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The role of gravel shoals on scour and erosion in the Yellowstone River during the 2022 flood event - initial observations

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ABSTRACT

In June 2022, the Yellowstone River experienced major flooding, leading to significant infrastructure and property damages. Data was collected in July 2022 and in October 2022 starting from the confluence of the Gardner and Yellowstone Rivers and continuing along the Yellowstone River through the town of Gardiner, Montana to the town of Livingston, Montana. Many of the significantly impacted river segments featured gravelly shoals and sandy-gravelly river banks, suggesting that in some of these locations the river banks were more susceptible to erosion than the shoals. Qualitative assessment of flow direction and velocity suggested that gravel shoals affected flow direction, and thus, the flow's angle of attack towards river banks or infrastructure such as bridge piers and abutments. Erosion was clearly enhanced at the affected river banks. Furthermore, bridges featured noticeable differences in scour and turbulence depending on the bridge pier/abutment alignment with the gravel shoals.

INTRODUCTION

The northern parts of the Yellowstone National Park and areas north and east of the Park experienced severe rain coupled with melting of winter snowpack in June 2022. This led to the largest flood event on record in this region, significant damages to infrastructure, and disruption to thousands of residents. This study is based on data collected through reconnaissance efforts by the Geotechnical Extreme Events Reconnaissance Association (GEER) conducted in July 2022 less than two weeks after the event (Lemnitzer et al. 2023) and focuses on a site along the Yellowstone River in Gardiner, Montana. In this area, damages to infrastructure included the destruction of utility lines crossing the river, the loss of buildings constructed at the riverbank, as well as many significant riverbank failure, erosion, and sediment relocation events. Scour and erosion at and near structures was observed at multiple locations. This manuscript discusses observations made during the July 2022 GEER reconnaissance mission regarding flow-structure-soil interaction at the Cinnabar Basin Rd bridge in Gardiner, Montana. Here, a gravel shoal was present upstream of the bridge location that seemed to direct flows asymmetrically at riverbanks, bridge piers, and abutments. Thus, it may be hypothesized that the gravel shoal increased the scour risk to bridge piers and abutments. The reader is referred to Lemnitzer et al. (2023) for a comprehensive presentation of observation made during the GEER July 2022 data collection.

A number of different processes led to the flood event in southern Montana in June 2022. First, an atmospheric river, a band of tropical moisture, carried significant rain- and snowfall into northwestern Wyoming and southern Montana, creating an extended period of high moisture that led to high water levels starting on June 11, 2022. Additionally, rivers in the proximity of Yellowstone Park carry typically higher flow in late spring from snow melt. However, snowmelt was unusually slow in 2022 pushing higher water levels into early summer. Both processes together led to the extreme water levels of June 2022. USGS Yellowstone River Gauge 06192500 in Livingston, MT, peaked at approximately 1557 m^3/s discharge, more than 300 m^3/s faster than previous flood conditions. USGS Yellowstone River Gauge 06191500 in Gardiner, MT, peaked at approximately 1388 m^3/s discharge, more than 450 m^3/s faster than any previously recorded event.

The local geology is characterized by glacial valleys and a history of glaciation, often resulting in U-shaped valleys with terraces of rounded gravels, cobbles and boulders in a largely sand matrix that the rivers incise. Alluvium in the canyons and river valleys is typically Holocene, while glacial deposits are generally Pleistocene with a few areas of more recent Holocene activity. Alluvium is often in terrace deposits. Terrace deposits can 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 (Lopes and Reiten 2003; Pierce et al. 2014).

Livingston, MT is located 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. Carters Bridge at the northern end of the Paradise Valley and the majority of the Paradise Valley represent glacial outwash deposits and alluvial terraces. North of the Yellowstone River Gorge, the Paradise Valley and most of the

Gardiner area represent a complex of alluvial terrace deposits, glacial terraces, glacial outwash, and Andesite vent facies, sills, flows, and breccias (Lopes and Reiten 2003).

