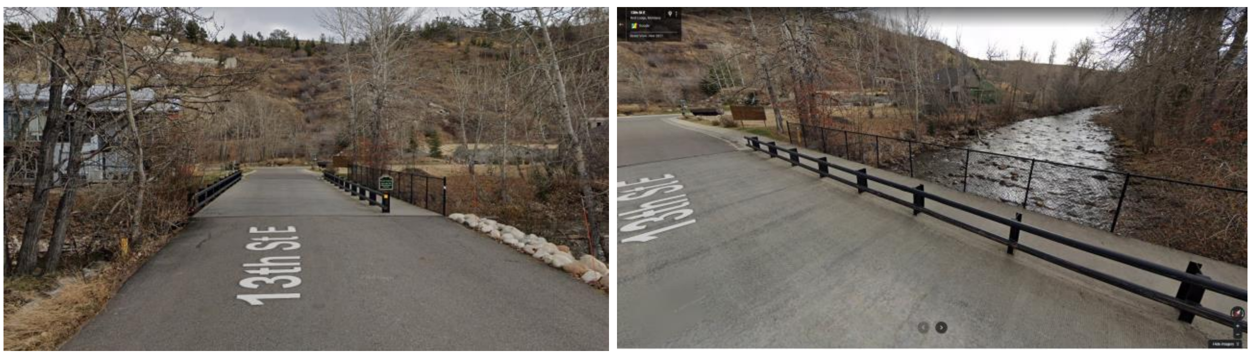

Figure 3.88: Bridge at 13th Street in Red Lodge prior to the flood. Google Street View image from Nov 2021, (45.1850339, -109.2432589)

Figure 3.89: Placeholder for UAV image of the 13th street bridge in Red Lodge. BYU team, please insert an aerial shot here. (45.1850339, -109.2432589)

The 9th Street/Kainu Avenue bridge in Red Lodge (45.1889 N 109.2428 W) constituted the most significant bridge collapse in Red Lodge. The 9th Street bridge was used by many residents on the east side of the creek to traverse the creek and enter Red Lodge. The bridge also carried several utilities including a high-pressure gas line. Figure 3.90 shows the bridge prior to the flood, a photo taken in November 2021. Figure 3.91 shows an aerial image obtained online showing the scene during the flood. The large erosion scarp as described previously is evident along with heavily destroyed residential house (which tilts into the river at the bottom of the picture) and the collapsed bridge to the right.

Figure 3.90: 9th Street/Kainu bridge prior to the flood (Source: google street view).

Figure 3.91: Bridge Collapse at 9th street and large erosion failure, Source: https://www.kulr8.com/news/officials-gather-in-red-lodge-to-discuss-flooding-impacts/article_d7e3a7b2-edbd-11ec-a518-9bfe1b67d2ad.html

Figure 3.92 shows an aerial image obtained through Google Earth that shows the natural flow of the Rock Creek River near the 9th Street Bridge.

Figure 3.92: Imagery of ninth street bridge and pedestrian peer taken 8/3/2013. The image shows the natural flow of the stream pre flooding events. Image courtesy of Google Earth

During the flood, the water scoured the leeside of the western abutment of the bridge and carried the bridge downstream. The floodwater scoured out the ground beneath two adjacent residences and carried those houses downstream as well. A pedestrian overlook, formerly an old railway bridge, with two large piers extends into the river approximately 140 meters to the south from the 9th street bridge shown in Figure 3.92. Debris collected behind two large piers, temporarily damming and rerouting flow to one side of the channel. This likely induced scour downstream of the overlook and towards the residential buildings shown at the bottom of Figure 3.93. Scour was severe in this area due to lack of vegetative armor along the shoreline and the bend that the 9th street bridge extended across. Figure 3.94 shows both remains of the onramp/former abutment location of the 9th Street bridge.

Located approximately 170 meters downstream from the collapsed bridge is a critical power transmission station that provides power for a large portion of the residents in the state of Montana. The city and county wanted to protect that transmission station at all costs. They rapidly placed a berm of angular and rounded boulders to redirect the floodwater back in the main channel rather than continuing into the transmission station. The efforts of these crews were successful, and the transmission station was not damaged.

Figure 3.93: Imagery of the 9th Street/Kainu Avenue bridge in Red Lodge. Top image shows the eroded and repaired abutment; bottom image is a screenshot from the 3D UAV SfM model (45.1889 N 109.2428 W)

Figure 3.94: Photographs of bridge abutment and onramp area of former 9th Street bridge. (45.1889 N 109.2428 W)

3.2.2.3. Observations along West Fork Road in Red Lodge

The team explored the West Fork Road adjacent to the West Fork Rock Creek, a small tributary creek to the Rock Creek River (Figure 3.95).

