User Manual

Version: 2.5

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Domain: https://floodpotential.erams.com

FLOOD POTENTIAL PORTAL

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National Stream and Aquatic Ecology Center

Field Services and Innovation Center – Water Resources

U.S. Forest Service

United States Department of Agriculture

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Contents

Executive Summary

Riverine floods are a leading environmental threat to life, infrastructure, and property. Climate change is likely changing these threats in some areas. To maximize infrastructure and floodplain resilience as well as knowledge used for stream and riparian ecosystem management, it is essential to develop enhanced understanding of riverine flood hazards and make this knowledge readily available to hydrologic professionals, to be incorporated into decision making.

The Flood Potential Portal (FPP; Yochum et al., 2024) was developed to assist practitioners with developing such enhanced understanding, using both traditional and new techniques that leverage the power of more than a century of streamgaging activities in the United States. The U.S. Forest Service's National Stream and Aquatic Ecology Center (NSAEC) collaborated with researchers and staff at Colorado State University's One Water Solutions Institute (OWSI) to develop a decision support system that presents the results of the flood potential method (Yochum et al., 2019) alongside the results of traditional riverine flood analysis methodologies. The intent is to help professionals understand how floods vary in space and time (from continental to catchment scales), to explore how floods differ across regions and predict flood magnitudes at points of interest using multiple methodologies. The stationarity assumption for streamgage analyses is tested, with the FPP providing adjustments that can be applied where trends in flood magnitudes are detected. Flood-frequency and flashiness trend results are also presented. Hence, the FPP provides tools to test and account for observed changes in large floods due to climate variability and change, and other non-stationarity mechanisms.

The Flood Potential Portal is a Catena Analytics-based web-tool (Figure 1). Catena Analytics offers powerful platforms for building accessible and scalable analytical tools and simulation models that can be accessed through web browsers on desktop or mobile devices. Since 2010 the OWSI team has been developing the Environmental Resource Assessment and Management System (eRAMS), an open-source technology that provides cloud-based geospatially-enabled software solutions as online services and a platform for collaboration, development, and deployment of online tools. The eRAMS web-based GIS framework, in combination with the Cloud Services Integration Platform (CSIP) framework, is used for developing, deploying, and supporting model and data RESTful web services, as the foundation of the Catena Analytics platform. These services are used to assist with strategic and tactical decision making for sustainable management of land, water, and energy resources.

The Flood Potential Portal includes multiple flood potential metrics and summarizes trends in the frequency and magnitude of floods. For watershed analyses, side-by-side presentation of multiple flood assessment methods, including flood potential, index flood, and USGS regional regressions (StreamStats), allows for seamless, simultaneous comparisons. Streamgage analysis tools are also provided, for developing flood-frequency relationships and informing decisions where gages are present. The use of multiple analysis methods for informing the selection of flood discharges for floodplain planning and infrastructure design provides redundancies that mitigate shortcomings present with each analysis method. Examples are provided to illustrate best practices for utilizing the results of multiple methods, for a well-informed design flood discharge value. Additionally, the FPP facilitates increased stakeholder engagement by making assessments more accessible. Use of the FPP can lead to greater understanding of floods and how these floods are changing; use of the FPP can contribute to the objective of improved societal resilience to riverine flood hazards.

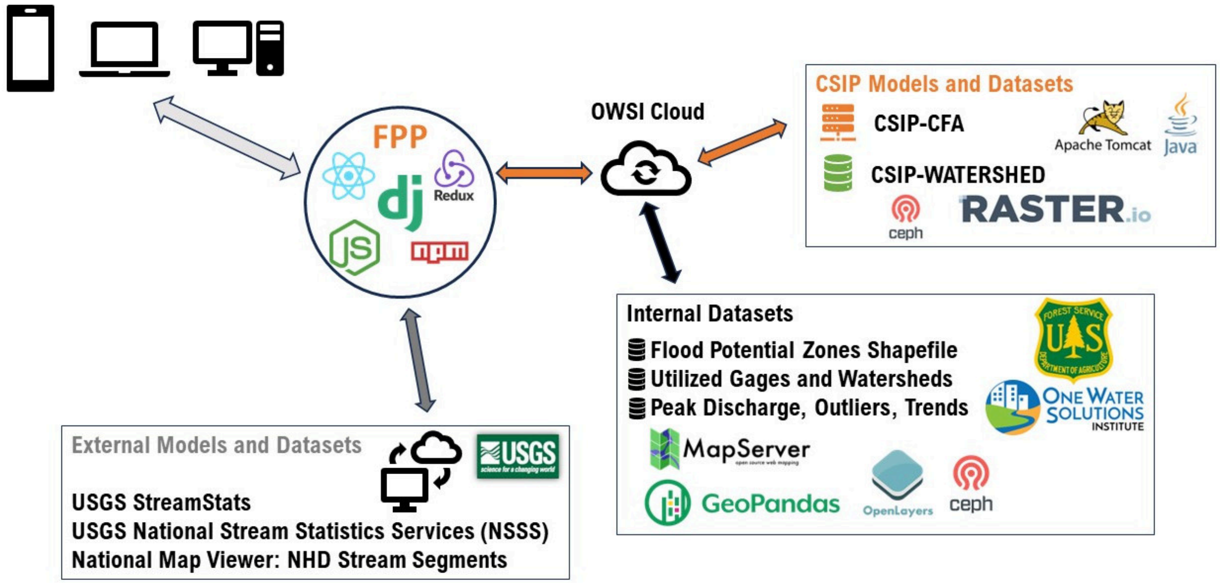

Figure 1: Flowchart describing the architecture of the Flood Potential Portal. This includes the relationships between internal and external datasets and modeling services, with logos of key architecture and processing software dependencies for internal components.

Who Should Use The Flood Potential Portal?

This decision support system was developed as a tool for professionals. While variability of floods in space and time, as displayed through the mapping and cross-section tools, can be useful for individuals with a wide range of experiences, the selection of appropriate design flood discharges requires specialized expertise. A well-educated and experienced hydrologist, floodplain manager, or civil engineer is needed for the thoughtful consideration of ensemble results, for the selection of most appropriate design flood and base flood discharge estimates. The Flood Potential Portal was developed to enhance decision making but does not replace this specialized expertise.

Need Help?

After reviewing the guide and other available information, if additional assistance is needed we are here to help! This manual is designed to provide instruction on commonly performed operations and answers many frequently asked questions. If you find any aspect of the Flood Potential Portal challenging or missing information from this guide, please engage an eRAMS expert to guide you through any hurdles. Contact us at: eramsinfo@gmail.com. If, after reading this manual, you still have specific questions on the appropriate use of results based on the flood potential method, contact steven.yochum@usda.gov.

Introduction

Purpose

The Flood Potential Portal (FPP) is a map-based decision support system for enhancing the understanding of riverine flood hazards in the United States, for infrastructure design, floodplain management, and stream and riparian ecosystem management. This tool helps users understand the observed spatial and temporal variability of floods and quantify flood magnitudes for determining design flood and base flood discharges.

Description

The Flood Potential Portal combines the results of the flood potential method, an approach for predicting, comparing, and communicating expected flood magnitudes and variability, with traditional flood-frequency analysis methods, including regional regression and streamgage analyses. The use of multiple analysis methods for informing the selection of flood discharges allows ensemble decision making that mitigate shortcomings present with each method, to provide more informed and likely more appropriate estimates while enhancing the understanding of flood variability in space and time.

By providing map-based tools for exploring the history of flooding as quantified by the nation's streamgaging record, as well as tools for utilizing these streamgage records for predicting flood discharges at user-selected points of interest, this decision support system supports the work of professionals to best quantify appropriate flood magnitudes. Due to the complex considerations involved in interpretations regarding expected flood magnitudes, professional expertise in flood hydrology are required for the proper use of results presented within the Flood Potential Portal. Additional information and supporting materials regarding the flood potential method are available on the project web page, including links to supporting materials and definitions of key terms and indices.

Features

The Flood Potential Portal has tools that (1) facilitate understanding on how floods vary in space and time, (2) quantifies large flood magnitudes at most stream locations using multiple streamgage-based approaches, and (3) provides streamgage flood-frequency analysis using automatically imported peak discharge data. Hence, this tool provides a freely available "one-stop shop" to help practitioners and managers understand and quantify flood risks, given the available observational record. Tools and features presented within the Portal include:

1. Mapping tools to view characteristics of floods, including: scale of floods experienced in a zone of interest, flashiness, flood variability, and dominant & secondary flood seasonality
2. Mapping tools to view trends in flood magnitudes, frequency, and flashiness over time
3. Tabular and graphical tools to view flooding characteristics within each flood potential zone, and quantifiably compare characteristics between zones
4. Cross-section analysis tool, to understand the role of topography in how floods vary across regions
5. Flood magnitude prediction using the flood potential method, reporting of whether there are trends in flood magnitudes, frequency, and flashiness in the area of interest, and providing adjustments for trends in flood magnitudes due to non-stationarity and climate change
6. Flood magnitude prediction using the index flood-frequency method, within flood potential zones
7. Flood magnitude prediction using USGS regional regression (StreamStats)
8. Streamgage flood-frequency analysis using the methods published in Bulletin 17B (IACWD 1982) and Bulletin 17C (England et al. 2018)

Supporting information is provided in a series of Appendices, to provide users details on the underly computational methods. Additionally, Appendix I provides information on research needs for further developing the field of flood hydrology.

Software and Supporting Information

- Domain: https://floodpotential.erams.com/
- Flood Potential Portal – Quick Start Guide: an abbreviated guide for new users of the Portal
- Flood Potential Portal – User Manual: a detailed reference on the use of the Portal, as well as details regarding the flood potential method and example applications
- Flood Potential Project Website: GIS layers, examples and references, and additional information
- Related tool for expressing the severity of current and selected historic floods across the contiguous United States: Flood Status Portal (https://floodstatus.erams.com)

Authorized Use Permission

The information contained in the Flood Potential Portal (the "Service") is for general information purposes only. The Colorado State University's One Water Solutions Institute ("CSU-OWSI") and the U.S. Forest Service's National Stream and Aquatic Ecology Center ("USFS-NSAEC"), and their team members, assume no responsibility for errors or omissions in the contents of the Service. In the Service (https://floodpotential.erams.com) you agree to hold neither the creators of the software platform nor CSU-OWSI and USFS-NSAEC (and their team members) liable for any action resulting from use or misuse of the Service. In no event shall CSU-OWSI and USFS-NSAEC (and their team members) be liable for any special, direct, indirect, consequential, or incidental damages or any damages whatsoever, whether in an action of contract, negligence or other sort, arising out of or in connection with the use of the Service or the contents of the Service. CSU-OWSI and USFS-NSAEC reserves the right to make additions, deletions, or modification to the contents of the Service at any time without prior notice.