FIELD LOCATION

One field site is considered for this article: the Cinnabar Basin Rd bridge. However, similar features were observed in other locations. The Cinnabar Basin Rd bridge crosses the Yellowstone River at N45°6'41.41" W110°47'35.05" in Gardiner, Montana (Fig. 1). The river has an approximate width of 84-94 m depending on water level (based on the Google Earth image shown in Fig. 1 from July 2014 and data from September 2019). The Yellowstone River is fairly straight for at least a kilometer upstream and downstream of the bridge. However, sediment deposits are visible in the inner sides of the light meanders with one inner bend shoal visible in 2014 only ~250 m upstream of the bridge at the southwestern river bank. More recent imagery shows that this shoal grew bigger by 2019, narrowing the river and increasing meandering just upstream of the bridge. The shoal is composed predominantly of gravel and cobbles, and is likely less erodible than surrounding sand-gravel mixtures along the river banks. It may be hypothesized that decreasing

Figure 1. Google Earth Image of the Yellowstone River Cinnabar Basin Rd Bridge in Gardiner, Montana, with blue arrows indicating the flow direction from southeast to northwest.

the river cross-section in the shoal section increases flow velocities and discharge just upstream of the bridge and that increasing meandering directs peak flows towards the outer bend, i.e., the northeastern riverbank, abutment, and bridge pier upstream of the bridge. The bridge represents the transition point from a west bend meander to and east bend meander, directing peak flows just downstream of the bridge to the southwestern river bank, and possibly at an oblique angle at the bridge.

U.S. Geological Survey (USGS) gauge 06191500 is located in the direct proximity to the bridge (Fig. 2). It recorded a high water level of 4.23 m on June 13, 2022 compared to 1.52 m in the previous year. The discharge during the 2022 flood event peaked at 1339.39 m^3/s.

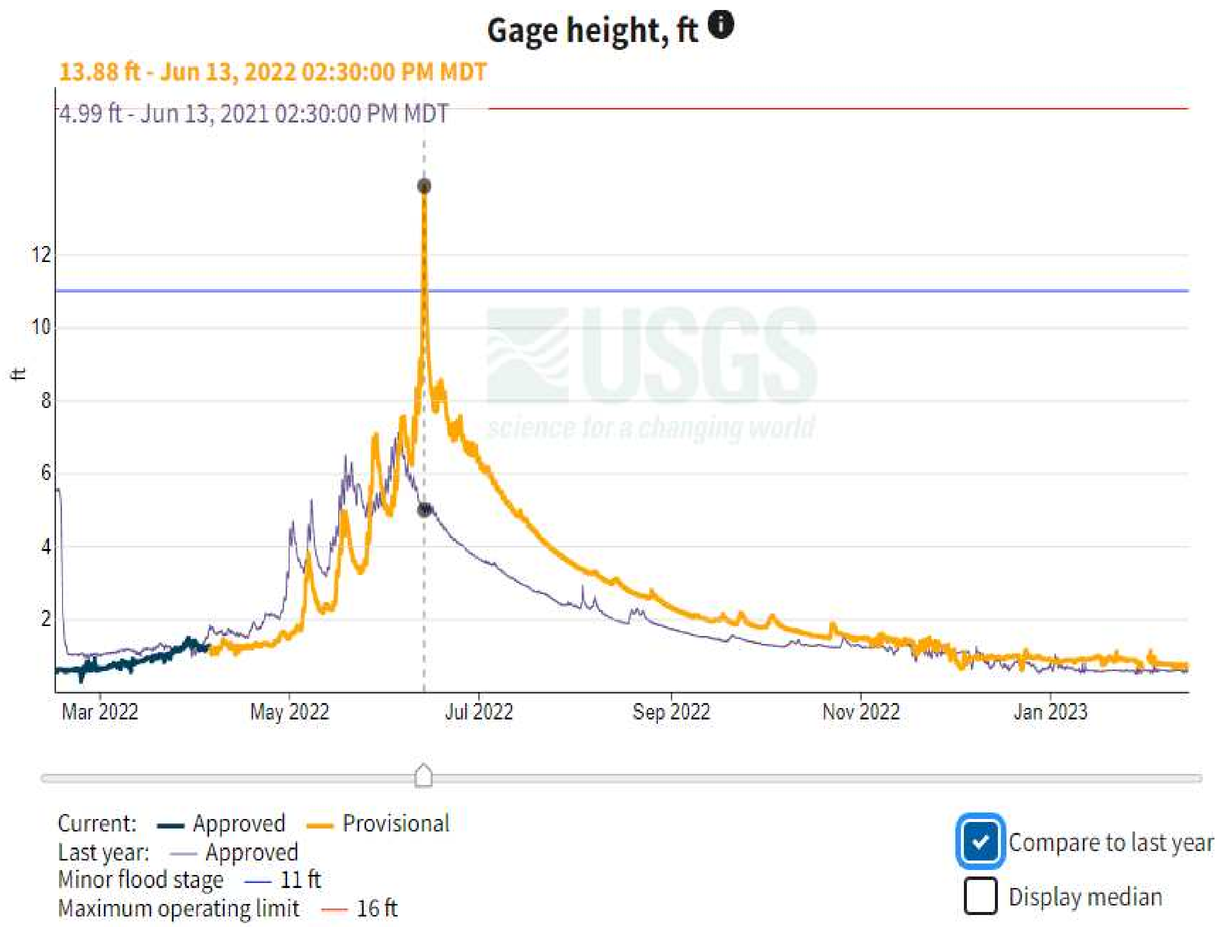

Figure 2. USGS gage 06191500 data for Mar 2022 to Jan 2023 (orange) and the previous year (purple). ***https://waterdata.usgs.gov/monitoring-location/06191500/***