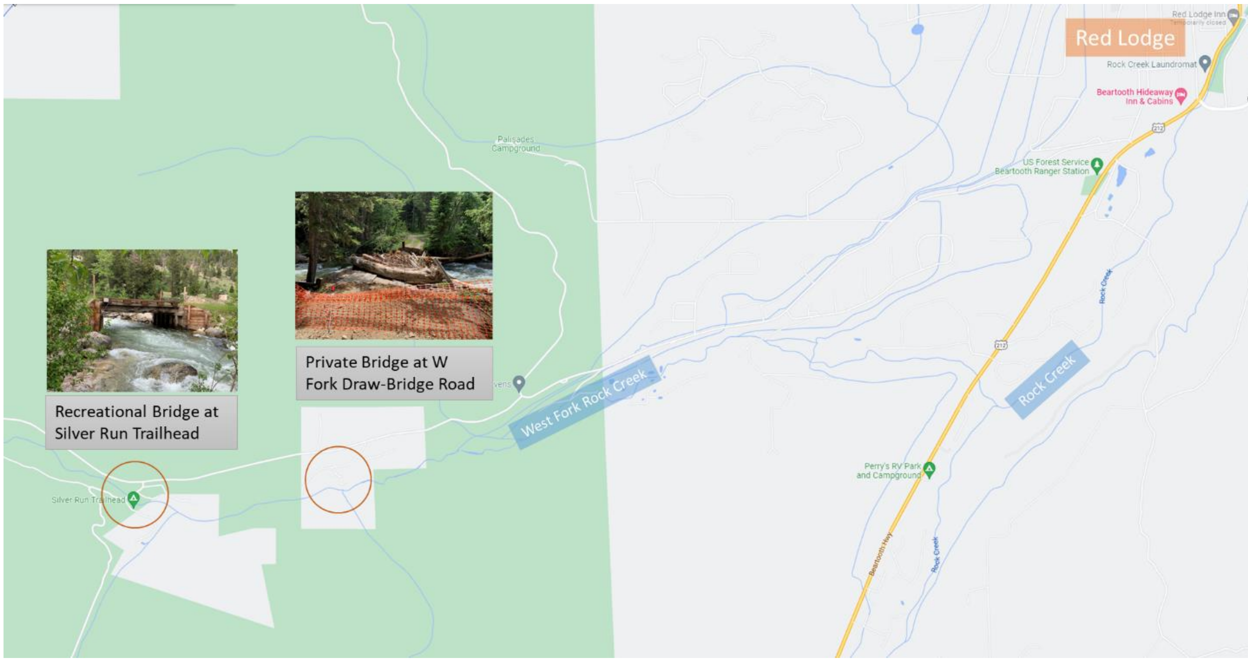

Figure 3.95: Location of West Fork Road relative to Red Lodge and Bridges Visited along West Fork Creek Road

Three bridges were listed as potentially damaged/affected on the county's official website. The first bridge was located along a private road and inaccessible to the team. The second bridge was located the Silver Run Trailhead (Figure 3.96) and showed no visible damage. This bridge was entirely constructed of wood, no damage was observed along the deck or in the abutment region. Heavy boulders protected the riverbanks, and no debris/flood remains were discovered.

The second bridge along West Fork Rock Creek was located further downstream of the W Fork Draw and Bridge Road (45.15076706523556, -109.3227090061891). This wooden bridge appeared to be a private bridge, accessing two small cabins across the West Fork Rock Creek. The bridge collapsed and was blocked off. Aerial imagery taken at the site showed one abutment area to be washed out. The bride consisted of wood decking above steel girders. Substantial amounts of wood debris was piled up on the upstream side of the creek. The bridge deck appeared to be intact (just dislocated), but its internal structure (steel truss with wood decking) was not damaged. Figure 3.97 also suggests the lack of a sturdy abutment wall. Some of the close-up images indicated that a dirt wall might have been erected, covered with some wood lagging to create a support for the bridge deck. The abutment area on the downstream-right side was completely washed out (Fig 3.97).

Figure 3.96: Bridge at Silver Run Trailhead (45.1504173, -109.3407552), no damage observed

Figure 3.97: Private Bridge of West Fork Creek Road, Collapsed and closed (45.1507670, -109.3227090)

3.2.4 Observations along East Rosebud Creek

The GEER team observed several bridges with differing damage amounts and patterns across East and West Rosebud Creeks, to the west of Red Lodge (see map in Figure 3.62). East Rosebud Creek drains from East Rosebud Lake, which is the gateway to a famous backpacking trail, the Beaten Path. The GEER team was unable to travel up the East or West Rosebud Creek Canyons to assess damages and collect data in the foothills of the Beartooth Massif due to a number of washouts on small county and US Forest Service roads. At the time of the GEER mission, the roads up into these canyons were closed. Thus, all GEER activities along these creeks were north of the foothills. East and West Rosebud Creeks are smaller tributaries to the Rock Creek River (to the east) and the Stillwater River (to the west). However, at the time of the GEER mission, these two creeks were still running at flood stage.

3.2.4.1 Damage Observations in Roscoe

The town of Roscoe, MT sits at the base of the foothills along East Rosebud Creek, in a similar position relative to canyons and foothills as Red Lodge on Rock Creek. Both Roscoe and Red Lodge are located where the grade of the creeks flatten and the valleys are just widening, allowing for shallower channels. Roscoe is a small town that serves as the base for adventurers accessing the Beaten Path at the top of the canyon. At the time of the GEER visit to Roscoe, significant repair work had been done to damages at bridges in Roscoe by locals. These efforts were not led by State or County personnel, but rather by the residents of the town and nearby ranchers. According to locals, as the flood waters rose in Roscoe and significant erosion began to the south of the main bridge compromising a natural levee and flooding homes, locals with heavy earthmoving equipment mobilized to initiate emergency repairs to the natural levee and arrest flooding to homes.

The layout of Roscoe is shown in Figure 3.98. The location of the major breach of the natural levee along East Rosebud Creek is central to the damages in the town. Notable is an undamaged bridge (Figure 3.98), large amounts of sediment deposited upstream of the breach from overland flow of the creek prior to the breach, and a new channel alignment that was cut by the creek down a small parallel brook channel. This new channel alignment of the creek cut through homes until rejoining the creek to the north of the town. Locals mobilized to repair the breach of the natural levee and redirect floodwaters back into the historic channel and under the main, damaged, bridge.