Acknowledgements

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The Flood Potential Portal project was initiated and overseen by:

- Steven Yochum (PhD, PE) , Hydrologist and Principal Investigator, USFS NSAEC
- Mazdak Arabi (PhD), Director and Principal Investigator, CSU OWSI

The Flood Potential Portal was developed by: Tyler Wible, Matthew Korsa, Mahshid Ghanbari, Dave Patterson, Lucas Yaege, Holm Kipka, Heidi Klingel, and Joel Murray, with design oversight by Steven Yochum.

The flood potential method was developed by: Steven Yochum, David Levinson, Julian Scott, Mahshid Ghanbari, and Heidi Klingel.

This user manual was written by Steven Yochum, Tyler Wible, Mahshid Ghanbari, and Sarah Millonig.

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Appreciation is also expressed to the USGS StreamStats development staff, as well as for the great many hydrologists, hydraulic engineers, and technicians who have collected and analyzed peak stage, discharge, and other streamgage data since the late 19th Century, and the U.S. Geological Survey and partner agencies who have collected and served data, provided technical expertise, and funded flood science across the United States.

Quick Start Guide

Click on the links below and follow this workflow to start using the Flood Potential Portal:

- Accessing the Tool
- Mapping Capabilities
- Cross-Section Analysis
- Watershed Analysis
- Streamgage Analysis

Additional details on utilizing this decision support system are available in the Using the Flood Potential Portal section of this user manual.

Where using the Flood Potential Portal for design flood discharge and flood-frequency predictions, thoughtful consideration of results from multiple methods is required for the selection of the most appropriate values – a well-educated and experienced hydrologist, floodplain manager, or civil engineer is needed for this interpretation. The Flood Potential Portal was developed to help with this decision making, but does not replace this expertise.

Accessing the Tool

The Flood Potential Portal is available at: https://floodpotential.erams.com

Mapping Capabilities

This tool is tabbed with the symbol: 

1. Orient yourself to the key features of the map tool.
    a. On the top-right of the map, base layer selection, zooming and panning, and enter location tools are provided
    b. On the bottom-left of the map, scale and scale ratios are provided
    c. Within the left panel, there are controls for adjusting layer opacity, label color, zone attributes to display, flood potential zones to focus on (which can also be selected on the map), and the desired unit system. There are also toggles for viewing the national hydrography dataset, utilized gages and watersheds (in the flood potential analyses), and watersheds that have experienced extreme floods.
    d. On the right, there are tools for adding and displaying GIS layers, and a settings tool where base layers can be selected from a number of alternatives.
2. Pan and zoom in on the map, to begin exploring the delineated zones, and select different base layers.
    a. Zones are areas that experience a similar flood response. Choose from the variety of attributes available, to learn about floods in each zone.
    b. Zoom to regions of interest to explore flooding characteristics.
    c. Select different base layers, to provide different perspectives within the mapping tool.
3. Select a zone in your area of interest, and toggle on/off "*View National Hydrography Dataset*", "*View Utilized Gages and Watersheds*", of the flood potential method, and "*View Extreme Flood Watersheds*". These will display when zoomed in sufficiently.
    a. Extreme floods are systematically identified through the flood potential method, and are compared using the flood extreme index (E_f). Higher E_f values and warmer colors indicate greater extremity.

4. With a zone selected, explore the flood potential zone characteristics displayed below the map. The primary tabs and characteristics are:
    a. ***Zone Summary***: Provides zone values and percentile ranks (compared to the entire extent), as well as equations for flood potential and index flood predictions.
    b. ***Zone Data***: Flood potential plot, showing utilized record peak discharges, expected flood potential regression (Q_{efp}), estimated maximum likely flood potential regression (Q_{mlf}), and low and high outliers. Floods greater than the Q_{mlf} are extreme. Hovering over each point provides information regarding the flood. A frequency plot of the largest annual 5% floods, by month, is also provided.
    c. ***Regional Comparison***: Comparative flood potential and flood hazard plots for the zone of interest and surrounding zones.

    Exporting tools for the tables and figures are provided.

Cross-Section Analysis

This tool is tabbed with the symbol: 

Explore the influence of topography on flood potential and variability through the use of the cross-section analysis tool, by cutting a cross-section across an area with multiple zones and topographic relief.

a) For more informative results, cut transects across distances from 100 to 500 miles (kilometers).
b) The calculation interval is varied, with the time required for the regeneration noted when entering a new interval.
c) Adjust the calculation interval to 1 or 2 mi (1 or 2 km), to view a more accurate rendition of the topography.

Watershed Analysis

This tool is tabbed with the symbol: 

The watershed analysis tool provides flood discharge estimates using both flood potential and traditional flood-frequency methodologies; the use of multiple approaches for quantifying expected flood magnitudes provides multiple perspectives and greater knowledge, for the selection of the most appropriate magnitudes for floodplain management and infrastructure design. The Portal includes three approaches to prediction: (1) the flood potential method; (2) an index flood method that utilizes flood potential zones, and (3) U.S. Geological Survey regional regression equations. Methods 2 and 3 provide flood-frequency distributions.

1. Zoom in to a scale < ~1:10,000 and select an outlet point, or enter the latitude and longitude coordinates. Select the most appropriate base layer to best identify this point within the stream system, which may be aerial imagery. View the National Hydrography dataset, if desired. Click ***Delineate Watershed From Outlet*** and wait for the delineation to be created. Note the ***Running…*** notification in the left panel.
2. Check the red delineated watershed boundary for accuracy. If the delineated watershed is small, compared to what is intended, click ***Delineate Large Watershed*** and (once results are updated) check the red delineated watershed boundary for accuracy.
3. Click ***Run Watershed Analysis*** and wait for the analysis results. Note the ***Running…*** notification in the left panel. Initially, the Flood Potential and Index Flood results will be displayed under the Calculations tab. The ***Running…*** notification will continue spinning until the USGS Regional Regression results are downloaded from the StreamStats application.

4. In some situations the Portal will stop attempting to download the results from the USGS, after a number of failed attempts. Click ***Fetch USGS USGS Regional Regressions*** to make additional attempts.
5. After the USGS regional regression results are downloaded from StreamStats, a second watershed delineation as determined by StreamStats is provided on the map (in yellow). Compare these watershed boundaries and their associated areas for consistency. If they do not sufficiently match, reselect the outlet point from a slightly different location and try again.
6. Inspect the results in the ***Calculations*** and ***Overview*** tabs, including the watershed areas, second predictors utilized in the regressions (other than watershed area), and the existence (or not) of trends in the observed magnitude and frequency of large floods. Pay particular attention to how the magnitudes compare between the different methods, including adjustments for trends in the flood potential magnitudes. The Overview tab also provides a summary of area-averaged indices (by zone) for the selected outlet point, which can be used to quantitively compare the flood risk between any two watersheds. Percentiles (compared to zones across the analysis extent) are also provided for these indices.
7. The ***Overview*** table can be exported for future reference and documentation. It is also advisable to take a screenshot (using an external program) of the map, for additional documentation.

Streamgage Analysis

This tool is tabbed with the symbol: 

The Flood Potential Portal has the capability to perform streamgage flood-frequency analyses as defined in Bulletin 17B (IACWD, 1982) and Bulletin 17C (England et al., 2018).

1. Draw or import a geometric shape to define an area of interest. Press the “Fetch Stations Within Bounds” button to activate a search for all streamgages with relevant data within this area.
2. Click on a point on the map or in the table to select a streamgage for analysis.
3. Create a plot of the annual peak discharges using the “Plot Annual Peak Discharges” button. Inspect these measurements through on-hover, and note how these values compare to the expected flood potential discharge (Q_{efp}) for this site.
4. Click “Review Tabular Data (17B)” to inspect each of the annual peak discharge values, dates, detected high and low outliers, and set the generalized skew and variance. Unselect any data to be excluded from the analysis.
5. After reviewing the tabular data, click “Run Bulletin 17B” to perform the streamgage flood-frequency analyses. Results are provided using the station skew and the weighted generalized skew.
6. To perform a Bulletin 17C analysis, click “Review Tabular Data (17C)” to inspect detected low outliers, set the generalized skew and variance, modify default perception thresholds, and inspect flood intervals. Perception thresholds are shown in the peak discharge plot.
7. Click “Run Bulletin 17C” to perform the second set of streamgage flood-frequency analyses.
8. Compare the four sets of results and select the preferred flood-frequency relationship.

Using the Flood Potential Portal

A modern web-browser is required to connect and utilize the Flood Potential Portal. Browser options (and minimum browser versions) include: Google Chrome (v.69), Mozilla Firefox (v.62), Safari (v.11.1), and Microsoft Edge (v.17).

The FPP is accessed by visiting https://floodpotential.erams.com. A token is generated for each unique session, and a custom URL is provided to share the analysis or return to previously completed projects. A user can bookmark each analysis for their own documentation, though the saved information is limited, and there are no guarantees on how long records of each token will be maintained in the cloud system by the One Water Solutions Institute.

Practitioners new to exploring flood risks in an area of interest are encouraged to explore all the tool's capabilities, to gain understanding on the status of flooding at a point of interest, and the variability of flooding in the area in both space and time. It is important to explore flood variability within a region of interest, to develop additional understanding of the characteristics of floods, and how these traits compare to other areas and change over time as quantified by the observational record. The mapping and cross-section tools are provided to facilitate such insights. The watershed analysis tool is provided for quantifying floods at specific points of interest, using multiple analysis approaches.

The landing page when arriving at the FPP is an ***Overview*** page (Figure 2), with general information on this decision support system. From this initial page, several tabs are provided on the left for utilizing the sections of the tool, specifically tabs for the ***Mapping***, ***Cross-Section Analysis***, ***Watershed Analysis***, and **Streamgage Analysis** modules.

