MAPPING EXTREME DISCHARGE IN THE YELLOWSTONE WATERSHED DURING HISTORIC FLOODING IN 2022

by

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ABSTRACT

On June 13, 2022, Yellowstone National Park (YNP) experienced a historic flood event. The proximate cause for flooding was heavy rain on a late snowpack. An atmospheric river storm hit YNP discharging a record amount of rain on melting snow in a short period, causing extreme flooding in the region. In YNP, the watershed received a combined 7.5-9.5 inches of rain and snowmelt in a 24-hour period. Because this type of event is relatively rare in the Greater Yellowstone region, and the June 2022 event is recent, many questions remain including ones as basic as how extreme and extensive it was. Initial evaluations suggested that the recent flooding was unprecedented, but judgments were informal or preliminary. Therefore, I quantified the relative magnitude of the Greater Yellowstone region flooding in 2022 using hydrological records. The goals of my project were to analyze hydrologic data to characterize the magnitude of event runoff in YNP and surrounding areas and link the hydrological response to the meteorology of the type of severe rain-on-snow event that caused it. To evaluate the severity and spatial extent of extreme runoff during the June 2022 flood event, I analyzed USGS discharge data for stream gauges in YNP and the Greater Yellowstone region. I evaluated 139 gauges with long records to identify ones with extreme peak flows in June 2022 compared to historic peaks, selected a representative subset with extreme or non-extreme event hydrographs, and mapped relative peak size using GIS. Hydrographs showed that runoff in the core area featured a steep rise and fall as well as extreme discharge measured as the ratio of June 2022 peaks to maximum historic annual peaks. Mapping this ratio showed that the spatial extent of extreme flows included northern YNP, the Absaroka-Beartooth Wilderness, and adjacent areas. Extremes were concentrated in the upper Yellowstone River Watershed, but also occurred in neighboring watersheds. The extent of extreme runoff was consistent with the type of narrowly focused Pacific Northwest atmospheric river storms intense enough to penetrate this far into the interior western mountains.

INTRODUCTION

1.1 Yellowstone Watershed Flooding in 2022

In June 2022, Yellowstone National Park (YNP) experienced unprecedented flooding throughout the park and the park's gateway communities. In a 24-hour period, the northern part of the park received between 7.5-9.5 inches of water combined from rain plus snowmelt (Poland et al. 2022; NWS 2022). The magnitude of the floods is thought to have surpassed any in the last 500 years at some locations (NPS 2022). Flooding damaged several sections of the park's entrance roads, and the rivers were so high they carved new channels and eroded streambanks, washing away infrastructure, houses, and bridges. Due to the extensive infrastructure damage, YNP access was limited through the summer and fall of 2022. Roads opened to all traffic with no restrictions following expedited repairs in 2022 to preserve the national park's public access. The impacts of the historic flooding event will lead to at least three years of projects to repair and improve the park's infrastructure (Yellowstone National Park 2023). Ecologically, community and ecosystem level impacts of flash flooding on aquatic and riparian ecosystems and the entire watershed were a major disturbance and stressor that may have long-lasting effects on the Greater Yellowstone ecosystem and interconnected communities.

While it will take more research to evaluate its role in the 2022 Yellowstone flooding, climate change is thought to be altering precipitation and runoff regionally (Taboveari 2020). Storms associated with atmospheric rivers often deliver extreme amounts of rain and snow in a short period (Poland et al. 2022; Goldenson et al. 2018). The increasing threat of Pacific Northwest atmospheric river storms that penetrate into the Rocky Mountain interior may be linked to climatic changes in annual and seasonal precipitation patterns. In the western North America region, the snowpack is an important seasonal water reservoir, which can be modified by unusual and extreme temporary events (Goldenson et al. 2018). When extreme amounts of rain from an atmospheric river fall on a preexisting snowpack, these events will lead to flooding (Neiman et al. 2008). The proximate cause for the June 2022 flooding in YNP was heavy rain on a late snowpack from an Pacific Northwest atmospheric river storm (Poland et al. 2022). The Greater Yellowstone Climate Assessment concludes there has been a significant change in the park's precipitation, its form (i.e., rain or snowfall), streamflow, and seasonality (Hostetler et al. 2021). In fact, scientists predict YNP will receive more spring rain and less winter snow with an increase in the overall annual precipitation and a shift in the location and timing of rain-on-snow events (Hostetler et al. 2021). Atmospheric dynamics are shifting in response to climate change impacts, including 1) shifting Pacific Northwest storm tracks associated with atmospheric circulation patterns, and 2) increasing moisture content of air (Hostetler et al. 2021; Payne 2020). Thus, climate variability may also increase the risk of Pacific Northwest atmospheric river storms that move into the Rocky Mountain interior and bring heavy wet rain that may cause flash flooding, heavy snow, and severe winds in YNP.

Initial hydrologic data suggested that the recent flooding was outside the historical range of variability. During the June 2022 flooding event, the gauge on the Yellowstone River at Corwin Springs surpassed 50,000 cfs according to provisional data. The highest previous discharge on the Yellowstone River at Corwin Springs (USGS gauge 06191500) near its exit from YNP was recorded in 1918 at about 32,000 cfs (Poland et al. 2022). Provisional data is real time streamflow transmitted from each station. Data may be subject to change and are not definite until reviewed and approved by the USGS.

Because this type of event is relatively rare in the Greater Yellowstone region, and the June 2022 event is very recent, many questions remain to be answered including ones as basic as how extreme and extensive it was. Therefore, the overall goals of my project were to analyze hydrologic data to characterize the unprecedented flooding in YNP and surrounding areas and link the hydrological response to the meteorology of the type of severe, focused Pacific Northwest storms intense enough to penetrate the interior west region. I had two core objectives:

1. To quantify how extreme the June 2022 event was in terms of relative river discharge compared to annual peaks and extremes at representative stream gauging stations across the region.
2. To map spatial patterns of June 2022 event runoff to evaluate the extent of extreme runoff within the Greater Yellowstone region.

I discuss results in the context of the unusual type of heavy rain-on-snow storm involved and potential effects of climate change based on research literature and federal agency reports.

METHODS

I evaluated the severity and spatial extent of extreme runoff during the June 2022 flood event by analyzing regional stream gauge data to measure event peak size relative to historic peaks, producing representative hydrographs showing the magnitude and abruptness of the flooding, and mapping the geographical discharge patterns using GIS. I explored data and methods in a summer 2022 class pilot project and modified and expanded on those for my professional paper.

2.1 Analysis Approach

The historic Yellowstone flooding began on June 13, 2022, and lasted for several days. I focused on that date and the days immediately before and after it but also examined discharge records for the entire month of June to be sure to represent the entire event. I worked with Dr. Paul Hook to identify and screen potential USGS stream gauging stations to use with long records for the Yellowstone River watershed and adjacent areas. Dr. Hook queried USGS databases with the USGS R dataRetrieval package (DeCicco et al. 2022) and downloaded discharge data as tab-separated files and excel files for analysis. After initial screening, only sites active in June 2022 with at least 25 years of instantaneous data were selected for further evaluation. To quantify how unusual or extreme conditions were at each station, I worked with Dr. Hook to calculate the relative magnitude of event discharge compared to historic annual peaks as these ratios: June 2022 peak/mean annual peak, June 2022 peak/maximum historic peak, and June 2022 peak/10th percentile annual peak. The preliminary ranking for site selection was based on the ratio of the June 2022 maximum instantaneous peak divided by the greatest previous annual peak. The top 10 of these matched the core storm region and were selected as “tier 1” sites. I selected additional “tier 2” sites by examining spatial variation of June 2022 peak flows and choosing stream gauging stations to represent the relative spectrum from extreme to non-extreme runoff in watersheds adjacent to the “tier 1” core area.

I examined discharge for the selected tier 1 and tier 2 sites in detail in Excel. To display the rise and fall of discharge during event runoff, I used line and scatter graphs that straddle the periods immediately before and after June 13, 2022. The specific periods covered by these representative hydrographs were chosen to show features of the flood event at different locations.

To show the spatial extent of extreme runoff, I mapped the ratio of the June 2022 peak/maximum historic peak using GIS. Stream gauge station locations (latitude and longitude) were compiled in csv files and imported into QGIS. On top of a base layer map, each USGS stream gauge was represented by a graduated symbol size to represent the magnitude of the 2022 event relative to the period of record for that selected station. The National Hydrography Dataset (NHD) and Watershed Boundary Dataset (WBD) layers for the project watersheds were downloaded from the USGS.gov website, extracted as a geopackage, and imported to QGIS. To represent areas with higher or lower relative runoff, watersheds corresponding to each gauging station were displayed with a graduated color scheme (darker saturation in watersheds with the greater peak runoff as a percent of the average).

2.2 USGS Discharge Site Selection and Data Acquisition

Streamflow data and statistics were acquired from USGS online databases using the R dataRetrieval package (DeCicco et al. 2022) and saved in csv and XLSX formats. The package’s “whatNWISsites” function was used to identify candidate USGS stream gauging stations within a 43-47° North latitude by 107-114° West longitude bounding box that had daily or instantaneous discharge values (Figure 1). This 4 degree latitude by 7 degree longitude search area was approximately 444 km X 550 km (342 X 376 miles) and centered on the northern edge of Yellowstone National Park between Gardiner, Montana and Tower Junction. Information for screening candidate sites was obtained with the "readNWISsite" and "whatNWISdata" functions, which retrieve site characteristics including coordinates, elevation, hydrologic unit codes, and drainage area and data summaries including start and end dates of records and number of days of data.

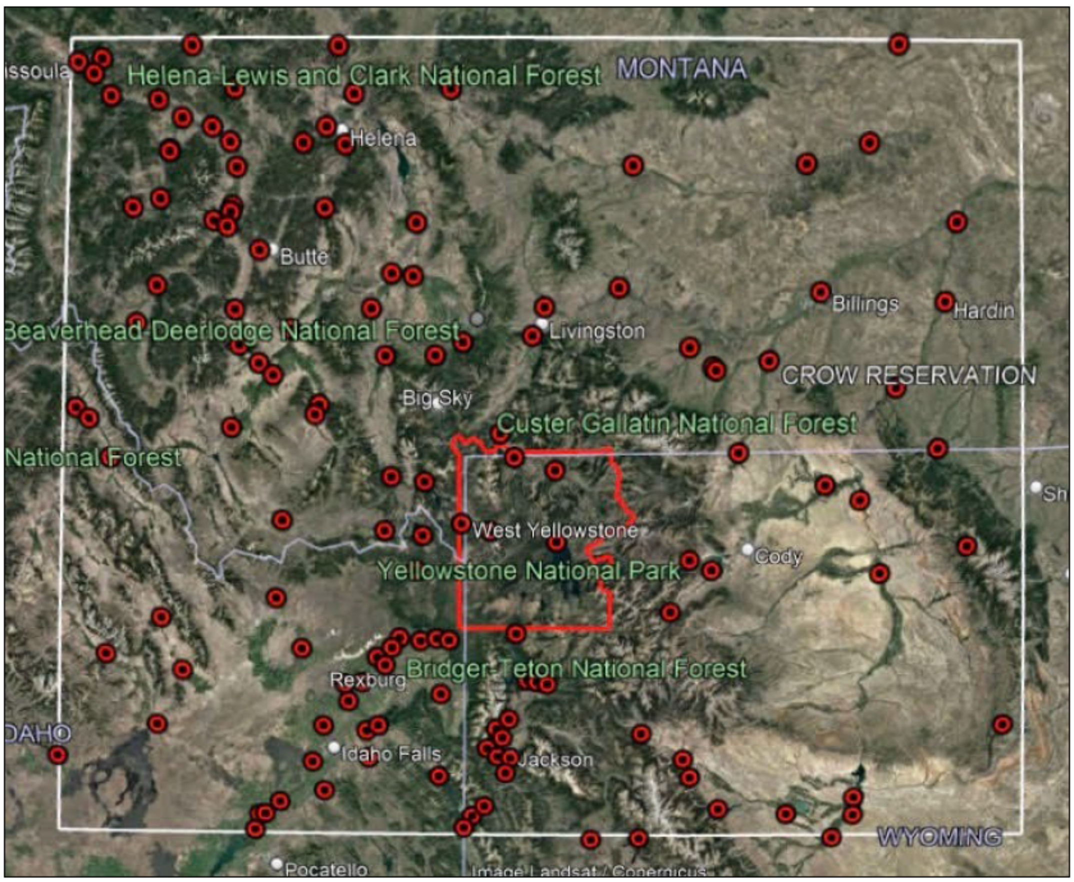

Figure 1. Snapshot of the 139 candidate sites within the target latitude and longitude bounding box.