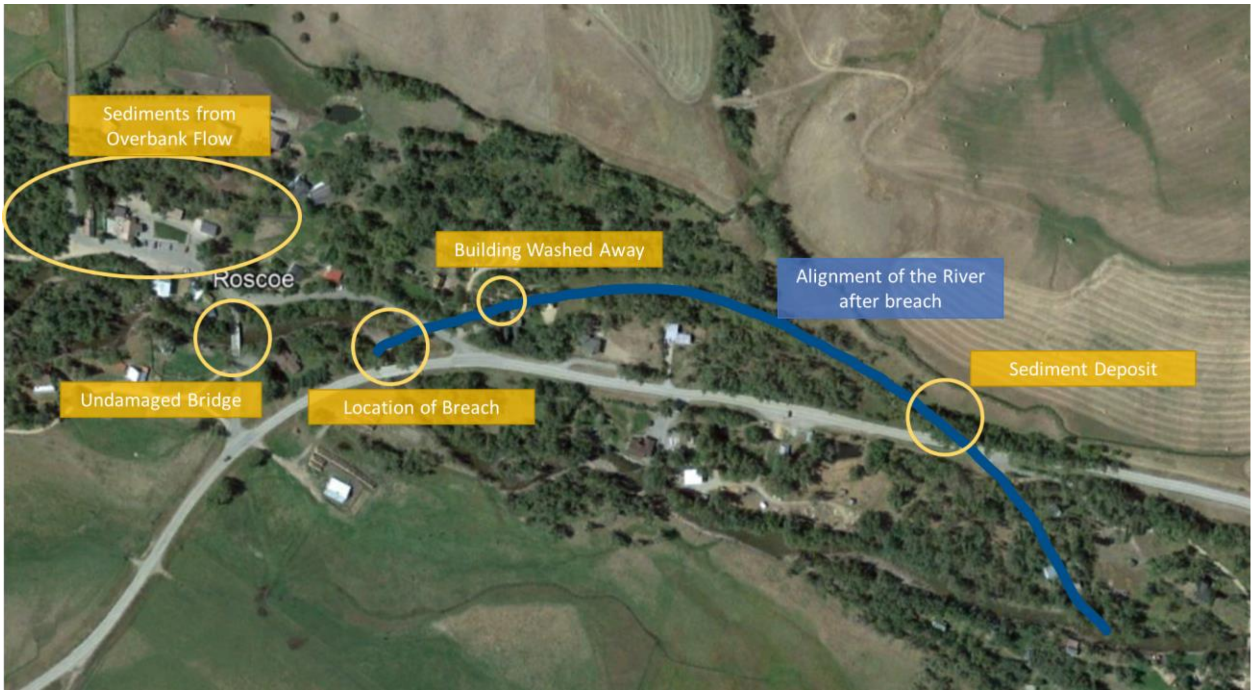

Figure 3.98: Overview of the Town of Roscoe and flood damage including new channel alignment after breach of the natural levee along East Rosebud Creek (45.34950, -109.49595). The figure is oriented with West at the top of the image, and north to the right.

Figure 3.99 shows the undamaged bridge upstream (south) of the breach located at E Rosebud Rd. The smaller undamaged bridge is reinforced concrete with reinforced concrete piers connecting to driven steel piles. Heavy vegetation armoring of the bridge was intact downstream of the bridge at the time of the GEER visit, while areas without vegetation armoring of the bank upstream of the bridge were heavily eroded. This undamaged bridge is not on a bend in the river, which kept fluid velocities lower. The bridge has little freeboard and was thus overtopped. Figure 3.99 also shows sediments left after floodwaters receded at this bridge, indicating that the bridge partially dammed the creek at this location and caused waters to jump the channel banks and spread throughout the town (see Figure 3.99 (bottom left) for the extent of these overland flow sediments). This bridge did have large and deeply embedded wing walls. The combination of large and deep wing walls, plus a straight channel alignment are proposed as major factors of why the undamaged bridge survived intact with no visible damage. Significant erosion occurred upstream of this bridge, with a cluster of willows and cottonwood trees who had grown in the channel scoured away on the west side of the channel, and a building destroyed and approximately 12-meters scoured out on the east bank.

Figure 3.99: Undamaged bridge in Roscoe, MT. Note sediments deposited from overbank flow. Areas lost to scour in the flood are indicated (45.349492, -109.495930).

Figure 3.100: Google Street View of E Rosebud Rd bridge prior to flood event (Nov 2021), Source: Google maps (45.34949, -109.495908).

Figure 3.101: Undamaged bridge along E Rosebud Rd in Roscoe (45.34949, -109.495908).

Downstream (north) of the undamaged bridge described above is where the natural levee between East Rosebud Creek and a small stream was breached by floodwaters. Significant damage to the north approach to this bridge occurred during the breach of the natural levee. Figure 3.102 shows an UAV image of the repaired breach and the bridge along HWY 78. Water at the top of the image represents remains of the flood in a small brook channel that the river coursed down after the breach. The unpaved road is part of the emergency repairs to the breach, and historically sat atop the natural levee.

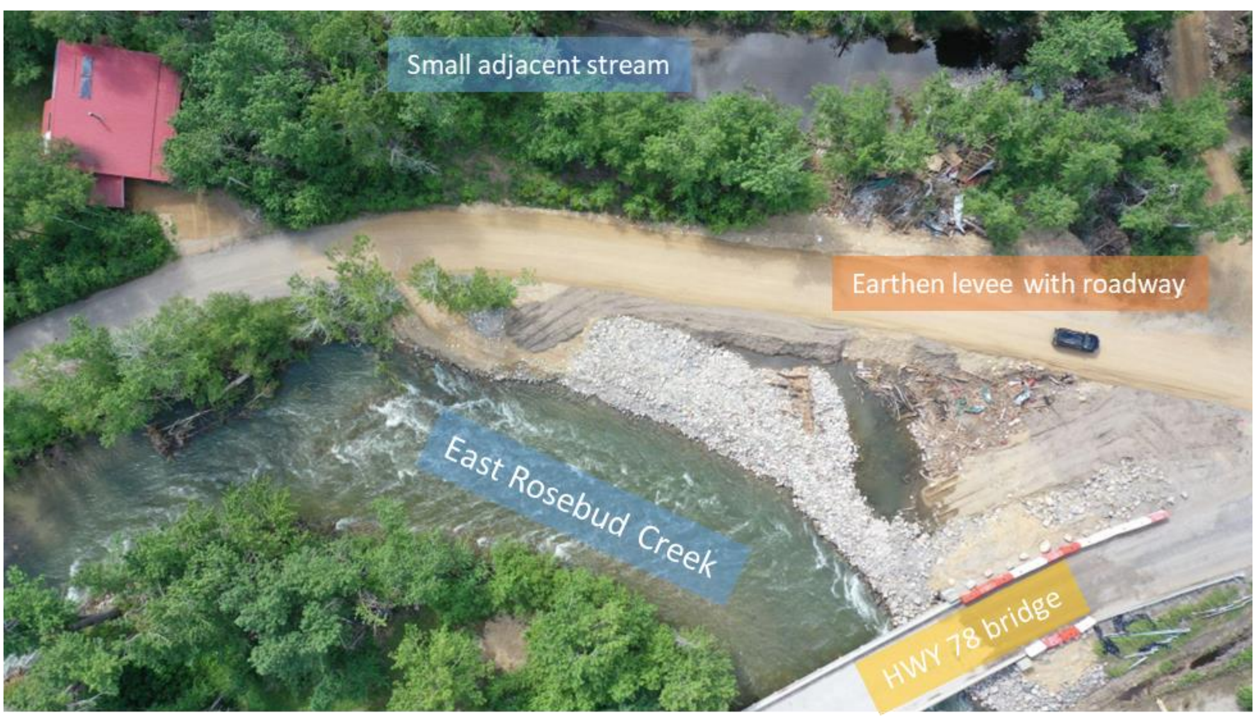

Figure 3.102: UAV image of the repaired breach and abutment scour damage that had been repaired at the time of the GEER visit. (45.35073, -109.4955034)