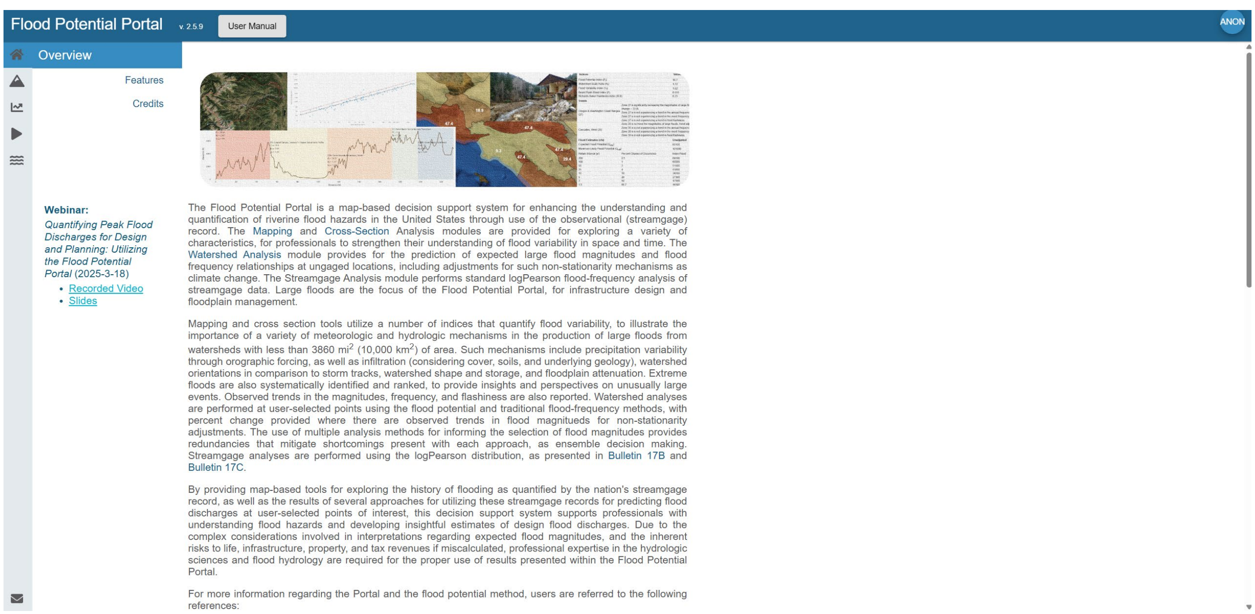


Figure 2: Landing page for the Flood Potential Portal (floodpotential.erams.com).

Mapping

Click  (the ***Mapping*** icon) on the left side of the FPP (red rectangle in Figure 3) to initiate the mapping functions. The contiguous United States is the initial map extent. At the top of the left panel a slider provides users the option to vary the displayed attribute opacity over the base layer. Additionally, label colors can be toggled between black (default), and white, to accommodate for different user-selected base layers. On the bottom-left corner of the map a scale is provided, along with the map scale ratio.

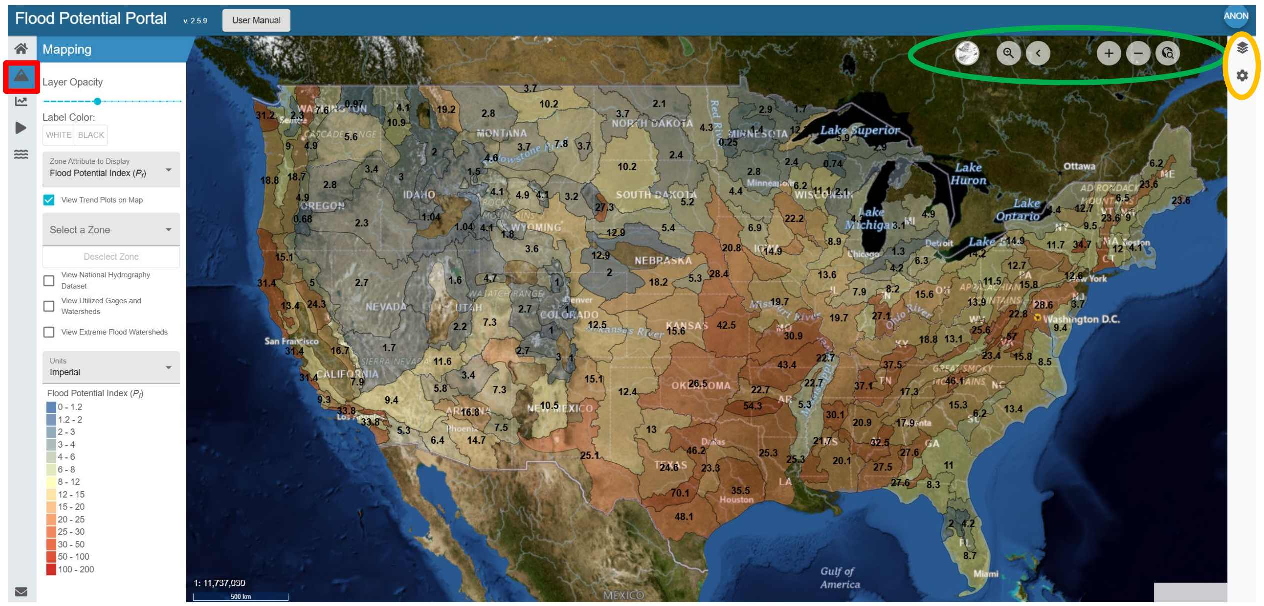


Figure 3: Default extent, base layer, and flood potential index (P_f) attribute within the Mapping tab of the Flood Potential Portal. Warmer colors indicate higher flood potential while cooler colors indicating lower flood potential. Comparisons of large flood magnitudes between zones can be performed using P_f values: for example, the zone with P_f = 70.1, in Texas, experiences floods 70.1/1.4 = 50 times larger, on average, than floods in the headwaters of the Mississippi River in Minnesota (P_f = 1.4).

Note: *When initiating a new Flood Potential Portal session, there is a delay before the Mapping, Cross-Section Analysis, Watershed Analysis, and Streamgage Analysis modules can be used, due to data being downloaded. An initial mapping download of a coarser map is shown until the high resolution map is downloaded. A "High Resolution Map Loading" note and loading icon is shown while this information is downloaded.*

Panning and Zooming

Panning and zooming tools are provided on the upper-right portion of the map extent (green oval in Figure 3), in addition to the typical scroll-to-zoom and double-click-to-zoom functionality common with web map tools. Tools are provided (from left to right, after the adjust base layer settings button) to click and drag a rectangle to zoom to, go to previous extent, go to next extent, zoom in to the map, zoom out the map, and to enter a location to zoom to, such as a specific street address.

Modifying Base Layer

Users are expected to have different preferences for background imagery, and with preferences that vary by the physical setting and objective. To address this, a variety of base layers are available. Options include: Open Street Map, Open Street Map Humanitarian, USGS Imagery, USGS Imagery Topo (default), USGS Hydro-NHD, USGS Shaded Relief, and None. To modify the base layer, click the base layer button in the upper-right of the map (left side of the green oval in Figure 4) or (the settings icon; red rectangle in Figure 4) on the right side of the Portal and click ***Back*** or ***Next*** to toggle between available base layers. Other available settings from this opened right panel include a pull down that allows users to zoom to default scale ratios and adjust the map toolbar. Click the base layer or settings icon again to close this right panel.

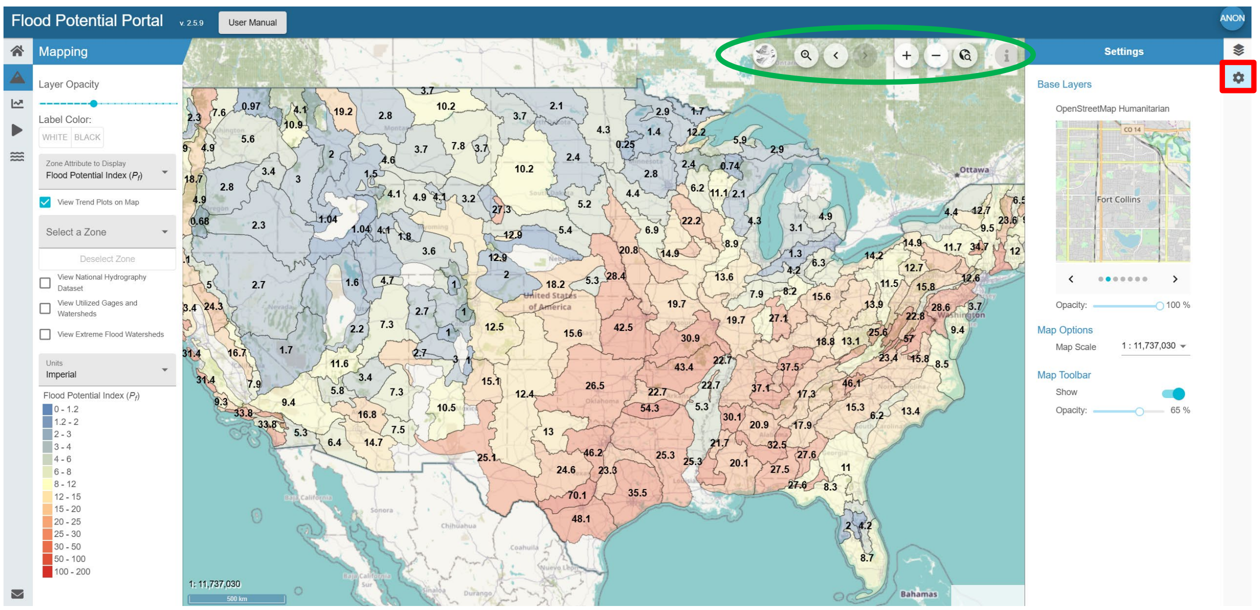


Figure 4: Modifying the base layer.