Candidate gauging stations found in the bounding box included 901 sites with daily discharge values and 344 sites with instantaneous (15-minute interval) discharge values. Of these, 190 sites had daily and instantaneous values for June 2022 and drainage area values. The length of records, measured as number of days with data divided by 365, ranged from 1 to 119 years for daily values and 1 to 36 years for instantaneous values. Daily values are means of instantaneous values for each date, but USGS did not routinely archive instantaneous values online until 1986, or later depending on the site, so records are often shorter than for daily values. Almost three quarters of the sites that had data for June 2022 (n=139) had at least 25 years of instantaneous data and were selected for further evaluation. Using a higher 30-year threshold would have reduced the site list by about a quarter and omitted some sites with long daily records.

Selected data and statistics for these 139 sites were downloaded from USGS databases using the dataRetrieval package. These included:

Instantaneous values for June 2022, for extracting 2022 event peaks and plotting event hydrographs (obtained with "readNWISuv" function).

Historic period of record annual peak flow values for comparisons to 2022 (obtained with "readNWISpeak" function).

Daily and monthly statistics for the period of record, also for comparison to 2022 (obtained with " readNWISstat" function).

The June 2022 instantaneous values were either officially approved values or provisional values still under review by USGS depending on the site. Peak flow, monthly statistics, and daily statistics were all official USGS statistics that have passed agency review for data quality and completeness. Not all these statistics were retained in the final analysis.

Final selection of sites for graphing and mapping was based on how extreme June 2022 peak flows were compared to historic annual peaks or average June discharge values. Sites were selected to include the ones that were most extreme (tier 1) and others that were representative of less impacted watersheds (tier 2).

2.2.1 Hydrographs

In Excel, I selected the instantaneous (15-minute intervals) discharge columns for the selected sites and the date/time column. I examined discharge statistics for the selected tier 1 and tier 2 sites. Then to display the runoff in a hydrograph, I selected the discharge data and eliminated the columns with no data (e.g., omitting the interval 6/1/2022 at 12:00:00 AM with no discharge (00:00:00)) and inserted a line and scatter graph. In the graph, the data series was formatted to select data that straddles a week before and the days immediately after June 13, 2022, to create the representative hydrographs of the flooding event (i.e., 06/10/2022 to 06/20/2022).

2.2.2 QGIS Mapping

For the QGIS mapping, I used data from site selection with the ratio June 2022 peak/maximum historic peak to show the spatial extent of runoff during the June 2022 flood event, and symbolize the map to represent the relative magnitude of discharge in QGIS. The outline is one of brevity for the steps to create a map in QGIS.

Convert Data to QGIS Format: Step 1 was to convert the data from excel format to a csv file to import the data into QGIS. In Excel, select data for the project including: USGS site id, USGS stream gauge site name, ratio of June 2022 peak/max peak, latitude coordinate, longitude coordinate, and HUC id, then copy and save file as csv. file. Save file as CSV UTF-8 (comma delimited) (*.csv) in the project folder for the QGIS project.

Import Data to QGIS: Step 1 was to open QGIS to add a delimited text layer to the project. Step 2 was to open the project tab and select a new project. Step 3 was to select the data source manager icon to search for the csv. file, select the csv. file, and upload it into QGIS. The geometry is automatically integrated into the QGIS platform to the latitude and longitude coordinates from the csv. file (i.e., USGS stream gauge site latitude and longitude). In a manual import of the data the geometry must be set up so that the import assigns the correct coordinate reference system (CR.S). The correct geometry for the transfer of the data is as follows a) geometry is in format latitude and longitude and b) geometry CR.S is EPSG:4269-NAD83. Then, click add the data to the project.

Add Basemap to QGIS: QGIS itself does not have the functionality to support many different types of basemaps. Basemaps can be added to QGIS by searching the web support feature and adding the proper map source into QGIS. Step 1 was to open the browser panel, locate the web tab then select from the dropdown menu *QuickMapServices*, right click to select *Search QMS*. Step 2 was to enter the topo map of the service which you would like to use in the search box, select *ESRI World Topo*, then add the new basemap layer to the project. Step 3 was to find the layer in the project layers, double click the newly added layer to add the layer to map. There are several layer projections which can be applied to the basemap. Step 4 was to select the projection in the project select the layer and go to the layer properties to change the CR.S projection to EPSG:6431- NAD83(2011) /UTM Zone 12N.

Add Hydrologic Unit Codes (HUCs) to QGIS: The Watershed Boundary Dataset (WBD) contains the USGS national Hydrologic Units that are delineated by successively smaller hydrologic units which are HUCs. The HUC is assigned a unit number that provides a watershed address to locate the water data. Step 1 was to search the browser for the USGS national map datasets at https://apps.nationalmap.gov/downloader/#/. Step 2 was to select the datasets Hydrography (NHDPlus HR, NHD, WBD) and choose the subcategory Watershed Boundary Dataset (WBD). Step 3 was to open the map viewer to use the extent tool to select a geographic area, then search the products, and choose the HUC geopackage, download the zip file, extract all the contents, and save the file to your project folder. Step 4 was to open the browser panel, then open the project folder to select the WBD geopackage WBD_10_HU2_GDB.gdb and add the geopackage to the project map. The WBD geopackage will have all the available HUCs which for the project select HUC 8. Step 5 was to open the WBD layer, go to the layer properties, open the source tab, and select the query builder option. The HUC code digits are built into an equation that selected the watersheds to display in the project map. Step 6 was to use the query builder, select the field as *huc8* for the operation *IN* then copy and paste the HUC codes in single quotes within parentheses. Then, click ok and apply the query to the project.

Add Symbology in QGIS: The symbology layer is part of the symbol attached to the data used to represent a map layer. The symbology is used to represent part of the HUC relative discharge defined by the June 2022 peak/max peak ratio. Step 1 was to open the project layers, to symbolize the USGS stream gauge sites in the properties layer. Step 2 was to click on the symbology tab. Step 3 was to choose the graduated (numerical) symbology. The data value fields will auto populate. Step 4 was to choose the value filed Ratio_Max. Step 5 was to open the classes option and click classify. Step 6 was to select the data and symbolize the size and color of the point to opacity that numerically represent the discharge ratio. Then, click ok to apply the symbology to the project. Finally, export the map to the pdf. map. In the map, edit the features to add the following map elements: legend, title, border, sources, north arrow, scale bar, and symbology, and save the project map.

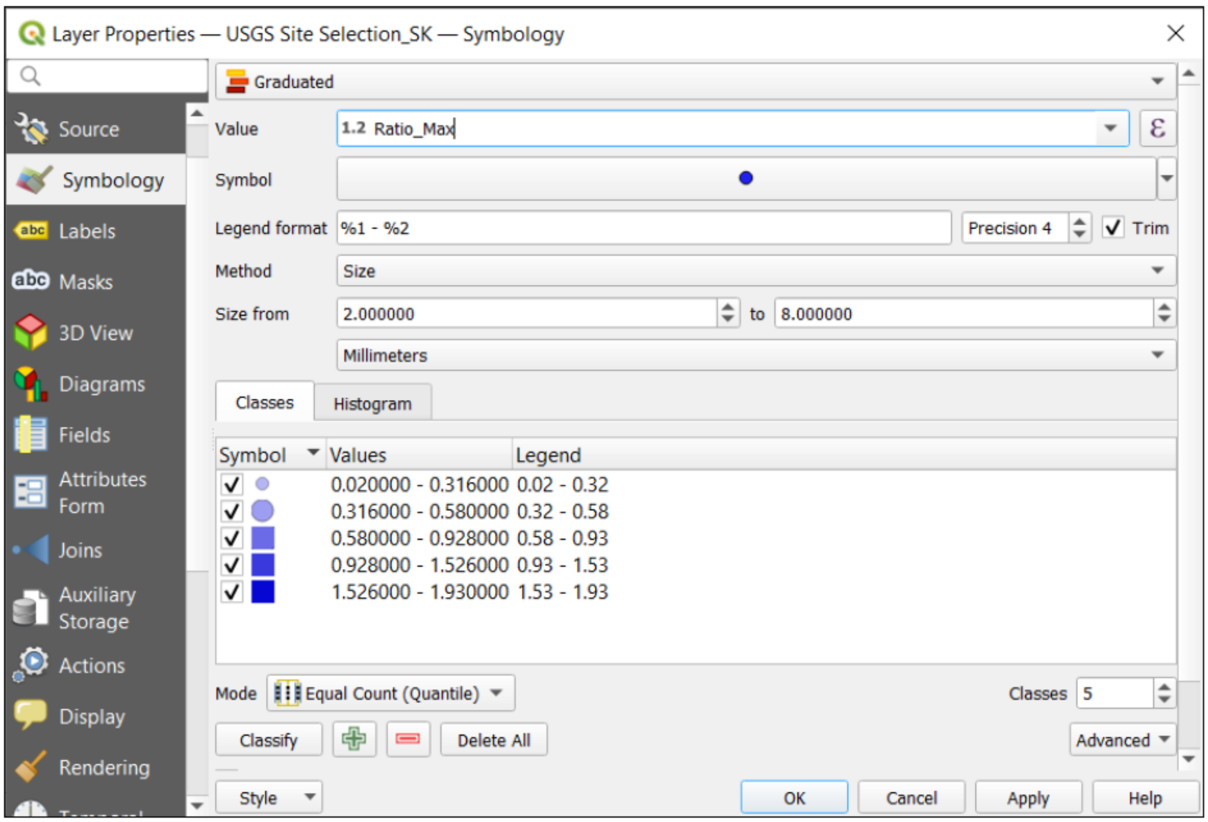

Figure 2. QGIS Symbology Classification

RESULTS

3.1 Site Selection

After initial screening, the list of candidate USGS stream gauge stations throughout YNP and the Greater Yellowstone region included 139 sites with at least 25 years data including June 2022. To reach this point, a list of sites that were active in June 2022 were ranked by length of instantaneous and daily discharge records to evaluate how many sites had long records using a threshold of 25 years gave a good balance between total number of sites and length of records. The final 139 sites have the longest, most complete hydrological records overall and also have instantaneous (15-minute interval) data for June 2022.

I ranked the 139 USGS stream gauging stations based on the ratio of the June 2022 maximum instantaneous peak divided by the greatest previous annual peak on record. The top 10 stations, called "tier one" sites here, had event peaks that exceeded the previous recorded peak, indicated by ratios greater than one (Table 1). Sites that spatially represent the spectrum of less extreme runoff in adjacent watersheds were chosen subjectively as "tier two" sites (Table 2).

The top ten tier 1 sites had annual peak flow from just over the previous record maximum peak flow to almost twice as high (Table 1). The peaks were 2 to 3.4 times greater than the mean annual peak. All the ratios were in the reach of the June 2022 event area the Greater Yellowstone region (i.e., Yellowstone River, Missouri River, Snake River, and Shoshone River).

Table 1. Ten USGS stream gauging stations with extreme peaks relative to historic peaks.