The main bridge in the town of Roscoe is located on Montana State Highway 78. This bridge is reinforced concrete with concrete piers connecting to steel piles. It has little freeboard above the creek and its wing walls were minimal. Prior to flooding, minimal rock armoring was present at the bridge and scoured away in the flood. This bridge is located at a major bend in the river and scour damage and breach of the natural levee occurred on the outside of the bend, where fluid velocities are highest. Figure 3.103 shows a photograph of the bridge at HWY 78 in Roscoe obtained from online sources taken during the flood, as well as one photograph taken by the GEER team during the reconnaissance visit. Figure 3.104 provides some additional angles of the HWY 78 bridge in Roscoe.

Figure 3.103: HWY 78 bridge across East Rosebud Creek in Roscoe during (top) and after the flood event; Source for top photo: https://nbcmontana.com/news/local/montana-national-guard-assists-with-search-rescue-efforts-amid-flooding; (45.35073, -109.4955034)

Figure 3.104: HWY 78 Bridge in Roscoe, with post-flood riverbank stabilization, also showing scoured abutment support (45.35073, -109.4955034).

Recalling Figure 3.102, a small stream ran parallel to East Rosebud Creek, approximately 50-meters to the west. A natural levee separated the low-lying areas of the brook from the main creek channel. A road had been constructed atop the natural levee. The brook runs parallel to Highway 78 and East Rosebud Creek through the town of Roscoe until passing under the highway and connecting with the Creek north of the town. During flooding, East Rosebud Creek cut through the natural levee and road, and breached into the low-lying area of the brook. The majority of flood waters left the historic channel and followed the alignment of the brook after the breach. This flooded the low laying area of the brook and washed a cabin away. Prior to breach of the natural levee, significant scour damage to the west abutment of the bridge occurred. During repairs of the breach, additional scour damage to the bridge abutment occurred. At one point, the west abutment was separated from the roadway by a distance of at least 5-meters by estimates of locals who participated in emergency repairs.

Repair of the natural levee and diverting floodwaters back into the channel became an immediate priority for locals, who mobilized equipment to perform the repairs shown in Figure 3.105. Rock was sourced from local glacial moraine hillsides to form the emergency repair. At the time of the GEER visit, the scour hole behind the west abutment had been repaired by county and state officials, local contractors, and ranchers. Repairs of both the natural levee and the bridge approach consisted primarily of dumping 0.2 to 2-m diameter rounded glacial moraine boulders to form a working platform. These boulders were dumped and spread with heavy equipment to a level at which geosynthetic sheets could be rolled out. Alternating layers of geosynthetics and rock were placed until a stable berm formed. For the bridge approach and west access road repairs, these rounded boulders were topped with mined angular 0.1 to 1-m rock armoring and engineered DOT spec base course material, reinforced with geosynthetics. Geosynthetics used in repairs appeared to the GEER team to be a mix of filter fabrics, woven separation fabrics, and higher strength fabrics composing whatever was available on short notice in the area.

At the time of the GEER visit, the rock berm shown in Fig. 3.105 and unpaved access road have replaced the natural levee to protect the homes in the low-lying land of the small brook that runs parallel to the creek. Most of the water in the low-lying area west of the natural levee had drained, but large pools remained. A cabin structure was washed away after the breach, and the site of the former structure is shown in Figure 3.106. The GEER team had no indication that a structure was there from visual inspection until locals pointed out the location. Upon closer examination, only small fragments of pavement, foundation, and utilities were left. This suggests that at least 1-m of material was removed from the low-lying area after the breach.

Figure 3. 105: Terrestrial view of the repairs of the breach, taken from the damaged bridge. Locals pushed rock from nearby moraines into the new channel that the river had cut to repair the breach of the natural levee. The road was constructed a few hours after the breach was repaired and the river redirected under the bridge.

Curiously, areas with healthy turf grasses resisted erosion and were present after the flood. Figure 3.106 shows some of those turf grasses closer to the small brook at the far side of the mass-eroded building site. At the top of the image are several cabins who had sustained minimal flood damage that sit atop the bank of the brook. In the low-laying area of the brook, this homeowner had armored the east side of the small brook several years ago with 0.5 to 1.5-m rounded boulders and geosynthetics. This bank of the small brook resisted erosion. Despite other areas with large boulder armoring seeing the boulders removed by high velocity floodwaters, these geosynthetic reinforced boulders remained intact.

Figure 3.106: Top: Location of a cabin that was washed away after the breach. Very little evidence of the shallow foundations are left. Note the boulder armoring from the neighboring cabin owners on the banks of the small stream (bottom photos); (45.351377 N 109.496156W)

In terms of boulders, the GEER team visited nearby glacial moraine exposures away from the creek that are nearly identical to the landform and geology that composed the natural levee between the creek and brook. These moraines contained a rich variety of rounded rock, from gravels, cobbles, and boulders up to 2m in diameter. This was consistent with other moraine exposures the GEER team encountered throughout the region, including in scour scarps on the several rivers and creeks observed.

The erosion and scour patterns along the brook and breach of the natural levee showed that 1) pavements, landscaping, and building are easily erodible unless reinforced and anchored, 2) boulders up to 2m in diameter were easily moved by the floodwaters, and 3) boulders with geosynthetic reinforcement, turf grasses, and well-anchored trees offer important resistance against erosion and scour.