Layers

Tools for uploading layers and tables, as well as for geoprocessing tools and CSIP services, are provided in the upper-right of the Portal (top of yellow oval in Figure 3). In addition, eRAMS provides access to numerous public datasets including US Geo Data, US Hydro Data and US EPA Water data. Click on the ***add from public data*** (globe+ icon) under the ***Upload and Display Layers and Tables*** tab and select desired datasets. Users can also upload their own spatial datasets for use by selecting the ***Upload Layer*** button in the top left of the Layers panel. Allowable layer formats include ArcGIS shapefiles (multi-selected for upload or included in a single zip-file), GeoJSON, and raster (.tif) files. Once uploaded, the file will be auto-projected into eRAMS' default global coordinate system, WGS 84, for presentation along with the other layers in the tool. After uploading, metadata about the layer will be included in the left panel, including type of feature (point, line, polygon, raster), its coordinate system, and symbology. Symbology can be edited by clicking on the legend for that layer which opens a new panel to specify single symbol types, categorical symbology, or ranges of symbology based on attributes in the layer. Users may also copy, zoom-to, view the attribute table, download, delete, or edit a layer once it is uploaded.

Zone Attributes

A number of flooding characteristics for each zone are provided as zone attributes, with these attributes providing information on the variability of large floods in space and time. These zone attributes are selected by using the ***Zone Attribute to Display*** pulldown on the left panel (green oval in Figure 5). Pan and zoom in on the map, to explore variability between the delineated zones. Choose a specific zone of interest by clicking on the map, or by using the ***Select a Zone*** pulldown (orange oval in Figure 5). This pulldown also includes a *Full Extent* option, to return a view to the whole default extent. Zones are areas that experience similar flooding. Choose from the variety of attributes available, to learn about floods in each zone.

These flooding characteristics are quantified using the flood potential method (Yochum et al., 2019). For an overview of this methodology, refer to Appendix A. Detailed information on the procedure used to develop the flood potential zones is provided in Appendix C.

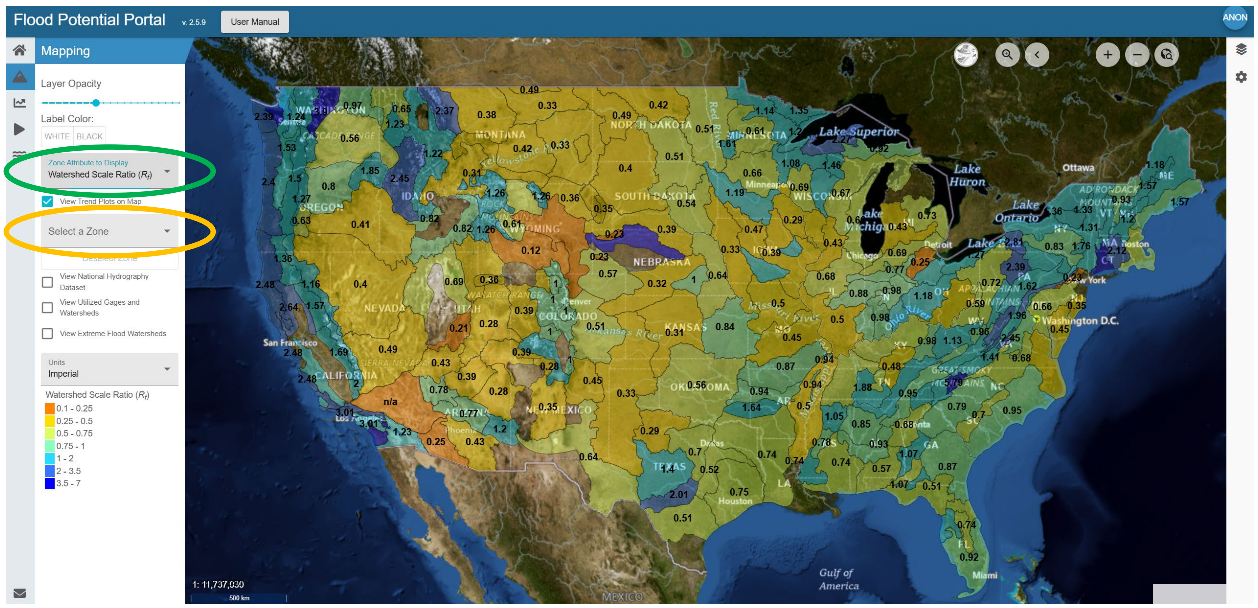


Figure 5: Attributes and zone selection, with the watershed scale ratio (R_f) attribute. Warmer colors indicate areas where smaller watersheds experience relatively larger floods, while cooler colors indicate areas where larger watersheds experience relatively larger floods. Zones with small R_f values, such as 1N along the Rocky Mountains Front of Colorado and Wyoming, experience floods in smaller watersheds that can be unexpectedly large compared to what is experienced in larger watersheds.

The default zone attribute is the *Flood Potential Index* (P_f; Figure 3), which ranks and compares flood potential (experienced flood magnitudes) between zones. Higher values and warmer colors indicate higher flood potential. As an example on how P_f is utilized for comparison, consider the Ouachita Mountains (zone 57; P_f = 54.3), and the Mississippi River Headwaters, South (zone 67S; P_f = 2.8). The Ouachitas experience some of the largest floods within the continental United States, as indicated by the high flood potential index. Floods in the Ouachitas are, on average, 54.3/2.8 = 19.4 times larger than in zone 67S.

Zone attributes include:

- *Flood Potential Index (P_f)*: ranks and compares experienced flood magnitudes between zones
- *Zone ID*
- *Zone Name*
- *Watershed Scale Ratio (R_f)*: lesser values indicate that smaller watersheds experience relatively large flood magnitudes, while greater values indicating that larger watersheds experience relatively large flood magnitudes.
- Flashiness indexes (higher values = greater flashiness):
    - *Beard Flashiness Index (F)*
    - *Richards-Baker Flashiness Index (R-B)*
- *Bimodality Index (B_i)*: ratio of the largest measured annual peak discharge to the typical (median) annual peak discharge
- *Flood Variability Index (V_f)*: variability of large floods, in space and time (with higher values = greater variability)
- *Flood Hazard Index* (H_f): subsumes both flood magnitude and flashiness, with higher values indicating greater hazard
- *Explained Variance (R^2)*: explained variance of the flood potential regressions
- *Dominant Flooding Month*: dominant large flood seasonality
- *Secondary Flooding Month*: second-most dominant month of large flood seasonality
- *Trends in Largest (5%) Flood Magnitudes*: largest 5% of annual peak discharges; labeled with percent change)
- *Q4: Trends in Largest Quarter Magnitudes (>4 yr RI)*: largest quarter of annual peak discharges, for events greater than a 4 year return interval (<25% chance of annual occurrence); labeled with percent change
- *Q3: Trends in Moderate Quarter Magnitudes (4 to 2 yr RI)*: 2^{nd} largest quarter of annual peak discharges, for events between a 4 year and 2 year return interval (25% to 50% chance of annual occurrence); labeled with percent change
- *Q2: Trends in ~Bankfull Magnitudes (2 to 1.33 yr RI)*: 3^{rd} larget quarter of annual peak discharges, for annual peak flows simular in scale to bankfull discharge, for events between a 2 year and 1.33 year return interval (50% to 75% chance of annual occurrence); labeled with percent change
- *Q1: Trends in < Bankfull Magnitudes (<1.33 yr RI)*: Smallest quarter of annual peak discharges, for annual peak flows less than bankfull (>75% chance of annual occurrence); labeled with percent change
- *Trends in Annual Flood-Frequency*: labeled with rates of change where trends are possible or significant
- *Trends in Event Flood-Frequency*: labeled with rates of change where trends are possible or significant
- *Trends in Flashiness (R-B)*: trends in flashiness as computed using the Richards-Baker methodology

The indices are defined in Appendix B, with descriptions provided below.

The watershed scale ratio (R_f) quantifies the slope of the flood potential curve, with lesser values indicating that smaller watersheds experience relatively large flood magnitudes and greater values indicating that larger watersheds experience relatively large flood magnitudes. In zones with low R_f values, it can be surprising how large floods are in smaller watersheds compared to those experienced in larger watersheds.

The two indices used to quantify flashiness are Beard *F* index (Beard,1975), which is computed using the variability annual peak discharges, and the Richards-Baker index (Baker et al., 2004), which is computed using then variability in average daily discharges. Provided values in the FPP are the averages for each zone. These indices are measures of the variability in the discharge data, rather than rates of hydrograph rise.

The bimodality index (B_i) quantifies the largest flood magnitudes compared to the typical (median) annual peak discharges. Zones with higher average B_i values (Figure 6) may be less well represented by the log-Pearson distribution in streamgage flood-frequency analyses (IACWD, 1982; England et al., 2018), due to the presence of bimodality (or multimodality) in annual peak streamgage records biasing results (Appendix G).

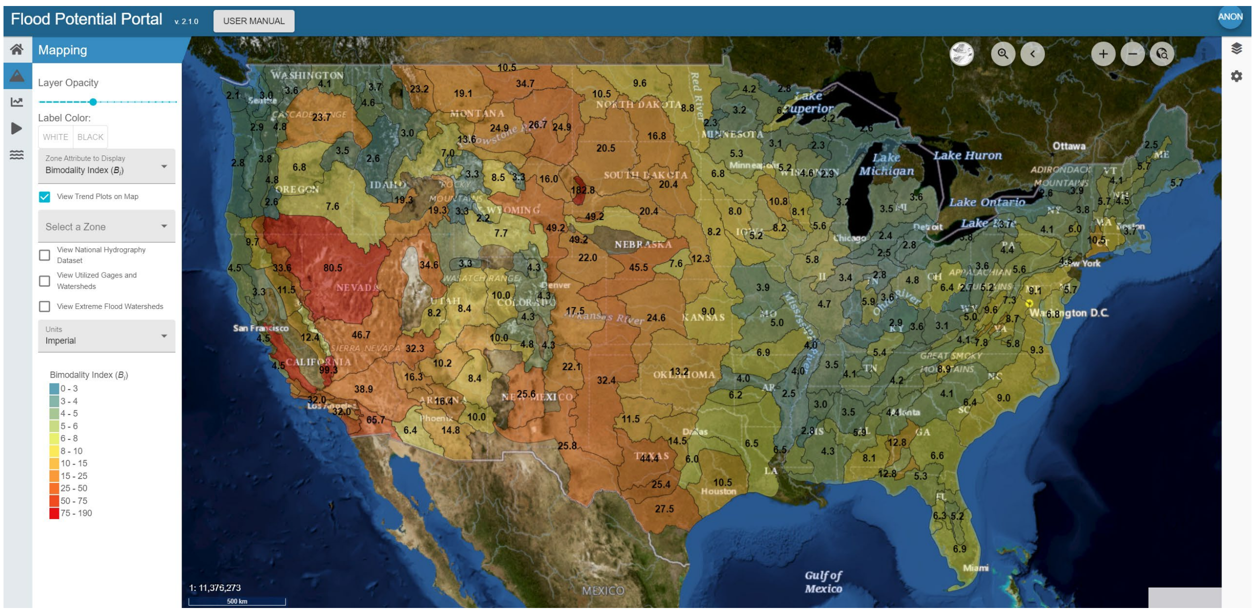


Figure 6: Average zone bimodality index (*Bi*) values across the contiguous United States. Areas with greater bimodality (or multimodality) may experience greater flood-frequency bias using the log-Pearson distribution, which is used as the current state of practice in the United States.