Site ID	USGS Stream Gauge Site Name	Ratio: June 2022 Peak/mean peak	Ratio: June 2022 Peak/max peak	Ratio: June 2022 Peak/10th perc. peak
06205000	Stillwater River near Absaroka, MT	3.44	1.93	5.35
06208500	Clarks Fork Yellowstone River at Edgar, MT	2.81	1.93	3.91
06188000	Lamar River near Tower Ranger Station, YNP	3.48	1.72	5.36
06207500	Clarks Fork Yellowstone River Belfry, MT	2.91	1.60	4.17
06191000	Gardner River near Mammoth, YNP	2.64	1.56	4.61
06191500	Yellowstone River at Corwin Springs, MT	2.71	1.53	4.14
06279940	North Fork Shoshone River at Wapiti, WY	2.34	1.51	3.75
06192500	Yellowstone River near Livingston, MT	2.57	1.36	3.79
06200000	Boulder River at Big Timber, MT	1.96	1.09	2.83
06214500	Yellowstone River at Billings, MT	1.98	1.02	3.00

The June 2022 record peak of the average previous peak were ranked for additional USGS stream gauge stations (Table 2). The tier 2 sites were selected from the ranked USGS stream gauge stations by an objective spatial analysis from the core discharge event in the Yellowstone watershed (Table 2). The selected stations demonstrate the most extreme peaks are two to three times greater than the average and other sites were less impacted but still in neighboring watersheds (Table 1, 2). As shown in Table 2, selected sites for spatial analysis used the remaining USGS stations, which included 15 that had June 2022 peaks of 72-94% of the previous maximum recorded peak, 31 with peaks of 60-69% of the previous record peak, and 85 with peaks <60% of the previous record peak. The selected USGS stations are geographically adjacent to the core analysis area (Table 2 and Figure 2).

Table 2. USGS stream gauge stations representative of less impacted watersheds adjacent to the core storm area.

Site ID	**USGS Stream Gauge Site Name**	**Ratio: June 2022 Peak/mean peak***	**Ratio: June 2022 Peak/max peak***	**Ratio: June 2022 Peak/10th perc. peak***
06043500	Gallatin River near Gallatin Gateway, MT	1.64	0.94	2.39
06037500	Madison River near West Yellowstone, MT	1.81	0.91	2.69
13011900	Buffalo Fork above Lava Cr. near Moran, WY	1.03	0.65	1.33
06281000	South Fork Shoshone River above Buffalo Bill Reservoir, WY	1.38	0.61	2.46
06036905	Firehole River near West Yellowstone, MT	1.57	0.72	2.45
06054500	South Fork Shoshone River near Valley, WY	1.34	0.56	1.93
06054500	Missouri River at Toston, MT	1.26	0.69	2.34
06279500	Bighorn River at Kane, WY	1.11	0.51	2.60
06274300	Bighorn River at Basin, WY	0.71	0.31	1.94
06195600	Shields River near Livingston, MT	0.60	0.22	1.28

06036650	Jefferson River near Three Forks, MT	1.03	0.51	2.47
13010065	Snake River above Jackson Lake at Flagg Ranch, WY	0.92	0.50	1.62
06127500	Musselshell River at Musselshell, MT	0.15	0.02	1.08
06120500	Musselshell River at Harlowton, MT	0.28	0.05	1.10
13011500	Pacific Cr. at Morgan, MT	0.71	0.34	1.17
06274300	Bighorn River at Basin, WY	0.71	0.31	1.94
13039500	Henry's Fork near Lake, ID	0.70	0.22	1.60
06211000	Red Lodge Cr. above Cooney Rd. near Boyd, MT	0.64	0.11	2.50
06285100	Shoshone River near Lovell, WY	0.74	0.26	1.61

3.2 Representative Hydrographs

The hydrographs in Figures 3-10 show discharge at selected USGS stream gauges during the historic June 2022 flooding. Each hydrograph shows how streamflow varies through time and reflects the runoff occurring in the watershed. The factors that affect the hydrographs include spatial and temporal distribution of rainfall, rate of snowmelt, stream hydraulics and channel storage, geology, watershed topography, and vegetation. Rainfall and snowmelt are water inputs that reflect storm characteristics and snowpack. The other factors are watershed characteristics that affect how much water becomes runoff and how quickly it travels. The hydrographs were chosen to represent the relationships between the rain-on-snow event inputs and runoff in watersheds with a range of response timing and peak magnitudes.

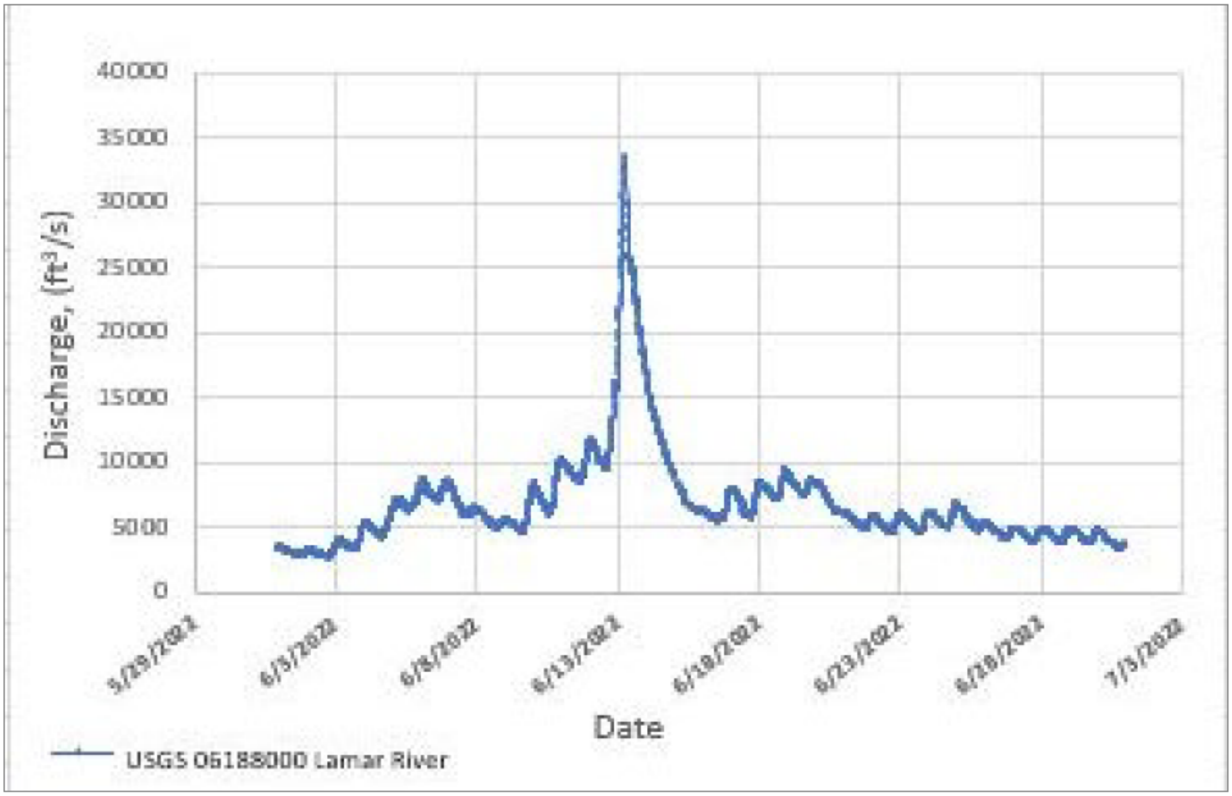

Figure 3. Daily discharge in cubic feet per second (cfs) from USGS 06188000 Lamar River near Tower Ranger Station, YNP from 5/29/2022 to 7/3/2022.

Both the Lamar River near Tower Ranger Station, YNP (USGS gauge 06188000) and the Gardner River near Mammoth, YNP (USGS gauge 06191000) had peaks that were very focused in time, with extremes lasting about 12-18 h (Figure 3 and 5). The Lamar River in the headwaters of the Yellowstone River had one of the most extreme and rapid peaks. The peak was concentrated in one day, and the entire runoff event lasted a few days. The Lamar River's rise was also more abrupt than other rivers in the core storm area. The reasons for this rapid, extreme runoff include high storm intensity, pre-storm snowpack conditions and watershed size. Rainfall occurred when runoff had already started due to snowmelt, so that the heavy rain was on top of snowmelt. Active snowmelt is shown by the daily runoff cycles before the storm. The details of the rain's timing and intensity were amplified by ongoing snowmelt and caused a spike in runoff so that the beginning of the rise was abrupt. The shorter runoff distances in smaller watersheds contribute to rapid responses, and the fall of the hydrograph was also concentrated in a short period of one to three days.

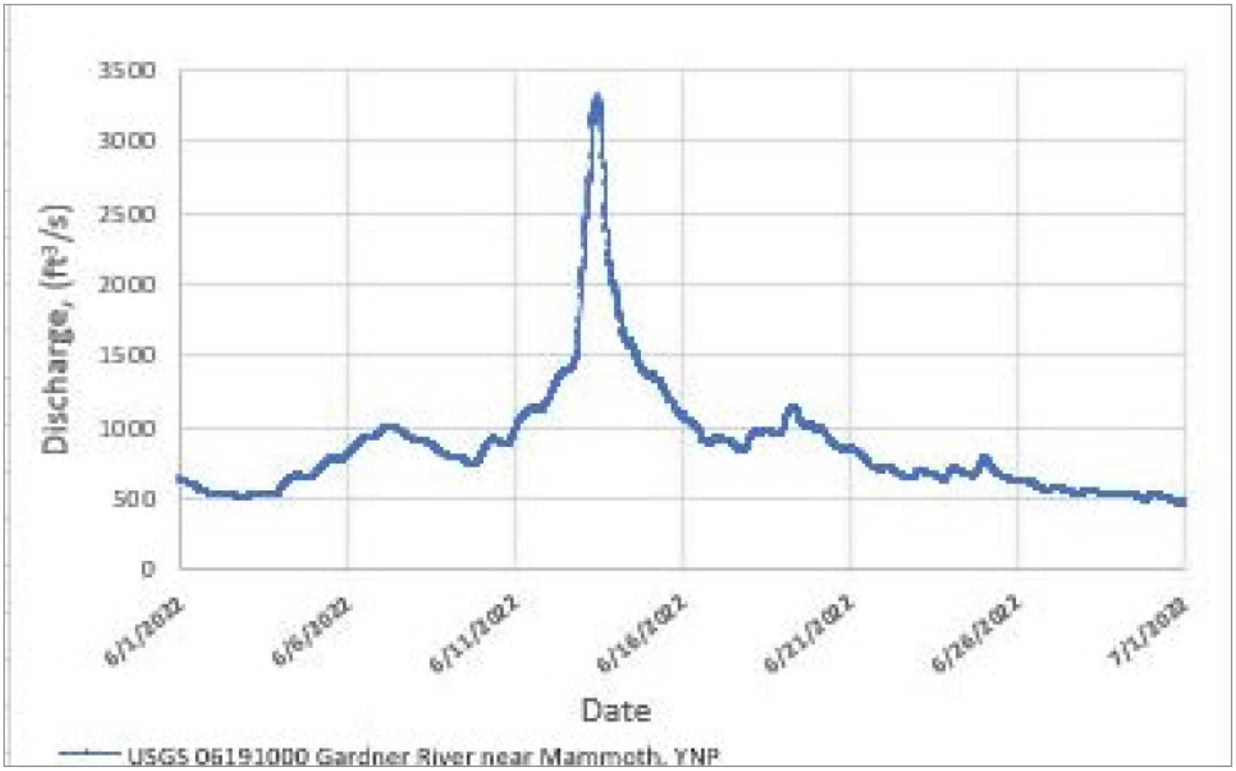

Figure 4. Daily discharge in cubic feet per second (cfs) from USGS 06191000 Gardner River near Mammoth, YNP from 6/1/2022 to 7/1/2022.

The peak on Gardner River near Mammoth was concentrated between one to 1.5 days, and the rise of the peak was focused in time over 12-18 h like the Lamar River. Both peaks were more abrupt, and brief compared to the peaks of rivers in bigger watersheds with extreme runoff such as the Yellowstone River at Corwin Springs (USGS gauge 06191500), Livingston (USGS gauge 06192500), and Billings (USGS gauge 06214500) (Figures 5, 6). Moving downstream, peaks were later due to the time to travel the longer distance and larger due to accumulating inflow. Peaks also became more spread out. One reason for this peak distribution is differences between tributaries. Flow increases downstream as tributaries connect into the river, but the timing of inflow entering the main branch differs between tributaries. High flow was strongly concentrated in time at the epicenter of the runoff event, but the timing of inputs became spread out downstream with more source areas contributing. As shown in maps below (Figures 11 and 12), the Lamar River watershed and areas to its northeast were at the epicenter of the flooding. Another reason is the general tendency of flood waves to spread out as they travel downstream.