Large sediment deposits up to 1-m thick were identified by the GEER team at Highway 78 where the brook passes beneath as it heads to its confluence with East Rosebud Creek. Figure 3.107 shows these sediments as well as flooded areas on the east of the highway that are an old meander of East Rosebud Creek prior to establishment of the town. These pre-development meanders flooded easily and remained flooded despite overall drainage of the area. These meanders had been undeveloped due to the marshy nature of the land.

Figure 3.107: Remnant sediments and water at the east-end of Roscoe where the new channel crossed over the highway and followed the path of the small brook back to East Rosebud Creek historic channel. Flooded areas are pre-development meander of the Creek.

3.2.4.2 Large DOT Bridge on State Road 78 over East Rosebud Creek

Unlike the damages seen to bridges in Red Lodge and Roscoe, a zero-damage case history located between Roscoe and Absarokee, approximately 10-km north of Roscoe is notable in contrast to the failures. This bridge also crosses East Rosebud Creek. This reinforced concrete bridge is founded on 3-m diameter drilled shafts and monopole columns. The abutments are set back from the channel 20-meters. The bridge is super-elevated 10-m above the creek's typical water surface elevation, providing a large freeboard. The bridge spans allow for a 100-m wide space for the creek to move. This bridge is shown in Figure 3.108. Very little scour or erosion was observed on any banks due to the wide, flat channel in this area. Super-elevation from large approach embankments and freeboard allowed for no damage to the abutments. This bridge is a “textbook” case of how to design a bridge to withstand 1,000 year or larger flood events.

Figure 3.108: Terrestrial oblique view of the Highway 78 bridge over East Rosebud Creek (45.4351 N, 109.4675W).

This bridge also provides a critical case history in impact loading to columns. Figure 3.109 shows a close-up image of the center pier of the bridge, in the middle of the channel alignment at the time of the GEER visit. This pier showed limited signs of impacts from boulders during the flood. These impact indications are difficult to see in the photo, but above and below the waterline are spalled and broken concrete on the upstream side only, indicative of impacts. Bridge designers typically account for impact loads from vessels, ice, and logjam flotsam. However, in the high-energy mountain creeks and rivers of Montana and similar geographies, boulder impacts need to be considered as well. Other boulder impacts observed on Rock Creek and the Stillwater River by the GEER team reinforce this notion. New gravel bar from flooding seen in the background along with minor erosion of the bank.

Figure 3.109: Large monopier supporting the HWY 78 DOT bridge across East Rosebud Creek at 45.4351 N, 109.4675W.

3.2.4.3 Double Bridge at the East Rosebud Creek

To the west of Montana Highway 78, a county road crosses over East Rosebud Creek. This crossing consists of two bridges approximately 40-m apart, with a small island between the bridges. Figure 3.110 shows the location of the double bridge along county road 419, the confluence of the East and West Rosebud creek, and the location of a bridge further north, after the East and West Creek confluence.

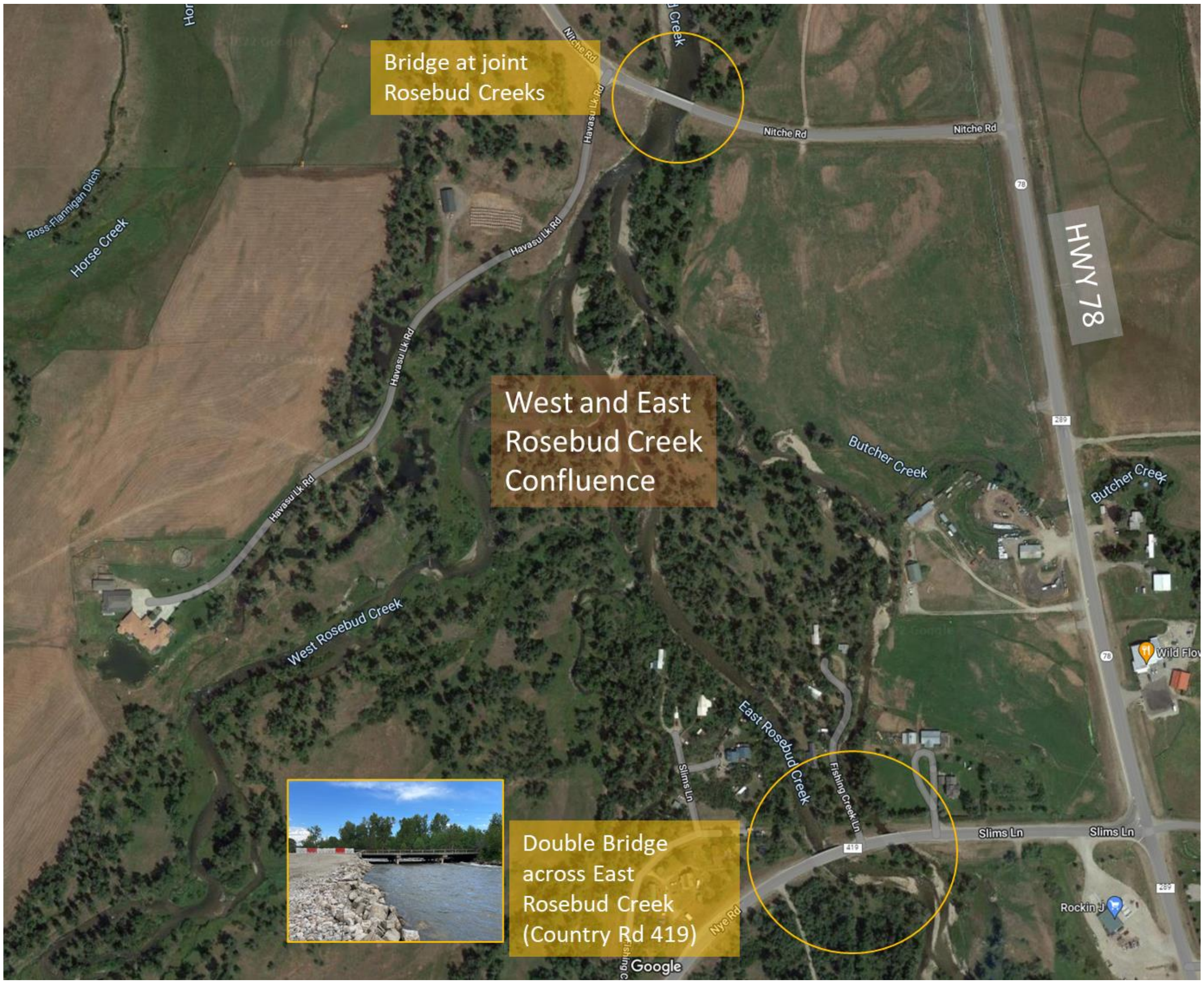

Figure 3.110: Location of the East Rosebud Double Bridge and the confluence of the East and West Rosebud Creeks.