The flood variability index (V_f) quantifies large flood variability in space and time, as the spread (of record peak discharges) between the expected flood potential and the maximum likely flood potential.

The flood hazard index (H_f) provides an index that subsumes both flood magnitude and flashiness, for overall flood hazard. Higher values indicate greater inherent flood hazard.

The dominant and secondary large flood seasonal peak months are computed by tallying the months of occurrence of the largest 5% of the annual peak discharge measurements, and computing each month's zonal average monthly percentages. The highest percentage is the dominant seasonality, with the secondary seasonality being a second peak or the second-most frequent month. More information on flood seasonality is provided within zone information.

Several trend analyses are presented to identify non-stationarity shifts in flood magnitudes, annual frequency, event frequency, and flashiness. Five trends in flood magnitudes were performed, to show how annual peak discharges are changing for a range in probabilities of occurrence (return intervals): the largest 5% of annual peak discharges across each zone; and four bins of quarters (divided by quartiles based on the Weibull plotting positions) of all the annual peak discharges across each zone. The trend analyses are performed using the flood extreme index (E_f), which normalizes discharges for each streamgage and allows grouping across each zone, to maximize statistical power for trend detection. The largest quarter (Q4) is associated with annual peak discharges greater than a 4 year return interval (< 25% change of annual occurrence), the 2nd largest quarter (Q3) is associated with annual peak discharges between a 2 and 4 year return interval (between 50 and 25% chance of annual occurrence), the 3rd largest quarter (Q2) is associated with annual peak discharges between 1.33 and 2 year return interval (between 75 and 50% chance of annual occurrence), and the smallest quarter (Q1) is associated with return intervals less than 1.33 years (> 75% chance of annual occurrence). Q2 is indicating trends in bankfull discharge, while Q1 is indicating trends in the annual peak discharges of dry years, when flows never reach bankfull.

Plots illustrating trends (or lack of trends) are available on-hover, for the trends in flood magnitudes and annual frequency attributes (Figure 7); these static jpeg plots can be copied to the clipboard or saved with a mouse click. (Trend plots are only available in the Mapping module.) To save an image, point the cursor at the zone of interest (check the zone ID in the axis labels), move the cursor into the extent of the graphic, and "right click" to copy to clipboard or use save as. These on-hover plots can be toggled off by unchecking "View Trend Plots on Map." The presence of trends in the largest 5% or 25% (Q4) of flood magnitudes suggests the need for design flood discharge adjustments from base values, while trends in frequency and flashiness may suggest needed adjustments in expectations regarding flooding in an area of interest, while not requiring increasing the design flood discharge. The presence of trends in Q3 through Q1 suggests the need for adjusting more frequent events in a flood-frequency relationship, or recognizing that dry years are becoming drier or wetter.

Trends in flood magnitudes were assessed on a zonal basis using flood extreme index (E_f) values of annual peaks for periods that include the earliest available data for each zone. The E_f ranks flood magnitudes and extremity, with higher values indicating larger or more extreme events, and values less than 1 indicating a flood is less than the expected flood potential discharge for this watershed. Percent change was computed by comparing averages of E_f values from the most recent 30-years of record to the entire record.

Trends in the frequency of floods were evaluated using both annual and daily data, with separate analyses that counted zonal floods in each year that exceeded a threshold based on a fraction of the expected flood potential discharge at each streamgage. Trends in Richards-Baker flashiness have also been computed, and are presented within the FPP.

More information on the trend analyses presented in the Flood Potential Portal are provided in Appendix E.

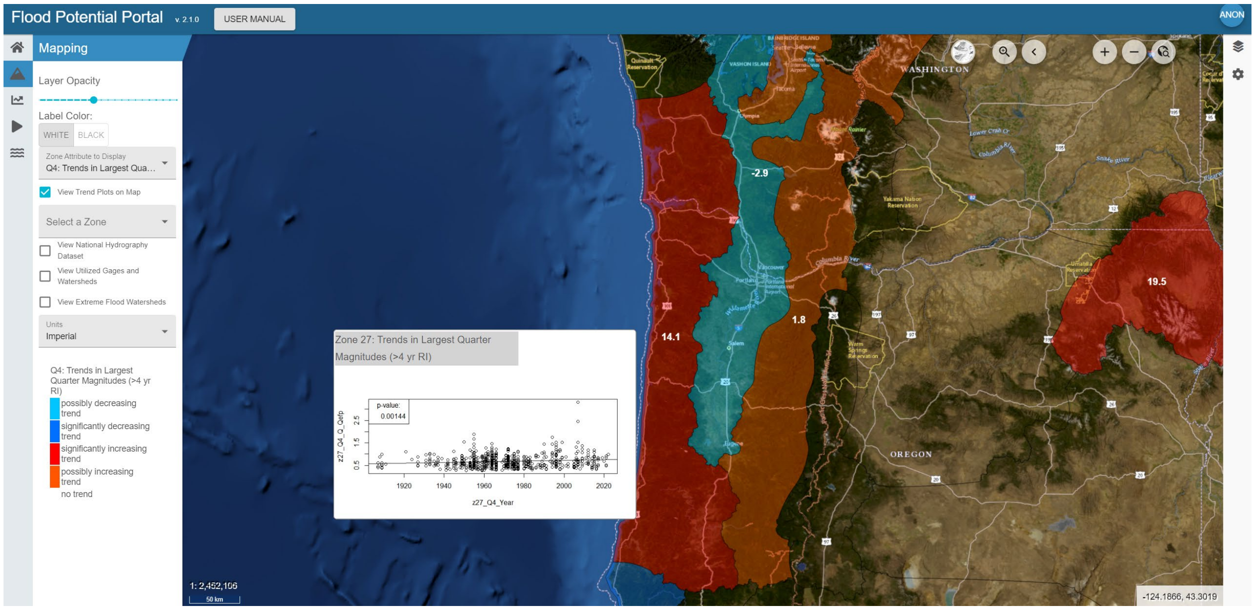


Figure 7: On-hover plot for trends in the largest quarter (Q4) of annual peak discharges, for zone 27 (Oregon and Washington Coast Ranges, +14.1%). A mouse click can copy this figure to the clipboard or "save as" to a drive. Increasing trends are also shown for a portion of Cascades (zone 28, +1.8%) and the Blue Mountains (zone 35, +19.3%), with a decreasing trend in the Puget Trough (zone 31, -2.9%). Trend plots can be toggled off by unchecking "View Trend Plots on Map."

Viewing Standard Layers

The left panel of the ***Mapping*** tab provides toggles to turn on a few standard GIS layers (green oval in Figure 8) that help users understand flooding within their area of interest. These layers include the national hydrology dataset (NHD), the streamgages and utilized watersheds in the flood potential algorithm derivations, and watersheds that have been systematically identified as having experienced extreme floods.

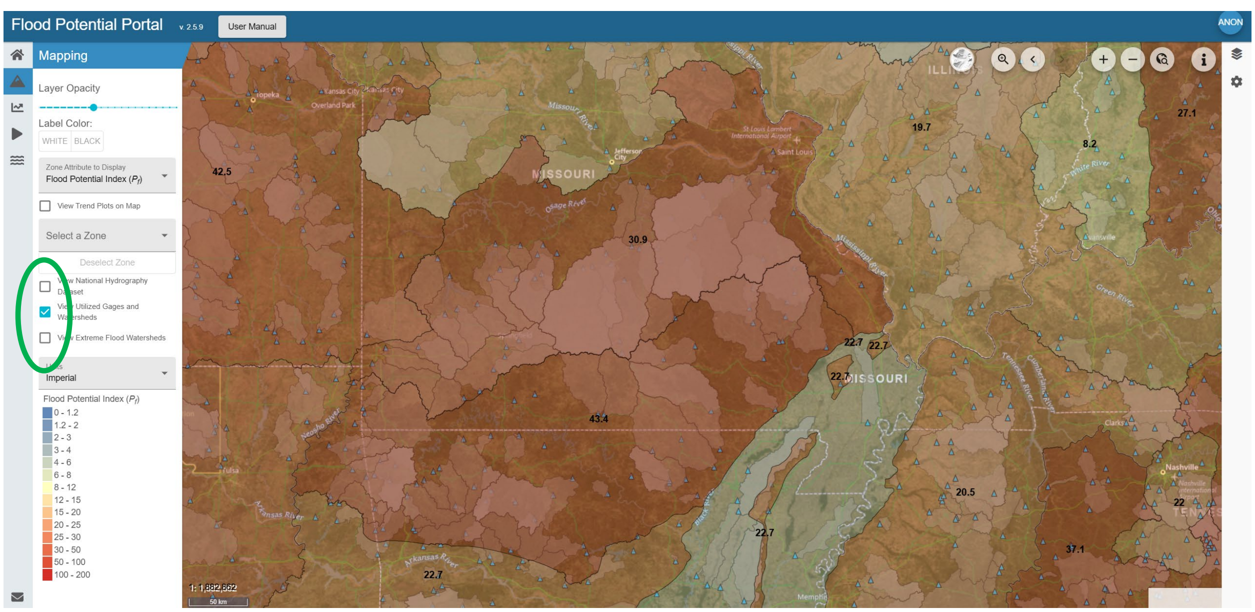


Figure 8: Toggles to turn on/off National Hydrology Dataset (NHD), Utilized Streamgages and Watersheds (in flood potential analyses), and View Extreme Flood Watersheds, for the Ozarks of Missouri and Arkansas and surrounding areas. View Utilized Gages and Watersheds is selected, with on-hover information for the record peak discharge at streamgage 07074250.