OBSERVATIONS

The bridge was in good condition during the GEER reconnaissance mission and fully functional. However, asymmetric flow seemed to apply to the northeastern versus southwestern bridge sides, and diagonal erosional and depositional sediment relocation patterns were visible. Figure 3 (top) shows the upstream side of the bridge looking from the southwestern side to the northeastern river bank. Comparison of qualitative flow appearance at the two bridge piers suggested no visible turbulence at the southwestern bridge pier but significant turbulence as well as debris wrapped around the bridge pier at the northeastern pier. Looking from the downstream side, whitewater in the shape of a horseshoe wrapped around the front and sides to the lee of the northeastern pier (Fig.

Figure 3. Photographs of the Cinnabar Basin Rd bridge from June 30, 2022: Top: from upstream southwestern bank; bottom left: from northeastern abutment; bottom right: from downstream southwestern bank.

3 bottom right), and a view from the northeastern abutment shows also significant turbulence between the northeastern abutment and bridge pier (Fig. 3 bottom left).

Significant erosion on the order of meters from the pre-flood location of the riverbank was visible on the upstream northeastern riverbank with significant erosion at the upstream side of the northeastern bridge abutment (Fig. 3 top), leading to undermining of the concrete structure and exposure of the metal piles (Fig. 4). The erosion of the riverbank exposed a gravelly sand top layer, underlain by sandy gravel, and a gravel bottom and toe. Even coarse gravel and cobbles seemed to be removed within a scour hole that developed in front of the upstream abutment corner (Fig. 4). On the other hand, the upstream southwestern river bank featured sandy deposits with multiple deposit terraces and ripple development with sand ripple wave length on the order of 10 cm (Fig. 5).

Vice versa, downstream of the bridge, erosion was prominent at the southwestern riverbank (Fig. 6). Reports from residents and high water marks confirmed significant inundation of the noticeably flatter downstream northeastern riverbank, but neither significant deposits nor significant erosion was obvious to the reconnaissance team

In summary, a diagonal pattern of erosion and deposition was observed from upstream to downstream of the bridge with strongest flows being directed at the northeastern bridge abutment and pier (Fig. 7). It is apparent that this results from slight meandering of the river that seemed to have increased over time with the bridge being located where the river meandering switches from a left-bend meander to a right-bend meander (looking downstream), and it may be hypothesized that this effect is exacerbated by inner meander deposition shoals being composed of coarse gravel and cobbles while riverbanks feature upper layers of sand and sand-gravel mixtures that are significantly more erodible.

Figure 4. Photograph of upstream corner of northeastern bridge abutment and riverbank.

Figure 5. Photograph of sand deposits upstream of the southwestern bridge abutment. Sand ripple wave length was approximately 10 cm.

Figure 6. Erosion at the southwestern riverbank downstream of the bridge.

CONCLUDING REMARKS

River meandering is a natural process that can change the flow angle of attack on aging infrastructure. Scour and erosion may then increase if flows start attacking abutments and piers at unfavorable angles. Erosion and deposition patterns in the vicinity of the Cinnabar Basin Rd bridge in Gardiner, Montana were investigated after the 2022 Yellowstone River flood in the area. Diagonal riverbank erosion patterns were in line with expectations considering the slowly increasing meandering of the river that can be observed in historic satellite images and the associated growing of an inner meander gravel shoal upstream of the bridge that is also constraining the river cross-section, and thus, likely leading to an acceleration of flows attacking

Figure 7. Annotated Google Earth image highlighting erosion and scour hotspots in the context of the river meander and gravel shoals.

the northeastern bridge abutment and pier. Erosion and scour may be exacerbated by the fact that inner meander shoals are composed of coarse gravel and cobbles while riverbanks feature top layers of more erodible sand and sand-gravel mixtures. While the investigated bridge remained undamaged during the flood event, increasing meandering and development of inner meander shoals may make the bridge more vulnerable with time. Identification of changes in the river course as observed here may assist with the development of mitigation strategies (for example, dredging of gravel shoals) and identification of possibly vulnerable locations. A more detailed investigation of the bridge followed including bathymetric measurements and confirmed scour evolution, but is out of the scope of this initial study.

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