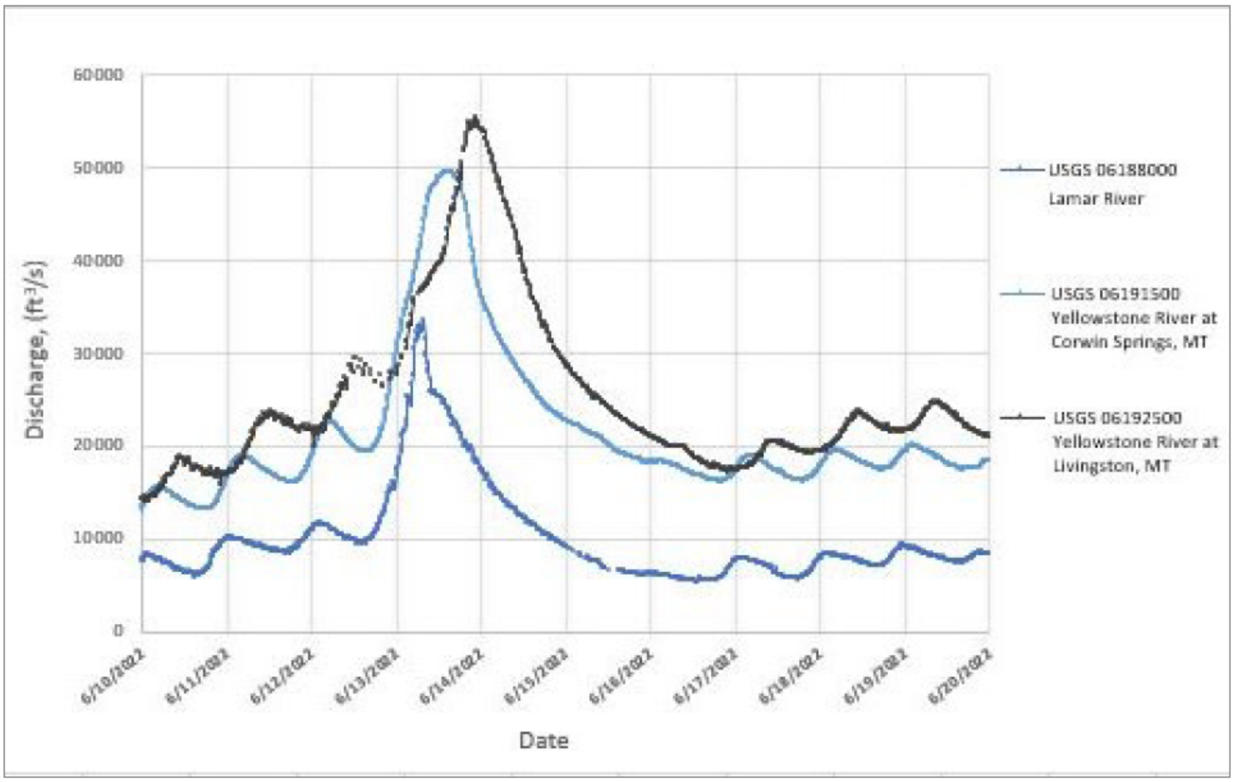

Figure 5. Daily discharge in cubic feet per second (cfs) from USGS stream gauge stations in the epicenter of the flooding from 6/10/2022 to 6/20/2022.

A characteristic snow-driven hydrograph represented the Yellowstone River, where average peak flows are greater during spring runoff compared to other times of the year and inputs cycle between night and day and between warm and cold spells. During June 2022, the micro peaks in Figures 5 and 7 occurred every 24 h due to snowmelt, which typically follows a

24-h cycle. At Corwin Springs, MT, there were micro peaks from the snowmelt, which was typical of snowmelt runoff in that the hydrograph displayed the flow moving downstream approximately 12-14 h later than melt, with discharge peaking in the early morning. The same type of hydrology is displayed in both the Lamar River and the Yellowstone River near Livingston, but the timing differs. The rise of each peak precedes or lags other stations due to the distance the flow travels. This can be seen with the three micro peaks leading up to the main runoff event and the peaks. Runoff gets to Corwin Springs and Livingston several hours later due to more distance to travel.

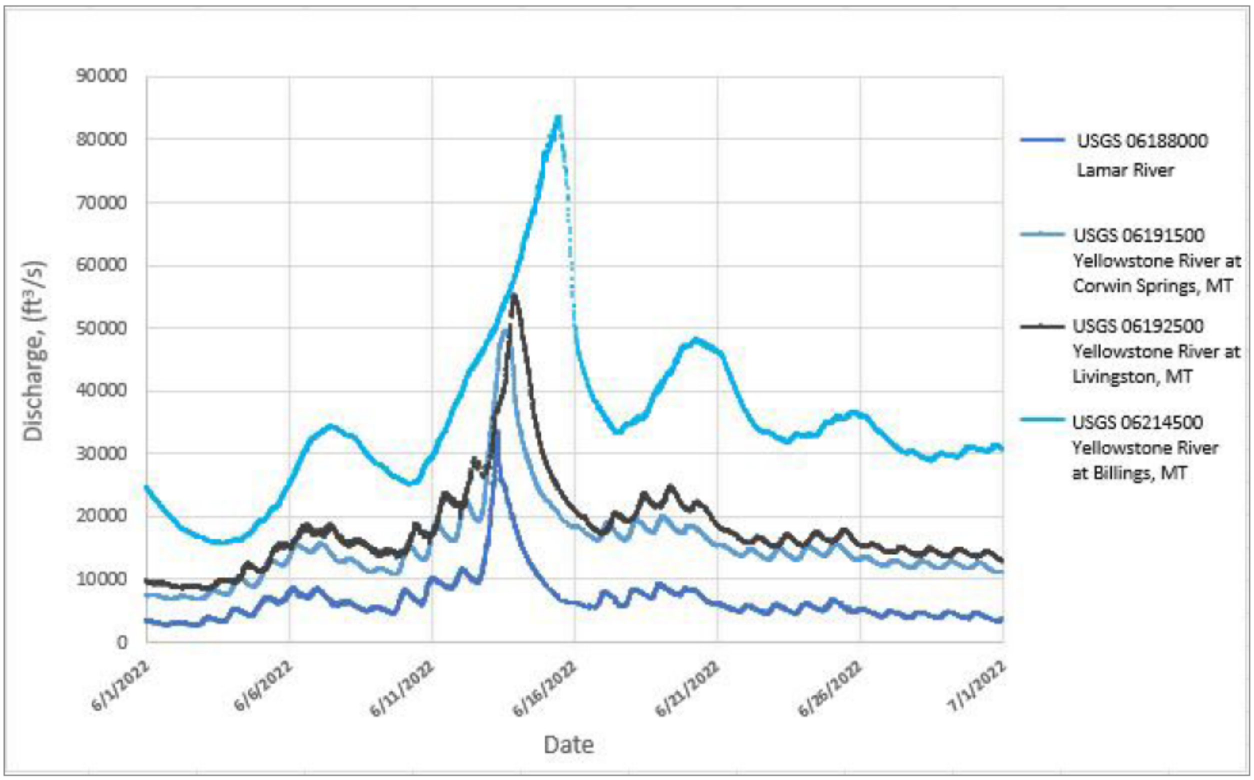

Figure 6. Daily discharge in cubic feet per second (cfs) from USGS stream gauge stations in the epicenter of the flooding from 6/1/2022 to 7/1/2022.

These differences continue downstream. In contrast to the Lamar and Gardner Rivers, with sharp peaks concentrated between one to one and a half days, at USGS gauge 06214500, Yellowstone River at Billings, MT, event discharge was spread over 5 days with much more gradual rise and later peak.

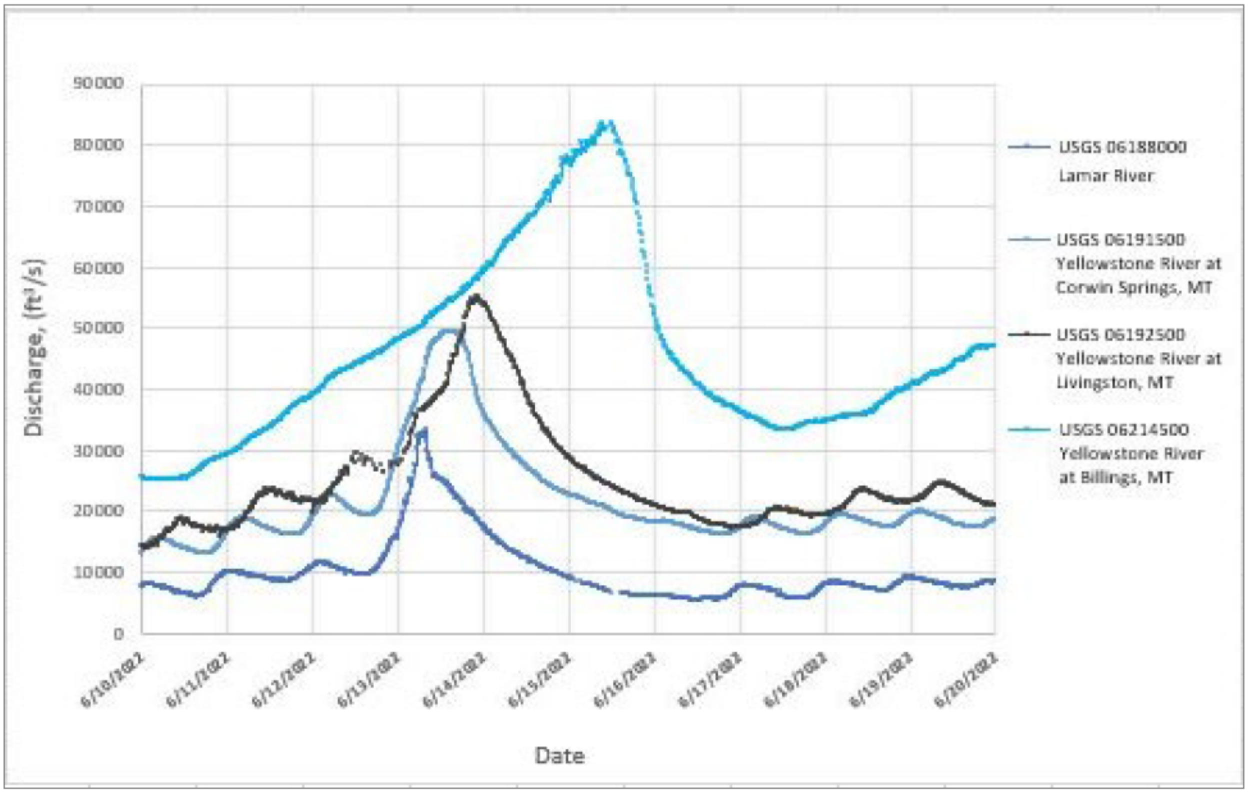

Figure 7. Daily discharge in cubic feet per second (cfs) from USGS gauge stations runoff from 6/10/2022 to 6/20/2022.

On the morning of June 14, 2022, the flow from the upstream sites in the Yellowstone watershed reached Billings, MT, almost two days past the beginning of the flooding on the Lamar River. At Billings, the rise to the peak took almost twice as long as on the smaller tributaries and upper Yellowstone (i.e., Corwin Springs and Lamar River stations) and very high flows lasted about two days until the runoff peak and began to fall (06/14/2022-06/16/2022). The stream gauging stations on the main stem of the Yellowstone River represent increasingly larger watersheds and rivers with greater runoff volumes, and their event hydrographs are more spread out and less abrupt compared to the peaks in the smaller watersheds.