During flooding, East Rosebud Creek backed-up as logjam flotsam blocked the flow. Minor flooding occurred from overbank flow on either side of the channel until the creek cut a new channel between the two bridges, completely eroding away the material behind the two abutments and wing walls. Piles were exposed beneath abutments at some point in the flooding. Piles were observed to be moderately corroded and showed no signs of impacts from large boulders. It is likely that water velocities were much lower in this location due to the flat grades.

Repairs were completed at the time of the GEER visit. Figure 3.111 presents the scenario. Although there is a wide channel and flat channel grade at this location, the bridges have less than 1-m freeboard at normal flow levels. During flooding, both bridges were overtopped, and the creek cut a new channel between the bridges, completely exposing the wing walls and abutments. Repairs by locals and the state included rebuilding of the island between the bridges with angular mined rockfill and local glacial moraine soils, known locally as “bank-run”. This rockfill consisted of cobbles and boulders up to 0.3-m. The local glacial moraine “bank-run” in this area do not include boulders but are instead cobble-rich. All rockfill was topped by DOT spec granular base course material. Prior to the flood the island consisted of the local bank-run coble material that can be seen in Figure 3.111.

Figure 3.111: Aerial UAV view of repaired double bridge location. Terrestrial photos show exposed pilings on both bridges post-repair. Corrosion of piling is moderate (covers ~60% of steel, 45.4805 N, 109.454 W).

The confluence of East and West Rosebud Creeks is approximately 15-km north of Roscoe, half-way between the towns of Fishtail (on West Rosebud Creek) and the confluence with the Stillwater River at the town of Absarokee. The confluence is in a wide and flat portion of the valley, where the grade of the creeks are nearly flat.

Downstream of the double bridge shown in Figure 3.111, at the confluence of East and West Rosebud Creeks, the flat valley bottom was flooded, and remained flooded at the time of the GEER visit. Figure 3.112 shows UAV image of some of these flooded areas north of the bridges. These areas were developed by cabins and ranches as they had not previously flooded due to natural levees on the banks of the channel. Breaches in the natural levee compounded with elevated water from logjam dams along the creek redirected water into these flat areas. These areas are in the paleo-meander zone for the creeks, but natural levees had been in place long enough to allow for sustained development. With breaches of the natural levees that allowed water in, flood waters persisted at the time of GEER visit since there was no drainage out of the lowlands.

Figure 3.112: Overbank flooding persisted several weeks after the main flood event from breaches in the natural levees along East and West Rosebud Creeks and pooling from log dams in the main and side channels. (45.482N, 109.456W)

The bridge at the confluence of the East Rosebud Creek and West Rosebud Creek (Figure 3.110, top) experienced no notable damage except for minor erosion of rock armoring near the abutments. Being located at a straight section of the creeks' channel and being of newer construction equipped with deep seated abutments, no flood-related observations could be documented by the GEER team.

3.2.5 Observations along the Stillwater River

Substantial flooding was experiences in the plains of the Stillwater River. In addition to damage to residential and agricultural structures, as well as substantial erosion along the Stillwater riverbanks, the GEER team observed several bridges that were either damaged or destroyed crossing the Stillwater River, as well as major erosion events with significant consequences to the local economy despite not being on major highways. As a reminder, in rural areas, county and forest roads may be vital links for major industry that supports the local economy. This is true along the Stillwater River, as the Mountain View platinum mine is a major employer, and is accessed by a county, rather than state, road. All GEER team activities along the Stillwater River were upstream of the town of Absarokee and focused on the reaches of the river near the town of Nye. Figure 3.113 shows several images immediately after the flood obtained from online sources to document the extent of the flood coverage outside of the Stillwater River Channel.

Figure 3.113: Aerial Images of the Stillwater River around Nye. Picture Credit: Larry Mayer, Source: https://billingsgazette.com/news/local/photos-aerials-of-stillwater-and-boulder-river-flooding/collection_9a55b73c-eb65-11ec-a418-237d88c84135.html#2

3.2.5.1 Mountain View Mine, south of Nye

Most observations by the GEER team on the north and northeast slopes of the Beartooth massif were out away from the mountains or even past the foothills. However, in the area of Nye, the damages observed by the GEER team were located at the immediate base of the Massif, with the Stillwater River at a steep grade and flow velocities high. The first major bend in the Stillwater River at the mouth of the canyon is immediately to the north of the Mountain View Mine. At this bend, the GEER team documented a major erosion event, with greater than 100,000 m^3 of soil removed by the flood event on the outside of the bend. Figure 3.114 shows a UAV image of the erosion site, while Figure 3.115 shows a terrestrial photo of the scarp.

Figure 3.114: Major erosion immediately below the Mountain View Mine on the Stillwater River. Approximately 300-m of road has scoured away, with a scarp approximately 20-m high. Ductile utility lines can be seen suspended above the river. The historic channel appears on the left as a gravel beach (45.39317N, 109.87111 W).

Figure 3.115: Terrestrial view of the Stillwater River and the Mountain View Mine in the background. Temporary utility lines are seen on the ground surface in orange. (45.39317N, 109.87111 W)

Figures 3.114 and 3.115 show several ductile utilities that were in the county road, hanging suspended from either end of the scarp. This erosion likely shifted the channel by approximately 20-meters to the west, leaving a large gravel beach/bar area in the alignment of the old channel.

The GEER team was unable to observe any erosion of the tailing piles of the mine, or any damage upstream of the washout shown here. However, conversations with the US Forest Service indicate that the bridges on the river south of the mine, into the canyon that service a campground and hiking trails were essentially removed by the flood. The GEER team was able to fly the erosion site and an orthomosaic has been created for community use.