To view the streamlines as digitized in the national hydrography dataset (NHD), toggle ***View National Hydrography Dataset*** in the left panel (Figure 8). It is necessary to zoom in sufficiently for this hydrography to display. The user also has the option of changing the base layer to *USGS Hydro-NHD* to view these streamlines.

To view the streamgages and watersheds utilized within the flood potential analyses, click on ***View Utilized Gages and Watersheds*** in the left panel. It is necessary to zoom in sufficiently for these points and polygons to display, and for the streamgage ID's to be labeled. Hovering over each streamgage point (Figure 8) provides the streamgage ID, the zone the streamgage is in, the observed record peak discharge, and the date of the record peak discharge.

To view extreme floods that have been observed at streamgages (with at least 10 years of data) click on ***View Extreme Flood Watersheds*** in the left panel (green circle in Figure 9). Extreme floods are systematically identified through the flood potential method (Appendix D), and are compared using the flood extreme index (Appendix B). Higher E_f values and warmer colors indicate greater extremity. Hovering over each watershed polygon provides key information regarding each of these events, including the gage ID, site description, E_f value, date, and peak discharge. In the example (Figure 9), the hovering information for shows that Jimmy Camp Creek at Fountain, Colorado experienced an extreme flood with E_f = 14.3 on June 17, 1965. This E_f value means that this event was 14.3 times greater than the expected flood potential discharge for this location, which is one of the most extreme floods recorded in the United States.

Extreme floods are valuable for identifying the upper envelope of experienced floods within zones of similar flood response, to understand how extreme floods have varied (at streamgages with at least 10 years of record). This is important for such applications as verifying the reasonableness of probable maximum flood studies. See Appendix D for more information on extreme floods as identified using the flood potential method.

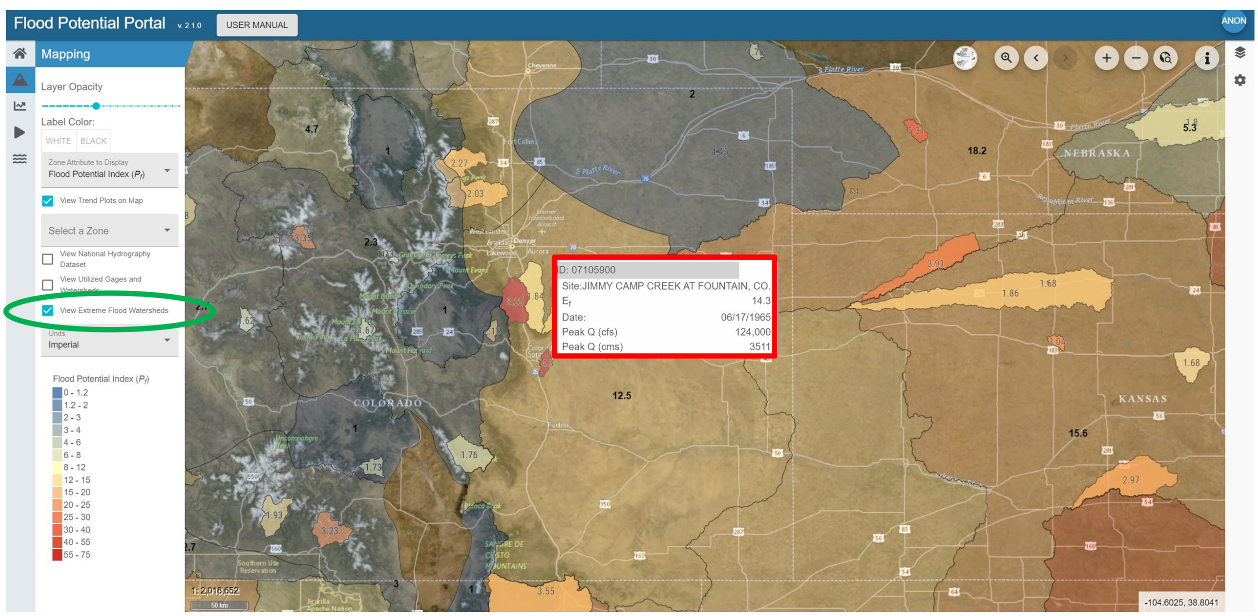


Figure 9: Extreme floods experienced along the Colorado Front Range, with on-hover information (red outlined) for Jimmy Camp Creek. This event was highly extreme, with E_f = 14.3 (124,000 cfs from a 65.3 mi^2 watershed), on 6/17/1965.

Units

Summary information and analysis results can be presented in either Imperial or SI unit systems. On the bottom of the left panel (green circle in Figure 10) the ***Units*** toggle allows users to select between desired unit systems. The default is Imperial.

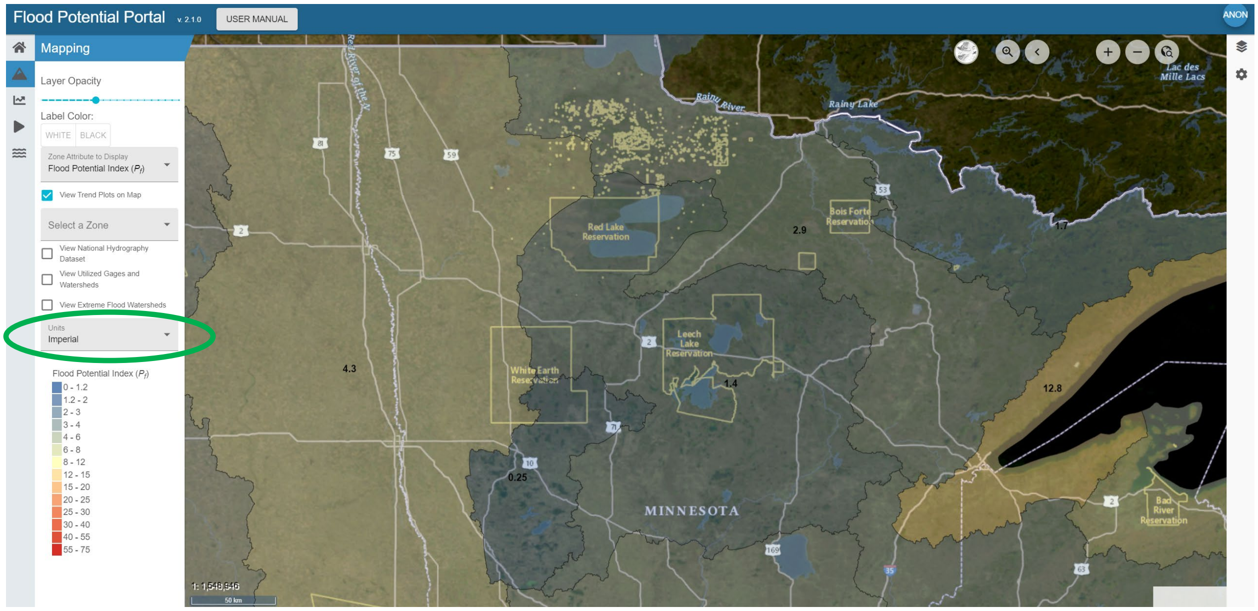


Figure 10: Flood potential variability in the Mississippi River headwaters and adjacent areas of Minnesota and North Dakota. The unit system of results presented with the Flood Potential Portal is changed by the pull down within the green oval.

Zone Summary Information

To view zone summary information for an area of interest, select a zone by clicking on the map within the zonal extent or choosing from the ***Select a Zone*** pull down in the left panel (green oval in Figure 11). Tabs for accessing zone summary, zone data, and regional comparison information are provided at the top of the table (Figure 11). The proportion of the display showing the map and table can be adjusted by dragging the boundary (red arrow).

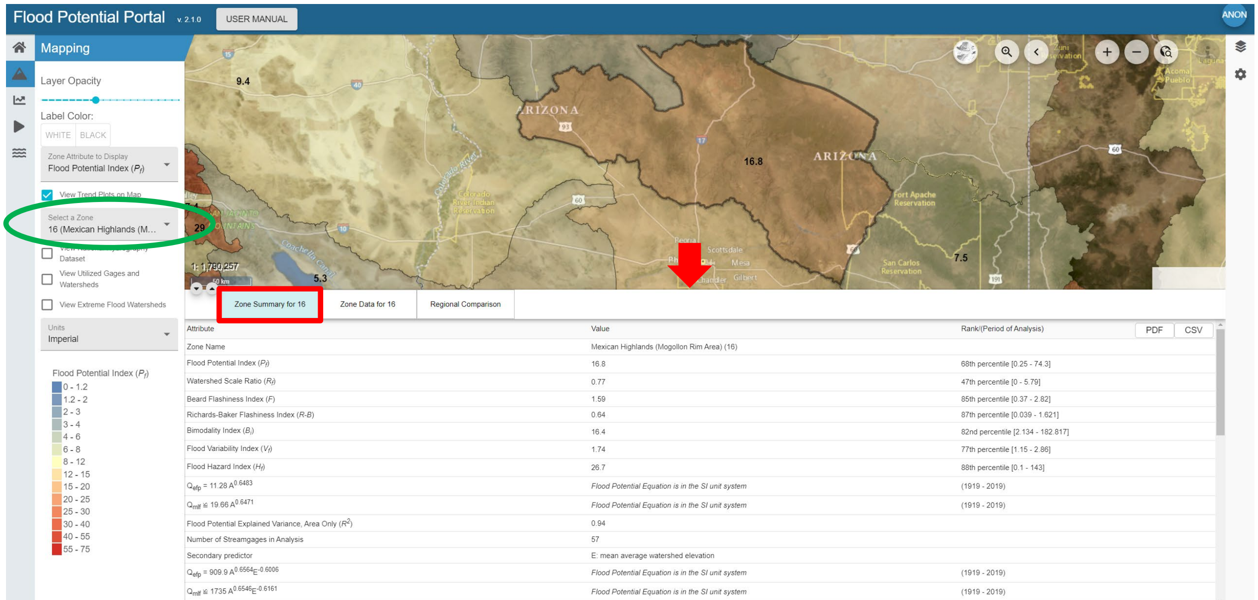


Figure 11: Zone information for zone 16 (Mogollon Rim area), with zone summary tab selected (red outlined). Map: "USGS Imagery Topo" base layer selected.