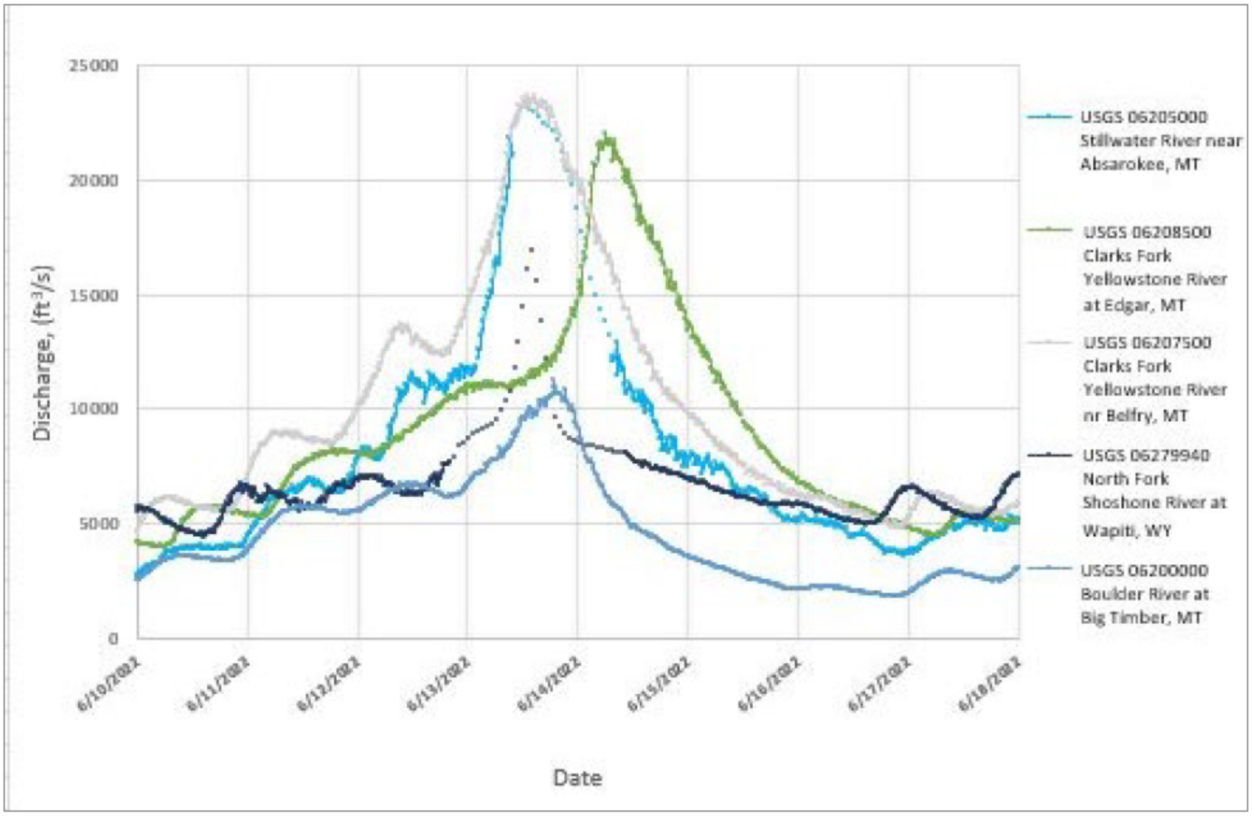

Figure 8. Hydrographs for USGS stream gauge stations outside the upper Yellowstone headwaters with extreme runoff, 6/10/2022 to 6/18/2022.

The other top 10 annual peak record-breaking rivers north and east of the Lamar River and upper Yellowstone River showed variations of the rain on snow event runoff, where the average peak flows are greater during the spring runoff compared to other times of the year and the micro peaks are characteristic of snowmelt pattern (Figure 8). Typical snowmelt runoff before the storm hit in that the flow moved downstream approximately 12-14 h later than melt, with discharge peaking in the early morning (Figure 8). As the discharge moved downstream, the contributions of the stream flow increased runoff in other regions in or near YNP that not necessarily where the rain occurred. The other top ten sites have less abrupt micro peaks that are not concentrated over 12-24 h (i.e., typical of a snowmelt cycle) as compared to the core sites in YNP such as Lamar River, Gardner River, and Corwin Springs (Figure 8).

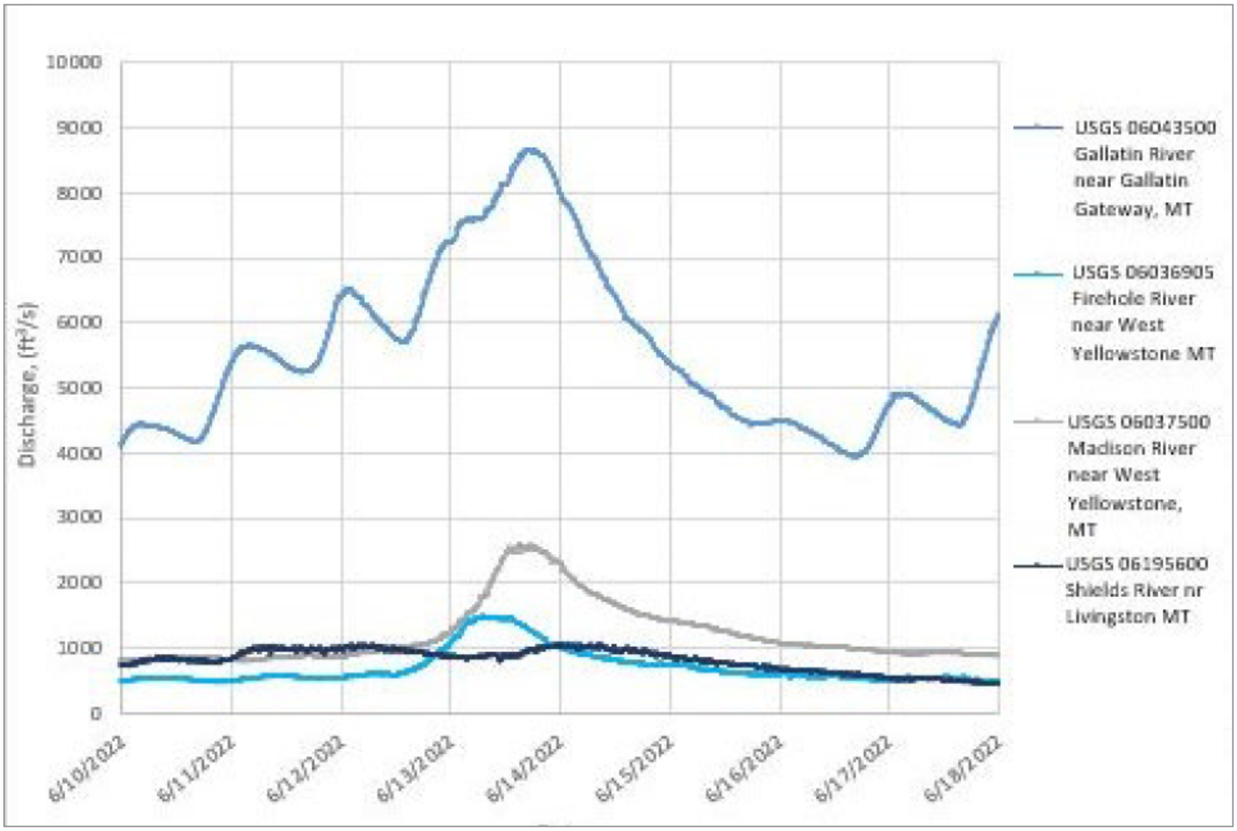

Figure 9. Daily discharge in cubic feet per second (cfs) at four USGS gauges outside of the core area of extreme runoff from 6/10/2022 to 6/18/2022.

Stream gauges outside the area of record-breaking peaks showed a range of responses from nearly as extreme to barely noticeable. Rain combined with rapid snowmelt was concentrated in the Gallatin River, and the response to runoff is substantially less in the Madison River. For the Gallatin River near Gallatin Gateway, MT (USGS gauge 06043500), the rise to the peak was more abrupt and higher, relative to historic peaks, compared to the peaks at less impacted watersheds such as the Madison River, Firehole River, and Shields River (Figure 9). Also of note, there were four micro peaks typical of snowmelt leading up to the storm event runoff, and event discharge was concentrated in one and one and half days before falling back to the pre-event baseflow.

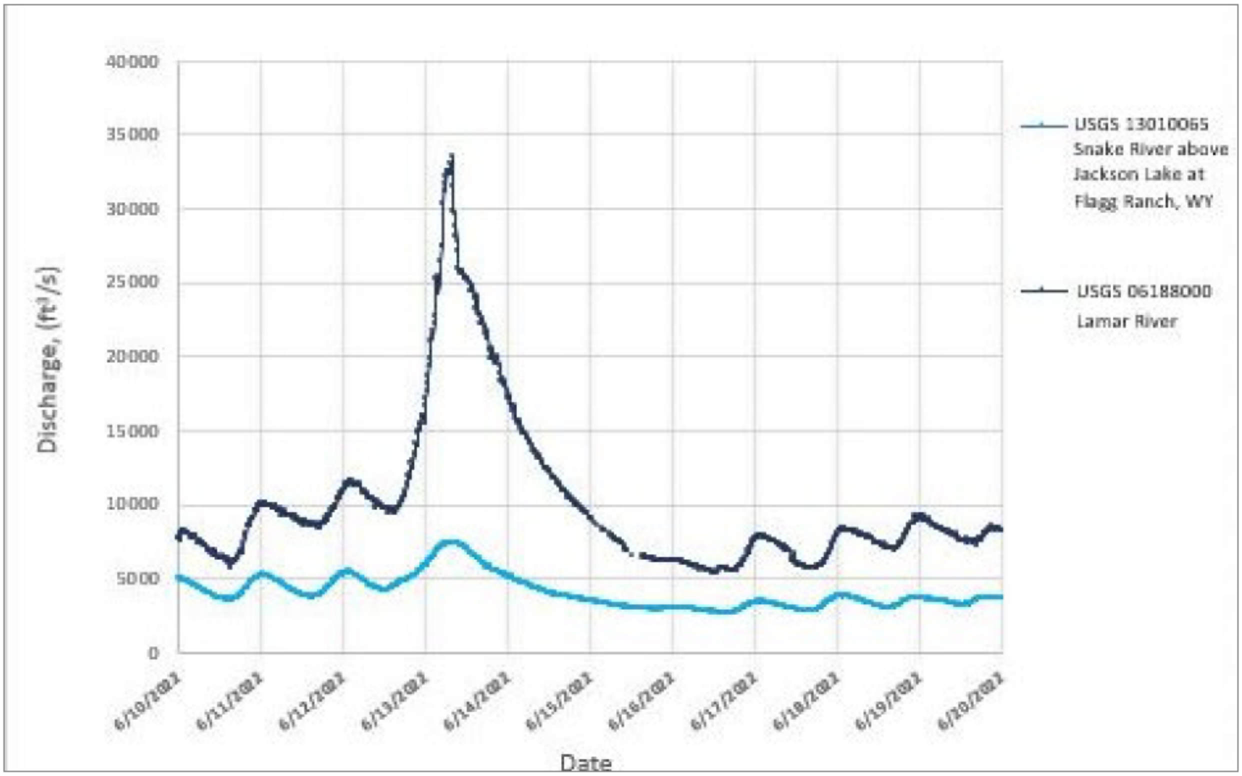

Figure 10. Daily discharge in cubic feet per second (cfs) from Lamar River in the epicenter of the flooding compared to the Snake River outside of the core area extreme runoff from 6/10/2022 to 6/20/2022.

The discharge from the Lamar River near Tower Ranger Station, YNP (USGS gauge 06188000) peaks were very focused in time, with extremes lasting about 12-18 h (Figure 10). The Lamar River in the headwaters of the Yellowstone River had one of the most extreme and rapid peaks. The peak was concentrated in one day, and the entire runoff event lasted a few days. The Lamar River's rise was also more abrupt than other rivers in the core storm area. High flow was strongly concentrated in time at the epicenter of the runoff event. Figure 10 shows the effect of the high flow runoff was barely noticeable in the Snake River above Jackson Lake at Flagg Ranch (USGS 13010065). The data demonstrate the storm hit when snowmelt was already ongoing that can be seen with the three micro speaks leading up to the main runoff event. During June 2022, both watersheds received above average precipitation except the Snake River watershed received much less precipitation. Both the Snake River and Lamar River display a similar rise and fall of the peak although Lamar River rise of the hydrograph peak is more abrupt (Figure 10).