Additional damage was observed downstream of the Mine, all along the channel. Much of the river is on private property between the town of Nye and the Mine, so detailed observations are limited. However, two other cases are worth noting. The first is a cabin, shown in Figure 3.116, that experienced significant scour, yet is still standing. The deck to the house has been torn off the structure, as the river cut into the bank about 20 meters. The gravel bar in the foreground appeared to be newly deposited and is at the approximate previous edge of the channel. Two additional buildings and a bridge were taken out at this location (45.396N, 109.864W), with erosion so massive that all traces of these buildings and bridge were gone at the time of the GEER mission. The only reason the GEER team could identify the losses were examination of satellite photos pre-event.

Figure 3.116: House on the Stillwater River to the North of the Mountain View Mine cantilevering over the new channel. Two identical buildings to the left have been swept away. (45.396N, 109.864W)

The second observation on the Stillwater River south of Nye was that several private bridges survived, while other private and US Forest Service Bridges were removed or heavily damaged by the floods. Due to the private land, these were only observed from the main county road in the distance, and the GEER team was unable to collect satisfactory photographs for this report. The surviving bridges all shared the following characteristics, despite age, method of construction, and bridge material. While concrete and steel bridges were destroyed, older timber bridges survived if they had the following three characteristics: 1) elevated approaches to the bridge that gave the bridge at least 3-meters of freeboard above the river surface at the time of the GEER visit; 2) a widened channel and multiple spans, with room beneath the bridge for the river to migrate and meander; and 3) large and deeply set wind walls at the abutments. All three characteristics were observed to be essential for bridges to survive this flood event, no matter the age, material, owner, or apparent fragility. One such bridge on private land appeared rickety and unsafe for heavy vehicles due to its aged timbers yet survived the flood with no apparent damage (from the flood). Figure 3.117 shows several washed out bridges in Nye, obtained from the local newspaper Billings Gazette and added for completion.

Figure 3.117: Bridge damage along the Stillwater River near Nye, photo Sources: https://billingsgazette.com/news/local/photos-aerials-of-stillwater-and-boulder-river-flooding/collection_9a55b73c-eb65-11ec-a418-237d88c84135.html#2

3.2.5.2 Beehive Bridge

16-km north and east of Nye on the Stillwater River is the cabin community of Beehive. This cabin community is dispersed across many km of the foothills. The county road Stillwater River Rd (#420) crosses the Stillwater River in a small pass between two large sandstone hills. At this location, a culvert was installed when the bridge was reconstructed some years ago as a diversion for irrigation for local farms. The bridge is a single span reinforced concrete structure on driven steel pile foundations. The approaches are at grade, with superelevation over the channel from the elevation of the bank on either side of the channel. This bridge is not on a bend in the river, but on a straight section of channel. This bridge is the only access for the community. Figure 3.118 shows a photo of the bridge prior to the flood.

Figure 3.118: Stillwater Rd Bridge along County Rd 420, across the Stillwater River prior to the flood event. Image obtained from Google Street view.

The washout of this bridge results in a 2-hour drive back to Nye and then over to the West Rosebud Creek drainage.

The GEER team was able to fly the bridge with UAV and to perform terrestrial laser scanning. The bridge was overtopped during the flood, and the channel cut behind the small wing walls and eroded behind the abutment, while also scouring out around the piles. Figure 3.119 shows this case history. Notable observations at the Beehive Bridge include boulder impacts to corroded piles (seen in Figure 3.119). Erosion of the sandstone up and down stream of the bridge at large bends in the river could be seen from the bridge with binoculars, showing that the flow velocity was sufficient to scour a finely bedded sandstone. Much of the rock armoring at this bridge was the same, which showed significant erosion damage if sandstone. The scour hole at the abutment is approximately 1 m wide and up to 2 m deep. Exposed piles are highly corroded. A boulder has impacted the pilings and is wedged between the piles and a pier for a previous foundation for a historic bridge.

Figure 3.119: The Beehive Bridge on the Stillwater River showing the washed-out north abutment (45.5033376, -109.6524668).

3.2.5.3 Cliffswallow

As fly-fishing recreation area along the Stillwater River, Cliffswallow bend is a favorite of locals for the flat grade of the channel. The GEER team documented with UAV flights a large erosion site shown in Figure 3.120. This site, located in a small alluvial terrace deposit and wedged between early paleocene sedimentary rock hills was characterized by exposed boulders which were not eroded, but left in place. The erosion occurred on the outside bend of the channel, as would be expected, where fluid velocities are high enough to carry away sand and gravel sized particles. However, the GEER team documented that boulders larger than 0.5-m simply rolled into the water here rather than being carried downstream en-mass. Thus, it appears that fluid velocities were low enough here to not carry away larger boulders, but sufficient to cut into the slope. Boulders exposed by the flood under the road have only moved a few meters downstream into the gravel bar. This location is only 2-km away from the Beehive Bridge site, where boulders moving down the channel were documented by the GEER team (boulder impact to bridge foundations). The grade of the channel flattens considerably downstream of Beehive Bridge, while the channel widens significantly once it makes its eastward turn at the sandstone outcrops north of the Beehive Bridge. Thus, significantly lower fluid velocities should be lower at Cliffswallow. Also notable at Cliffswallow was a lack of vegetation armoring of the channel banks in the area, and minor erosion was almost continuous in this area.

Figure 3.120: The 100-m long scour event along the Stillwater River at the Cliffswallow Fly Fishing Recreation Area (45.5108N, 109.63666W). Scarp is approximately 8-m high.

3.2.6. Clarks Fork River

Media reports investigated prior to the GEER Team's arrival in Montana cited significant flooding and damage in the rural city of Fromberg along the Clark's Fork Yellowstone River. A GEER Team member visited the city to document any apparent damage or effects from the flood. As he explored the city, no visible evidence of flooding could be seen anywhere. Curiously, some residents living immediately adjacent to the river were observed to be "mowing or watering their lawns" at the time of the GEER visit.

Upon speaking with local residents, the GEER team member was informed that the entire eastern portion of the city east of Highway 310 (Figure 3.121) was "under a few feet of water for a few days." Flooded residents were housed temporarily in the local school gymnasium. However, residents were clearly living in these flooded houses again at the time of our visit, and no apparent evidence of the flooding - including sediment deposits - was observed during the GEER team visit. Therefore, no additional efforts to document flood damage in Fromberg were undertaken by the GEER team.