Zone summary information (Figure 11) provides fundamental information on large floods experienced across the selected zone, with percentile ranks to compare with the overall analysis extent. Provided attributes include:

- Zone Name
- Flood Potential Index (P_f)
- Watershed Scale Ratio (R_f)
- Average Beard Flashiness Index (F)
- Average Richards-Baker Flashiness Index (R-B)
- Average Bimodality Index (B_i)
- Flood Variability Index (V_f)
- Flood Hazard Index (H_f)
- Expected flood potential equation (watershed area only)
- Maximum likely flood potential equation (watershed area only)
- Explained Variance (R^2) of the watershed area only regression
- Secondary predictor (if any are significant)
- Two-variable (watershed area + secondary predictor) expected flood potential equation (if it exists)
- Two-variable maximum likely flood potential equation (if it exists)
- Explained Variance (R^2) of the multiple variable regression
- Index flood equations (1.5- through 500-year)

- Explained Variance (R^2) of the index flood equations
- Dominant Flooding Month (primary seasonality)
- Secondary Flooding Month (secondary seasonality)
- Trends in:
    - Flood Magnitudes
    - Annual Flood-Frequency
    - Event Flood-Frequency
    - Flashiness (*R-B*)
- Average of utilized watersheds:
    - Elevation
    - Slope
    - Precipitation
- Minimum Watershed Area of utilized watersheds
- Maximum Watershed Area of utilized watersheds

For index values and other general zone characteristics, ranking is provided to place values as percentiles with respect to the 207 flood potential zones. Additionally, analysis periods are provided for the flood potential and index flood-frequency analyses, and the eight trend analyses. The period end year is the last water year of data included in each analysis. Analyses are periodically updated, with priority given to zones that have experienced recent substantial flood events.

Details on the computations of these attributes are provided in Appendix A, Appendix B, and Appendix E.

Zone data information (Figure 12) provides expected flood potential and frequency of floods by month (seasonality) plots for each flood plod potential. These plots can be exported in multiple formats using the chart content menu button (green circles).

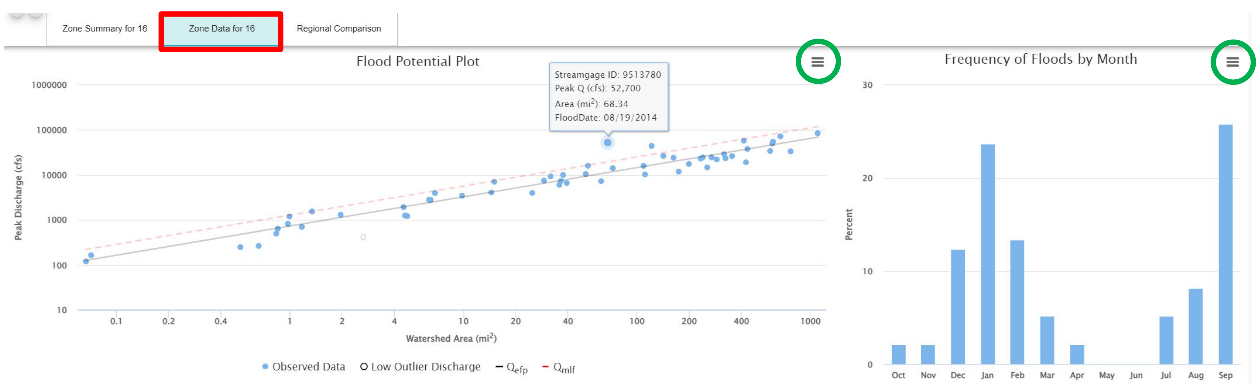


Figure 12: Zone data tab (red outlined) with flood potential and large flood seasonality plots, for zone 16 (Mexican Highlands; Mogollon Rim Area) in Arizona.

On the left, the flood potential plot provides the expected flood potential regression (black line), as defined using only the watershed area predictor. The red dashed line is the maximum likely flood potential (upper 90% prediction limit), while the blue points are the experienced record peak discharges for all the utilized streamgages. Low and high outliers, which are not used in the regressions, are also provided (where they exist). Experienced discharges that are above the maximum likely flood potential line are extreme, with the departure indicating the degree of extremity. Hovering over each of the points provides key information on the flood, specifically the peak discharge, watershed area, and the date of the flood event. Within Figure 12, the hovering information provides details regarding the most extreme flood experienced in zone 16.

On the right, the seasonality of observed large floods is presented, specifically the largest 5% annual peak flood discharges. Hovering over each bar provides the percent of total for each month. For zone 16 (Figure 12), large floods occur in two seasons, with a primary peak in September and a secondary peak in January. This seasonality differences is due to differing meteorological mechanism that induce large floods in this zone, with the summer peak due to the North American Monsoon, and the winter peak due to atmospheric river activity that extends across the Mojave Desert to the Mogollon Rim.

The ***Regional Comparison*** tab (Figure 13) provides information on how floods compare between the zone of interest (16) with its neighboring zones. These plots can be exported in multiple formats using the chart content menu button (green circles).

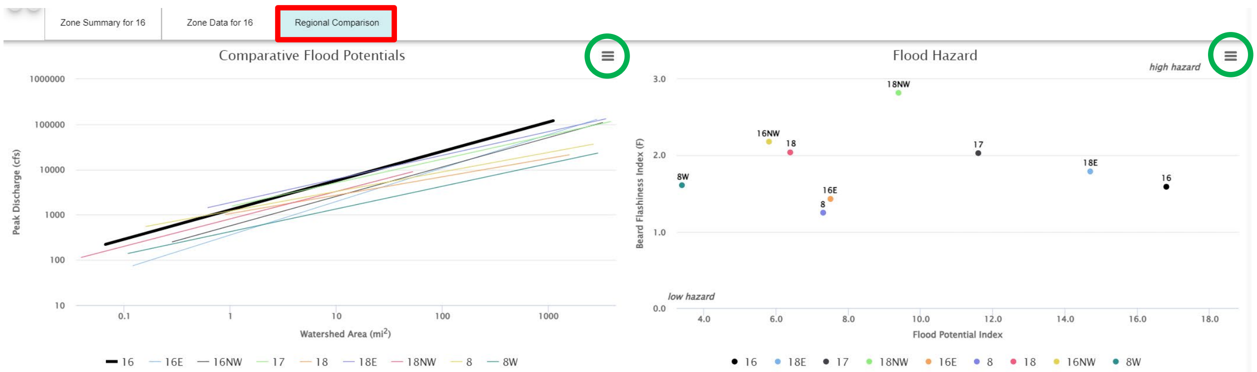


Figure 13: Regional comparison tab for zone 16, showing comparative flood potentials and flood hazard plots.

Comparative Flood Potential plots, without the underlying points used in their derivations, are provided in Figure 13, on the left. The zone of interest (16) is the thicker black line, while the flood potential in the neighboring zones (16E, 16NW, 17, 18, 18E, 18NW, 8, 8W) are the thinner lines. The higher flood potential in zone 16 is illustrated by the higher flood potential plot compared to the neighboring zones. Hovering over any of the flood potential lines provides key information, specifically the zone ID and the flood potential index (P_f).

A comparative ***Flood Hazard*** plot is provided on the right. Flood hazard is defined as the product of the flood potential index and the Beard flashiness index (Appendix B). The flood hazard plot provides the flood potential index on the x-axis, and the Beard flashiness (F) index on the y-axis. Zones that plot to the bottom-left have the lowest flood hazard, while zones that plot to the upper-right have the highest hazard. The zone of interest (16) is plotted as the black point, and has a high flood hazard to due relatively high P_f and moderate F values. Hovering over any of the flood hazard points provides key information, specifically the flood potential index, the Beard flashiness index, and the flood hazard index.

Cross-Section Analysis

A primary mechanism for flood variability is topography, with the windward and leeward effects dramatically impacting flood potential in many places. Orographic forcing on windward slopes and higher relief commonly generate enhanced precipitation and subsequent floods. Even small amounts of elevation gain can induce substantially greater flood potential, as experienced in Iowa and southern Minnesota as elevations rise from both the Missouri and Mississippi Rivers and flood potential doubles or triples compared to lower relief areas such as the upper Des Moines River basin (Figure 14). To help users understand this relationship between topography and flood potential, a regional-scale cross-section analysis tool was incorporated into the Flood Potential Portal. The color pallet of the cross-section matches that of the selected zone attribute. The flood potential index is the default attribute, though any attribute can be selected for the plots.

***Note:** When initiating a new Flood Potential Portal session, there is a delay before the Mapping, Cross-Section Analysis, Watershed Analysis, and Streamgage Analysis modules can be used, due to data being downloaded. An initial mapping download of a coarser map is shown until the high resolution map is downloaded. A "High Resolution Map Loading" note and loading icon is shown while this information is downloaded.*

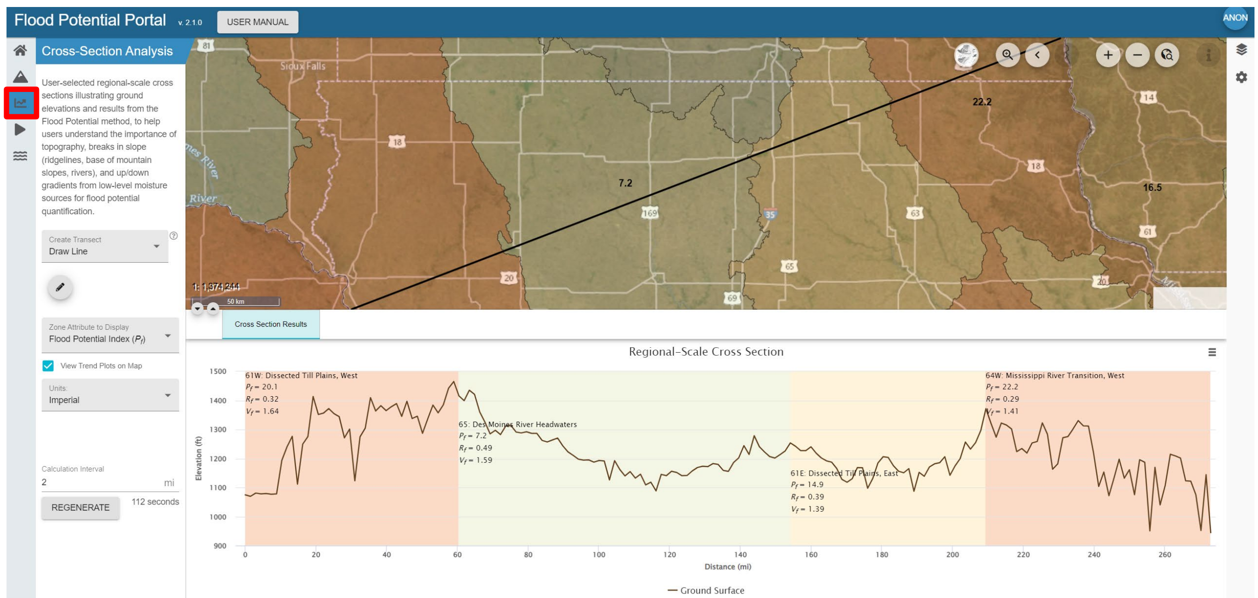


Figure 14: Regional-scale cross-section between Sioux City Iowa and the west bank of the Mississippi River adjacent to La Crosse, Wisconsin, with the De Moines River Headwaters zone having 1/3 the flood potential as the Dissected Till Plains, West zone (which rises from the Missouri River) and the Mississippi River Transition, West zone (which rises from the Mississippi River). Warmer color indicate higher flood potential, while cooler colors indicate lower flood potential. 2 mile calculation interval.