3.3 Spatial Extent of Extreme Runoff

Based on the hydrological analysis, discharge during the June 2022 event was elevated above average in most of the major watersheds with headwaters in the Greater Yellowstone region (i.e., Yellowstone River, Missouri River, Snake River, and Shoshone River) but not to the same degree. On June 13, 2022, the most extreme flooding in YNP area was concentrated in the upper Yellowstone River watershed (Figure 3). At the most extreme, as measured by the ratio of the June 2022 maximum instantaneous peak divided by the greatest previous annual peak, flows exceeded previous records in the following Hydrologic Units: Upper Yellowstone, Upper Yellowstone-Lake Basin, Yellowstone Headwaters, Clarks Fork Yellowstone, Gallatin, and Stillwater. All of these are parts of the Yellowstone River watershed above Billings, MT. The North Fork Shoshone watershed also displayed record high flow based on the June 2022 peak and maximum historic peak. This watershed is directly next to the upper ends of the Lamar River and Clarks Fork Yellowstone River watersheds but drains easts to the Bighorn River. The greatest measured discharge was observed at the following stream gauges stations: Yellowstone River at Corwin Springs, MT, Lamar River near Tower Ranger Station, YNP, Yellowstone River near Livingston, MT, Gardner River near Mammoth, YNP, and Stillwater River near Absaroka, MT (Table 1). Some of these peaks were far outside the historic range of recorded annual peaks.

The spatial extent of extreme flows included northern YNP, the Absaroka-Beartooth Wilderness, and neighboring watersheds. Extremes were concentrated in the upper Yellowstone River Watershed but also occurred in neighboring watersheds. The extent of extreme runoff area is concentrated in 150 miles in diameter (Figure 1 and 11). The range of the most extreme runoff reflects the mountain ranges directly north, northeast, and west of YNP (e.g., Gallatin Range and Absaroka -Beartooth Wilderness) where the response outside the core area is barely noticeable in the Madison Range and south region of YNP. At the most extreme, the greatest measured discharge was observed at the following stream gauge stations: Yellowstone River at Corwin Springs, MT, Lamar River near Tower Ranger Station, YNP, Yellowstone River near Livingston, MT, Gardner River near Mammoth, YNP, and Stillwater River near Absaroka, MT (Table 1). Based on the study findings, the annual peak discharged compared the maximum historic peak flow was 2-4 times the average at most stations in the YNP. The extent of extreme runoff was consistent with the type of narrowly focused Pacific Northwest atmospheric river storms intense enough to penetrate this far into the interior western mountains.

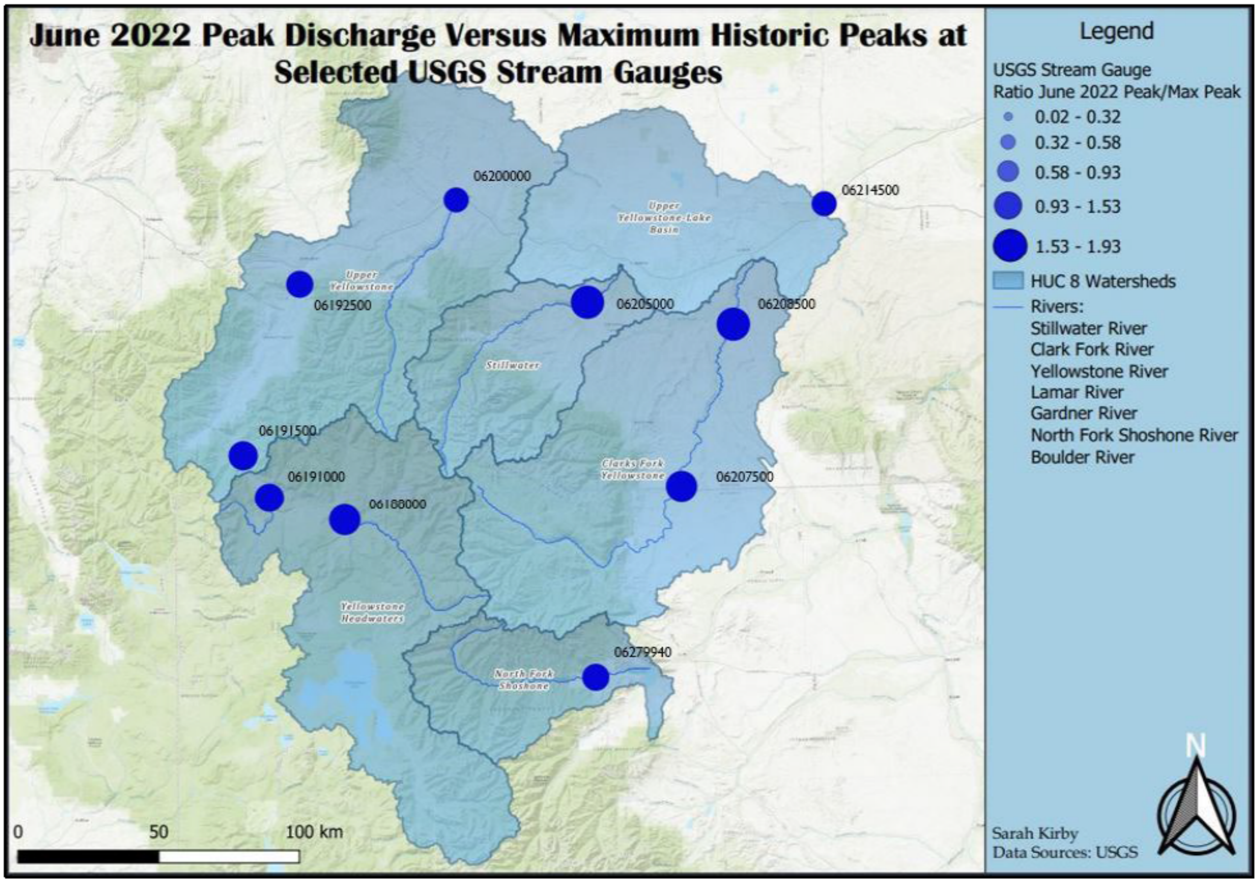

Figure 11. Tier 1 Sites Ratio of June 2022 Peak Discharge Compared to Historic Annual Peaks.

Discharge during the June 2022 event was elevated above average in most of the major watersheds with headwaters in the Greater Yellowstone region (i.e., Yellowstone River, Missouri River, Snake River, and Shoshone River) but not to the same degree (Figures 11, 12).

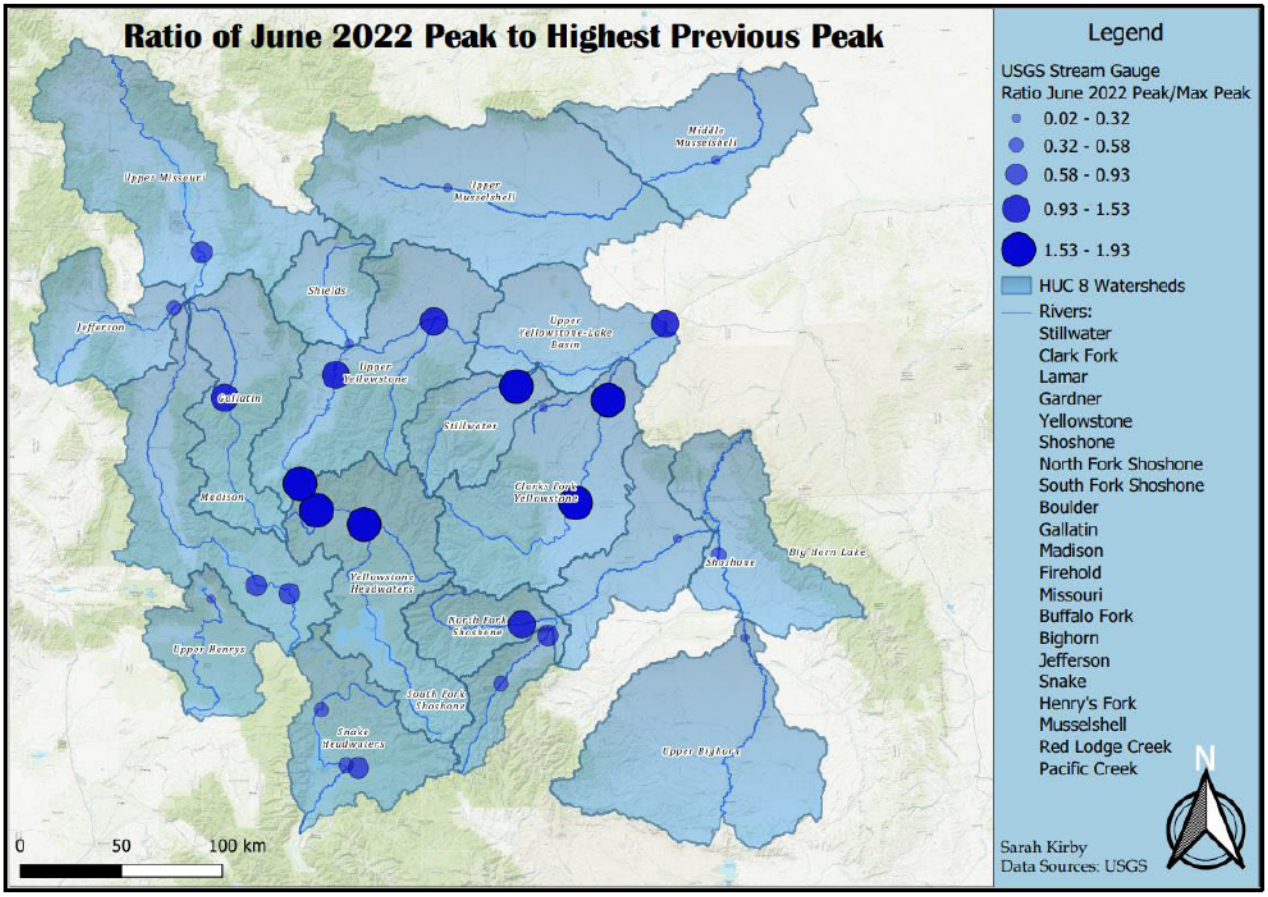

Figure 12. Geographic Extent of June 2022 Flooding - Ratio of June 2022 Peak Discharge Compared to Historic Annual Peaks.

DISCUSSION

4.1 Pilot Study

My pilot study shows the previous results during the June 2022 event that were conducted as a preliminary hydrological analysis (Figure 13). The key challenges with the pilot study were retrieving and screening USGS stream gauge sites. The discharge records were not consistent for all the USGS stream gauges in pilot study area (Park Co., WY, Park Co., MT, and Gallatin Co., MT) as a majority of the USGS stream gauges lacked 30 years of daily discharge data. As a result, the map reflects the available data, which are not uniform across the region. This may skew the results for the watershed-scale analysis of the June 2022 flooding event. Expanding the study area overcame the lack of available discharge data and increased the number of gauging stations with long records that were used in the analysis.

Based on my findings, discharge during the June 2022 event was elevated above average in most the watersheds but not to the same degree. On June 13, 2022, the most extreme flooding in YNP area was concentrated in Livingston, MT, Gardner, MT, the west entrance of YNP, and the north entrance of YNP. The results of the pilot study are consistent with the extent of extreme runoff demonstrated in the expanded hydrological analysis. At the most extreme (measured as relative percent of the 30-year average), flow in the Lamar River was 384% of average, Firehole River was 380% of average, Madison River 279% of average, and the Yellowstone River near Livingston, MT was 192% of average. The Upper Lamar and Lower Lamar watersheds also recorded the greatest storm precipitation in the Yellowstone National Park region. Overall, flow was 2 to 4 times above the 30-year average discharge at most stations in the Yellowstone National Park region.