Figure 3.121: Satellite image of Fromberg identifying the area that was flooded according to local eye-witness accounts. No apparent evidence of flooding was observed by the GEER Team during our visit

4. Summary of key Take-Aways

The following bullet points summarize key take-aways of the 2022 Southern Montana/Yellowstone flood event and are based on observations, findings, and interpretations of the team observed through field documentation and in-situ measurements performed in July 2022.

- Flood flow velocities supported the transport of boulders in several instances
- Abutments with deeply seated and wide wingwalls survived better than those with small or shallowly bedded wingwalls
- Bridges with extra width for channel migration survived better
- Bridges with additional superelevation that allowed more freeboard survived better
- Bridge foundations suffered many boulder impacts but fared well unless corrosion was significant or other factors compromised the structural integrity of the piles or shallow foundations. Timber piles fared as well as steel or concrete piles.
- Large diameter drilled shaft foundations and monolithic piers performed well at all locations observed by the GEER team.
- Bridge failures and scour damage to infrastructure were almost always on the outside bend of the channel, where higher fluid velocities lend to greater erosional forces
- Timber bridges, even of advanced age, survived well, with minimal damage, if other compromising cofactors were not present (on a straight section of the channel, with good wingwalls, extra width and super-elevation, etc.).
- Mine tailings were highly erodible, even with rock armoring (armoring washed away early in the flooding)
- Sloped steepened by scour had not failed in some cases at the time of the GEER mission but large tension cracks were documented and are in danger for failure in the next freeze-thaw cycle and/or wet season
- Scour holes were common at bridge bents, and gravel dynamics were evident at many locations along the rivers
- Vegetation armoring of banks was highly effective in healthy stands of trees, with diverse species of trees, shrubs, forbs and grasses.
    - Overly dense stands of trees with little diversity and no understory were more susceptible to erosion than more widely spaced trees with a diverse understory
    - Turf grasses were highly resistant to scour if dense and deeply rooted, and especially if complemented by shrubs and native forbs
    - Trees with few to no sinkers were quite vulnerable to scour, as were isolated trees without support from healthy grassland or shrubs

- Natural levees were relied on by local communities but were frequently compromised by flood waters not seen in these communities since before World War II.
- Flexible utilities were able to survive erosion, and continued operation in some cases despite being suspended above or along scarps
- The presence of gravel shoals near sandy riverbanks appeared to enhance symmetry of flow, erosion, and scour.

5. References

American Society of Civil Engineers (ASCE). (2022). Yellowstone flood damage will take years to repair. Accessible at https://www.asce.org/publications-and-news/civil-engineering-source/civil-engineering-magazine/article/2022/08/yellowstone-flood-damage-will-take-years-to-repair. Last accessed on August 9, 2022.

Billings Gazette (2022). "Photos: Aerials of Stillwater and Boulder River flooding"; from the Series "Flood Coverage: Severe flooding pummels Mountain West, Yellowstone National Park series. By Gazetter Staff, June13th, 2022. Retrieved from: https://billingsgazette.com/news/local/photos-aerials-of-stillwater-and-boulder-river-flooding/collection_9a55b73c-eb65-11ec-a418-237d88c84135.html#2

City of Red Lodge (2022). Official Website of the City, accessed at https://www.cityofredlodge.net/

Daily Mail (2022). "Dramatic moment Montana National Guard aircrews rescue dozens of people trapped in Yellowstone floods", accessed at https://www.dailymail.co.uk/news/article-10924951/Dramatic-moment-Montana-National-Guard-rescuing-dozens-people-trapped-Yellowstone-floods.html

Geraghty, E. (2013). Geologic map of the Stillwater Complex within the Beartooth Mountains from Laramide triangle zone South Central Montana. *Montana Bureau of Mines and Geology Open File Report MBMG 645*.

Lopez, D.A. and Reiten, J.C. (2003). *Preliminary geologic map of Paradise Valley South Central Montana.* Montana Bureau of Mines and Geology Open File Report MBMG 480. Accessed through https://mbmg.mtech.edu/pdf-open-files/mbmg480-ParadiseValley.pdf

Lopez, D.A., (2005). Geologic map of the Red Lodge Area, Carbon County, Montana. Montana Bureau of Mines and Geology Open File Report MBMG 524.

Montana.Gov (2022) Official State Website of Montana. Published by the Montana Department of Transportation. Accessed through https://www.mdt.mt.gov/travinfo/beartooth/

National Aeronautical and Space Administration (NASA). (2022). Catastrophic Flooding in Yellowstone. Accessible at https://earthobservatory.nasa.gov/images/150010/catastrophic-flooding-in-yellowstone. Last accessed on August 9, 2022.

National Integrated Drought Information System (NIDIS). (2022). Drought Conditions for Park County. Accessible at https://www.drought.gov/states/wyoming/county/Park. Last accessed on August 9, 2022.
National Weather Service (NWS). (2022a). June 2022 Unprecedented Flooding in South-Central Montana. Accessible at https://www.weather.gov/byz/June-2022-Unprecedented-Flooding. Last accessed on August 9, 2022.
National Weather Service (NWS). (2022b). Advanced Hydrologic Prediction Service. Accessible at https://water.weather.gov/ahps2/hydrograph.php?wfo=byz&gage=corm8 and https://nwis.waterdata.usgs.gov/mt/nwis/peak?site_no=06191500&agency_cd=USGS&format=html. Last accessed on August 9, 2022.
United States Geological Survey (USGS). (2022). Peak Streamflow for Montana. Accessible at https://nwis.waterdata.usgs.gov/mt/nwis/peak?site_no=06191500&agency_cd=USGS&format=html. Last accessed on August 9, 2022.
Yellowstone National Park. (2022). Photos for the news media. Accessible at https://flickr.com/photos/yellowstonenps/albums/72157668680150793. Last accessed on August 9, 2022.
Gardiner Chamber of Commerce and CVB (2019). *Annual Report,* retrieved from https://www.visitgardinermt.com/images/2019_Annual_Report_FINAL.pdf