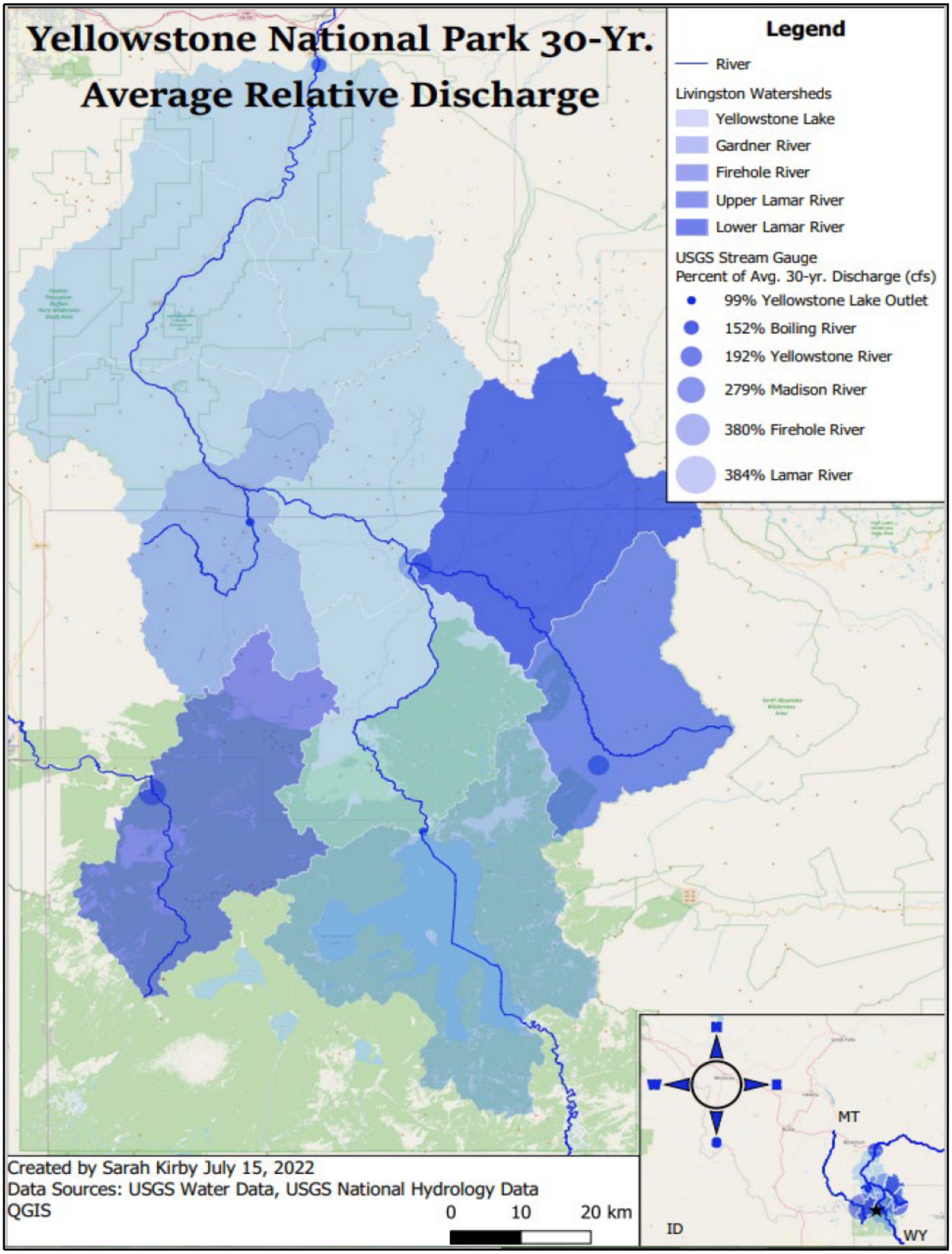

Figure 13. Pilot Study Map of YNP Core Area 30 Year Average Relative Discharge.

My expanded analysis accomplished two objective goals: a) represent the hydrological runoff, and b) documented the spatial extent of extreme flows. I related this to descriptions of storm intensity and climatology compiled by the National Weather Service, which link the flooding to an atmospheric river storm causing heavy rain onto melting snow. The findings may lead to an improved scientific understanding of the link between the YNP region and Pacific Northwest wet weather systems that rarely reach so far inland.

4.2 Expanded Hydrological Analysis and Mapping Extreme Discharge

Starting the morning of June 10 and extending until June 13, 2022, an atmospheric river storm hit the Beartooth and Absaroka Mountains in and near YNP. The storm was classified as a maximum category 5 atmospheric river storm, resulting in near-record rainfall in a short period of time combined with rapid snowmelt ongoing before the storm event (NOAA 2022). The streams and rivers in the Yellowstone River watershed were already running near nuisance flood stage before the storm delivered extreme amount of 7.5-9.5 inches of water from rain and snowmelt overnight (Poland et al. 2022; NOAA 2022; NWS 2022). During the warmer overnight temperatures, the rain caused an accelerated melting of the existing snowpack that had not previously melted due to a cool and snowy spring. The expanded hydrological analysis at selected USGS stream gauges shows the relationship between the rain on snow event and the historic magnitude flooding in the major watersheds (Yellowstone River, Missouri River, and Shoshone River). Based on this analysis, discharge at many stations in the YNP region exceeded average annual peaks by two to three times, and that some were nearly two times greater than the maximum historic peak (Yellowstone River, Lamar River, Gardner River, Shoshone River, Stillwater River, and Boulder River). Extreme discharge was concentrated in the upper Yellowstone River Watershed but also occurred in neighboring watersheds.

The Lamar River, Gardner River, and Corwin Springs, demonstrate the element of timing (Figures 3-5). When the rain occurred, it may have fallen on an already melting snowpack which led to an increase in the discharge on June 13, 2022. The Yellowstone River shows a characteristic snow-driven hydrograph, where average peak flows are greater during spring runoff compared to other times of the year and inputs cycle between night and day and between warm and cold spells. During June 2022, the micro peaks seen in Figures 5 and 7 occurred every 24 h due to snowmelt, which typically follows a 24-h cycle. At Corwin Springs, MT, there were micro peaks from the snowmelt, which was typical of snowmelt runoff in that the hydrograph displayed the flow moving downstream approximately 12-14 h later than melt, with discharge peaking in the early morning. The same type of hydrology is displayed in both the Lamar River and the Yellowstone River near Livingston, but the timing differs. The rise of each peak precedes or lags other stations due to the distance the flow travels from the source. This can be seen with the three micro peaks leading up to the main runoff event and the peaks. Runoff gets to Corwin Springs and Livingston several hours later due to more distance to travel. The magnitude of the flooding was concentrated to the upper Yellowstone headwaters although other stream gages outside the core area experienced discharge beyond historical range. The other top ten annual peak record-breaking rivers north and east of the Lamar River and upper Yellowstone River showed variations of the rain on snow event runoff, where the average peak flows are greater during the spring runoff compared to other times of the year and the micro peaks are characteristic of snowmelt pattern (Figure 8). The hydrographs displayed in Figure 8 were typical of snowmelt runoff before the storm hit in that the flow moved downstream approximately 12-14 h later than melt, with discharge peaking in the early morning. As the discharge moved downstream the contributions of the stream flow increased runoff in other regions in or near YNP that were not necessarily where the heavy rain occurred. The spatial extent of the elevated runoff is shown in Figures 6 and 7, with extreme discharge reaching as far downstream as the Yellowstone River at Billings, MT, as contributions of upstream flow led to the peak between June 13 to 18, 2022.

The snow-driven hydrographs in the above figures demonstrate how the magnitude of flooding was a result of an atmospheric river storm that hit YNP during annual snowmelt typical of spring. It was the combination of the degree of rain combined with rapid snowmelt that pushed runoff beyond its historical range. At the epicenter of the flooding, there are three micro peaks leading up to the rise of peak in both the Lamar River, Gardner River, and Corwin Springs, typical of a snow-melt cycle (Gardner et al. 2010) (Figures 3-5). Due to warmer temperatures between 72-81°F on June 9 to 11, 2022, the micro peaks indicate that spring snowmelt was in progress. The peak rainfall occurred between June 12 to 13, 2022, with the hydrograph peak of the sites in the core storm area lagging the peak rainfall by 12-14 h on June 13 to 14, 2022. I relate that to the timing of rain on an already melting snowpack that caused the runoff in the June 2022 historic flood. Furthermore, the topography of the YNP region may have been a geographic factor that focused the extent of the precipitation event towards northern YNP, the Absaroka-Beartooth Wilderness, and adjacent areas where it delivered extreme amounts of rain and snow in a short period (Poland et al. 2022; Goldenson et al. 2018). Based on the initial evaluation of sites, the extreme discharge at most stations were in the YNP region, although the flow in the Snake River Plain was not exceptional compared to the flooding in other major watersheds including Yellowstone River, Missouri River, and Shoshone River. As the Pacific Northwest atmospheric river storm moved across the Snake River Plain the elevation was approximately between 2,000-2,800ft, and produced little rain. The storm continued to carry moisture as it climbed into the YNP region where the elevation is approximately 8,000ft over a large area, and the storm released an extreme amount of rain.

The hydrographs and maps of June 2022 peaks show the risks of extreme flooding posed by atmospheric river storms with heavy rainfall on melting snow in the YNP region. In the future, the National Weather Service and computer-based hydrological forecasting models are predicting warming trends and extreme weather events, so spring floods may increase in frequency and could fundamentally alter the YNP region (Uccelini et al. 2019). Atmospheric dynamics are shifting in response to climate change impacts including (1) shifting Pacific Northwest storm tracks associated with atmospheric circulation patterns and (2) increasing moisture content of air (Hostetler et al. 2021; Payne 2020). Thus, climate change may also increase the risk of Pacific Northwest atmospheric river storms that move into the Rocky Mountain interior and bring heavy wet rain that may cause flash flooding, heavy snow, and severe winds in YNP.

4.3 Atmospheric River Storm and Climate Change Increase Extreme Precipitation in YNP

An atmospheric river storm is a system of warm and extremely wet air that originates in the tropics and delivers moisture on the west coast and sometimes reaches the Rocky Mountains. Research has shown that rising ocean surface temperatures and air temperatures are increasing the amount of moisture in atmospheric river storms, and as a result there is an increase in the rainfall on land (Huang et al. 2020). The amount of moisture carried by atmospheric river storms will drive more extreme precipitation and increase the risk of flooding. Pacific Northwest atmospheric river storms do not typically penetrate the interior of the Rocky Mountain interior in late spring to summer (Rutz et al. 2014). Based on the atmospheric river intensity scale developed by the Center for Western Weather and Water Extremes (CW3E 2023), the June 2022 event in YNP was a maximum category 5 or "exceptional" atmospheric river storm, a type that can produce record rainfall in one to three days and carries the greatest risk for flooding. The result in YNP was truly historic flooding. In parts of YNP, there was extreme rainfall of 2-3 inches that fell overnight and combined with the warmer overnight temperatures, caused accelerated melting of snowpack that had not previously melted due to a cool and snowy spring.

In the Pacific Northwest, including Idaho and western Montana, atmospheric river storms like those of June 2022 are expected to increase in frequency, and atmospheric and climate scientists who study connections between climate and hydrology have concluded that these storms are likely linked to climatic changes in annual and seasonal precipitation patterns and will lead to more frequent extreme flooding by the end of the century (Huang et al. 2020; Matthews et al. 2018). Because these types of storms are infrequent and less studied in the Greater Yellowstone region (Rutz et al. 2014; Goldenson et al. 2018), effects of climate change are more uncertain there. Overall, the increase in frequency of heavy rainfall and rain-on-snow events will likely cause more flash flooding and could fundamentally alter the Greater Yellowstone Ecosystem. In YNP, the meteorological significance and long-term impact of the unprecedented flooding will only become clear over time, but the relative amount of runoff across the region affected by the June 2022 rain-on-snow event can be analyzed now and used as an example of possible future events.

4.4 Limitations of the Study and Recommendations for Future Implementation and Research

My study has important limitations resulting from methodology and insufficient published research of rain-on-snow events in the interior of the Pacific Northwest region. The methodological issues included the methods used to select the USGS stream gauge sites. In my summer 2022 pilot study, I used the USGS NWIS database but lacked a reliable retrieval method to efficiently extract data. For simplicity, I limited site selection to core area watersheds with at least 30 years of consistent data. In this final study, I expanded the site list to include sites with 25-30 years of data, which increased the sample size but may still have omitted some useful sites. Using a large latitude and longitude bounding box to identify USGS stream gauge stations throughout YNP and the Greater Yellowstone region greatly increased the number of sites available. Nonetheless, although there was a large sample size across the region, there was less than detailed coverage of some core areas due to the locations of gauges and gaps in records at other gauges. For example, USGS gauge 06187915 Soda Butte Creek at Park Boundary at Silver Gate, was near the center of the storm but was excluded because it had less than 25 years of data.

For future research, I recommend a different approach to spatial analysis for the tier two sites, which include neighboring watersheds near the core area. Instead of using judgment to select sites for mapping, the geography of runoff should be analyzed with spatial statistical methods and include a larger set of streams in the Upper and Lower Yellowstone River watershed and other basins in the Greater Yellowstone region. As the focus of this study is a rain-on-snow event, I also recommend an analysis of the extent that the storm covered in the region using a geographical sampling method to select stream gauge sites based on whether they were within watersheds that actually received the storm rainfall and snow. This approach was not taken in this study. Instead, the June 2022 peak discharge map is a best representation of the spatial impact from the storm's runoff moving downstream.

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APPENDIX A

LIST OF 139 SITES RATIO OF JUNE 2022 MAXIMUM INSTANTANEOUS PEAK

DIVIDED BY GREATEST PREVIOUS ANNUAL PEAK

Site ID	*June 2022 Pk/ mean peak**	*June 2022 Pk/ max peak**	*June 2022 Pk/ 10th perc. Peak**
Stillwater River near Absaroka, MT	3.44	1.93	5.35
Clarks Fork Yellowstone River at Edgar, MT	2.81	1.93	3.91
Lamar River near Tower Ranger Station, YNP	3.48	1.72	5.36
Clarks Fork Yellowstone River near Belfry, MT	2.91	1.60	4.17
Gardner River near Mammoth, YNP	2.64	1.56	4.61
Yellowstone River at Corwin Springs, MT	2.71	1.53	4.14
North Fork Shoshone River at Wapiti, WY	2.34	1.51	3.75
Yellowstone River near Livingston, MT	2.57	1.36	3.79
Boulder River at Big Timber, MT	1.96	1.09	2.83
Yellowstone River at Billings, MT	1.98	1.02	3.00
Gallatin River near Gallatin Gateway, MT	1.64	0.94	2.39
Madison River near West Yellowstone, MT	1.81	0.91	2.69
Gallatin River at Logan, MT	1.65	0.88	2.54
Madison River at Kirby Ranch near Cameron, MT	1.39	0.79	2.57
Red Rock Cr. above Lakes, near Lakeview, MT	1.44	0.79	2.43
Pine Cr. above Fremont Lake, WY	1.11	0.75	1.45
Salmon River at Salmon, ID	1.47	0.75	3.39
Bull Lake Cr. above Bull Lake, WY	1.51	0.73	2.52
Fall River above Yellowstone Canal Near Squirrel, ID	1.30	0.72	1.89
Wind River above Boysen Reservoir Near Shoshoni, WY	1.53	0.72	4.22
Firehole River near West Yellowstone, MT	1.57	0.72	2.45
Madison River below Ennis Lake near McAllister, MT	1.38	0.71	2.28
Missouri River at Toston, MT	1.26	0.69	2.34
Fall River near Ashton, ID	1.14	0.66	1.58
Buffalo Fork above Lava Cr. near Moran, WY	1.03	0.65	1.33
Wind River at Riverton, WY	1.37	0.65	3.45
Fish Cr. at Wilson, WY	1.02	0.64	1.35
Green River at Warren Bridge near Daniel, WY	1.24	0.62	1.84
Shell Cr. above Shell Cr. Reservoir, WY	1.47	0.61	2.40
South Fork Shoshone River above Buffalo Bill Reservoir, WY	1.38	0.61	2.46

Big Hole River at Maiden Rock near Divide, MT	0.98	0.60	1.86
Granite C above Granite Supplemental near Moose, WY	1.03	0.60	1.32
Teton River above South Leigh Cr. near Driggs, ID	1.15	0.60	1.75
Lemhi River below 1.5 Diversion near Salmon, ID	1.44	0.60	4.31
Middle Fork Rock Cr. near Philipsburg, MT	1.07	0.60	2.03
Rock Cr. near Clinton, MT	1.12	0.59	2.35
Wind River above Red Cr. near Dubois, WY	1.21	0.59	2.02
Wind River near Kinnear, WY	1.35	0.58	3.15
South Fork Shoshone River near Valley, WY	1.34	0.56	1.93
South Fork Teton River near Rexburg, ID	1.03	0.56	2.58
Fall River near Squirrel, ID	1.11	0.56	1.59
Ruby River below Reservoir near Alder, MT	1.67	0.55	3.21
Wind River near Dubois, WY	0.95	0.55	1.46
Little Bighorn River at State Line near Wyola, MT	1.30	0.55	2.74
Big Hole River near Glen, MT	0.99	0.54	2.50
Clark Fork near Galen, MT	1.13	0.54	3.10
Yellowstone River at Yellowstone Lake Outlet, YNP	1.05	0.53	1.70
Warm Springs Cr. near Anaconda, MT	1.11	0.53	2.21
Dinwoody Cr. above Lakes near Burris, WY	1.75	0.52	2.99
Lemhi River near Lemhi, ID	1.32	0.52	3.24
Bighorn River at Kane, WY	1.11	0.51	2.60
Jefferson River near Three Forks, MT	1.03	0.51	2.47
Snake River above Reservoir near Alpine, WY	0.99	0.50	1.48
Big Hole River below Mudd Cr. near Wisdom, MT	0.92	0.50	2.30
Fall River near Chester, ID	1.24	0.50	1.89
Snake River above Jackson Lake at Flagg Ranch, WY	0.92	0.50	1.62
NF Belowackfoot R above Dry Gulch near Ovando, MT	0.78	0.50	1.50
Warm Springs Cr. at Warm Springs, MT	1.37	0.49	3.46
Snake River below Flat Cr. near Jackson, WY	0.88	0.46	1.42
Clark Fork at Turah Bridge near Bonner, MT	0.97	0.45	2.22
Jefferson River near Twin Bridges, MT	0.87	0.45	2.11
Henrys Fork near Island Park, ID	0.72	0.45	0.93
Hyalite Cr. at Hyalite Reservior near Bozeman, MT	0.98	0.44	1.70
Henrys Fork at St. Anthony, ID	0.96	0.43	1.63
Spring Cr. at Sheepskin Rd. near Fort Hall, ID	0.66	0.42	0.83
Greys River above Reservoir near Alpine, WY	0.90	0.42	1.46
Snake River at Moose, WY	0.81	0.41	1.19
Little Lost River below Wet Cr. near Howe, ID	0.72	0.41	1.39
Big Hole River below Big Lake Cr. at Wisdom, MT	0.90	0.40	2.68
Flat Cr. below Cache Cr. near Jackson, WY	0.67	0.40	0.94
Flint Cr. near Drummond, MT	1.02	0.39	3.27
Gros Ventre River at Zenith, WY	0.95	0.39	1.84
Ruby River aboveove reservoir near Alder, MT	1.37	0.38	2.26

Clark Fork at Deer Lodge, MT	0.87	0.37	2.44
Teton River near St. Anthony, ID	0.21	0.36	1.77
Big Lost River below Mackay Reservior near Mackay, ID	0.73	0.36	1.58
Belowackfoot River near Bonner, MT	0.73	0.35	1.51
Willow Cr. near Harrison, MT	1.14	0.35	2.48
Pacific Cr. at Moran, WY	0.71	0.34	1.17
Madison River below Hebgen Lake near Grayling, MT	1.29	0.33	1.99
Little Lost River near Howe, ID	0.78	0.32	1.20
Henry's Fork near Ashton, ID	0.65	0.32	1.01
Bighorn River at Basin, WY	0.71	0.31	1.94
Silver Bow Cr. at Warm Springs, MT	0.82	0.30	1.99
Salt River above Reservoir near Etna, WY	0.61	0.29	1.30
Missouri River below Hauser Dam near Helena, MT	0.72	0.27	1.77
Snake River near Irwin, ID	0.55	0.27	0.80
Big Hole River near Melrose, MT	0.83	0.27	1.88
Shoshone River near Lovell, WY	0.74	0.26	1.61
Belowackfoot River near Shelley, ID	0.71	0.26	1.25
Bighorn River above Tullock Cr. near Bighorn, MT	0.94	0.26	2.33
Missouri River below Holter Dam near Wolf Cr., MT	0.63	0.25	1.63
Clark Fork aboveove Missoula, MT	0.77	0.25	1.68
Belowackfoot near Belowackfoot, ID	0.46	0.25	0.66
Red Rock R below Lima Reservoir near Monida MT	0.94	0.25	1.41
Clark Fork near Drummond, MT	0.66	0.23	1.57
Flint Cr. near Southern Cross, MT	0.47	0.23	1.32
Cache Cr. near Jackson, WY	0.63	0.23	1.42
Shields River near Livingston, MT	0.60	0.22	1.28
Henrey's Fork near Lake, ID	0.70	0.22	1.60
Smith River below Eagle Cr. near Fort Logan, MT	0.54	0.21	1.48
Snake River near Moran, WY	0.42	0.20	0.66
Boulder Cr. at Maxville, MT	1.20	0.20	2.87
Silver Bow Cr. below Belowacktail Cr., at Butte, MT	0.46	0.20	0.82
Snake River above Eagle Rock near Idaho Falls, ID	0.50	0.20	0.83
Bighorn River near St. Xavier, MT	0.62	0.19	2.06
Snake River near Heise, ID	0.49	0.19	0.76
Beaverhead River at Barretts, MT	0.49	0.17	0.74
Clark Fork at Gold Cr., MT	0.63	0.15	1.73
Snake River at Belowackfoot, ID	0.39	0.15	0.88
Boulder River near Boulder, MT	0.73	0.14	1.71
Medicine Lodge Cr. near Small, ID	0.42	0.13	0.91
Snake River near Shelley, ID	0.43	0.13	0.89
Silver Bow Cr. at Opportunity, MT	0.46	0.12	1.11
Five mile Cr. near Shoshoni, WY	0.49	0.12	1.02
Snake River near Belowackfoot, ID	0.32	0.11	0.80

Red Lodge Cr. above Cooney Re near Boyd, MT	0.64	0.11	2.50
Snake River at Lorenzo, ID	0.31	0.11	0.51
Camas Cr. at Camas ID	0.27	0.10	1.00
Henry's Fork near Rexburg ID	0.97	0.09	1.93
Flint Cr. at Maxville MT	0.52	0.08	1.26
Willow Cr. near Boyd MT	0.42	0.08	2.13
Nevada Cr. above reservoir, near Helmville MT	0.25	0.08	0.88
Little Bighorn River near Hardin, MT	0.67	0.07	2.40
Prickly Pear Cr. near Clancy, MT	0.52	0.07	1.25
Little Belowackfoot River near Garrison, MT	0.44	0.07	1.44
Beaverhead River near Twin Bridges, MT	0.23	0.07	0.54
Smith River near Ft. Logan, MT	0.31	0.06	1.17
Tenmile Cr. near Rimini, MT	0.77	0.06	1.93
Willow Cr. below Tex Cr. near Ririe, ID	0.17	0.05	0.52
Musselshell River at Harlowton, MT	0.28	0.05	1.10
Tenmile Cr. near Helena, MT	0.45	0.05	1.90
Middle Fork Powder River near Barnum, WY	0.44	0.05	1.41
Willow Cr. near Ririe, ID	0.10	0.03	0.34
Musselshell River near Roundup, MT	0.18	0.03	1.16
Little Wood River near Carey, ID	0.34	0.02	1.18
Musselshell River at Musselshell, MT	0.15	0.02	1.08
Musselshell River at Mosby, MT	0.04	0.01	0.24