These regional cross-sections hint at several mechanisms at play that contribute to the variable flood potential between different zones. Specifically, precipitation variability through orographic forcing and other mechanisms that drive, for instance, the sizes of storms that induce the largest floods, as well as watershed orientations in comparison to storm tracks, watershed shape and storage, and floodplain attenuation.

Consider a cross-section cut across the Coastal and Sierra Nevada Mountains of Northern California, to the Great Basin (Figure 15). This area experiences its largest floods in the winter, due to atmospheric river events driven onshore and up (and down) these mountain ranges, with the Great Basin also experiencing (relatively) large floods during the summer (the secondary seasonality). These atmospheric rivers induce large floods, with substantially higher flood potential in these mountains compared to the Rocky Mountains. From the Pacific Ocean, on the left, these atmospheric rivers produce the largest floods (zone 25; P_f = 31.2) in the coastal ranges, with the flood potential dropping by more than half on the leeward side of the coastal ranges and Sacramento Valley (zone 24; P_f = 13.4). Zone 25 experiences floods, on average, 31.2/13.4 = 2.3 times larger than zone 24. Once the western slopes of the Sierra Nevada Mountains are encountered, the flood potential increases (zone 23N; P_f = 14.3) again until the crest, after which flood potential decreases by 80% in a transition zone (zone 22; P_f = 5.0), and again decreases in the Great Basin (zone 21NW; P_f = 2.7). Close to the Pacific Ocean, on the windward side of the coastal ranges, the flood potential is 31.2/2.7 = 11.6 times greater than the flood potential in the Great Basin.

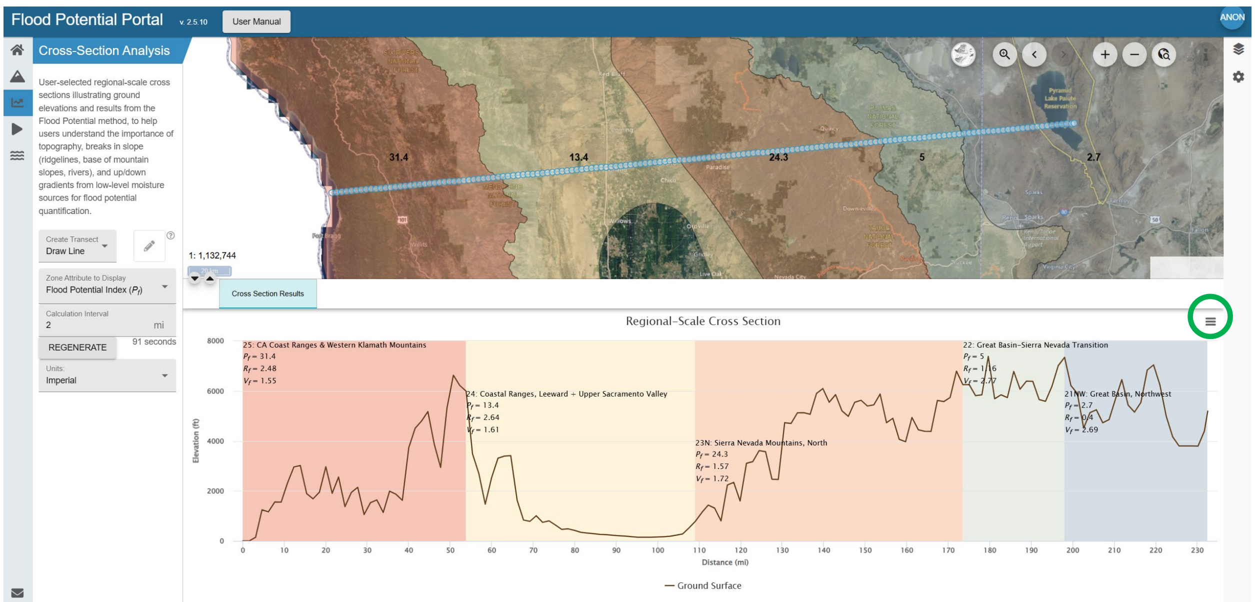


Figure 15: Regional-scale cross-section across Northern California, from the Pacific Ocean through the Coastal Ranges, Sacramento Valley, Sierra Nevada Mountains, and the Great Basin. Warmer color indicate higher flood potential, while cooler colors indicate lower flood potential. 1 mile calculation interval.

Initially, the interval of the cross-section line is coarse (10 mi, when working in the Imperial unit system). This allows for rapid plotting the cross-section. Though users are encouraged to reduce the calculation interval to see more details regarding the topographic relief. For the example of Figure 15, choosing a 1 mi interval provided a regeneration estimate of 180 seconds. Input a new calculation interval and press ***REGENERATE*** to render the higher resolution topography.

Additional features embedded in these regional cross-section plots include an on-hover feature of the ground line that provides distance along the section line and the ground elevation. Additionally, the cross-section plot can be exported from the chart content menu (green circle). Finally, the create transect tool also allows the use of an imported GIS layer (Features from a User Layer). This allows a section to be cut along an irregular line, such as a river profile.

Watershed Analysis

The **Watershed Analysis** tool provides peak flood discharge estimates at user-selected points of interest using both flood potential and flood-frequency methodologies. The use of multiple approaches for quantifying expected flood magnitudes provides enhanced perspectives and greater knowledge, as an ensemble approach for selection of the most appropriate magnitudes (i.e. design flood discharge, base flood discharge) for infrastructure design and floodplain management, as well as for stream and riparian ecological management.

For details in performing specific watershed analyses, see the Analysis section. Information on the basis and thoughtful use of the of analysis results are initially presented below.

Generally, methods utilized by practitioners to inform design flood discharges include:

1. Q_{efp}: expected flood potential discharge, the central tendency of record peak discharges across a flood potential zone
2. $Q_{100,\ index}$ (1% annual chance of exceedance flood): 100-year (return interval) discharge from an index flood analysis, using flood potential zones
3. $Q_{100,\ regional}$ (1% annual chance of exceedance flood): 100-year (return interval) discharge from USGS regional regression equations, as served through StreamStats
4. $Q_{100,\ streamgage}$ (1% annual chance of exceedance flood): 100-year (return interval) discharge at a streamgage location (at-a-station analysis), from a log-Pearson analysis of annual peak data
5. $Q_{100,\ rainfall\text{-}runoff}$ (1% annual chance of exceedance flood): 100-year (return interval) discharge as determined through a rainfall-runoff analysis, using an appropriate rainfall intensity-duration-frequency relationship

The first four methods are included in the Flood Potential Portal.

Fundamentally, all methods for estimating design flood discharges can be inadequate in certain circumstances. Flood-frequency techniques (regional regressions, index, streamgage analyses) are essential, but can provide biased estimates due to the nature of peak discharge records at streamgages. These records have a wide variety of lengths and periods, and most notably, frequently contain data of floods induced by multiple mechanisms, at different scales (fundamentally different flood magnitudes – bimodality). Alternatively, the flood potential method can predict flood magnitudes that may be exceedingly high in some areas.

An ensemble approach to decision making, using multiple methods for flood peak discharge prediction, is required for the selection of the most appropriate design flood discharge estimates – a well-educated and experienced hydrologist, floodplain manager, or civil engineer is needed for this interpretation. The Flood Potential Portal was developed to help with this decision making but does not replace this expertise.

Identified trends in flood magnitudes are also an important consideration in the selection of the most appropriate design flood discharges, to account for such non-stationarity mechanisms as climate change. The FPP automatically accounts for trends in large flood magnitudes in flood potential results and provides percent change values that can be applied to adjust other results, such as index flood and USGS regional regression predictions, for observed non-stationarity.

When utilizing freeboard in a design, this freeboard discharge need not exceed the maximum likely flood potential discharge (Q_{mlf}); floods larger than Q_{mlf} are extreme and unreasonably large for the design of most stream valley infrastructure. Hence, Q_{mlf} can be utilized as a check on the reasonableness of the freeboard discharge, for a more thoughtful application of freeboard depth above the design flood discharge stage. However, if large wood transport and other considerations elevate risk for a site, or if the geomorphology of a setting allows for greater discharges to safely pass for minimal additional cost, over designing for discharge may be appropriate.

A summary of the Watershed Analysis module methods are provided below, followed by details on the use of the Flood Potential Portal to perform watershed analyses for design flood discharge and flood-frequency selections. Analysis examples are also provided.

Flood Potential

The flood potential method provides *expected flood potential* (Q_{efp}) and *maximum likely flood potential* (Q_{mlf}) discharges (Yochum et al., 2019; Yochum and Levinson, 2023). (For an overview of the flood potential method, refer to Appendix A.) The expected flood potential is a discharge estimate computed as a regression of the record peak discharges for the streamgaged watersheds within the flood potential zone, with the maximum likely flood potential being the upper 90% prediction limit, floods beyond this limit being extreme, and departure indicating the degree of extremity. Flood predictions utilizing Q_{efp} predict flood magnitudes based on the central tendency of large floods experienced within zones of similar flood response. Considering streamgaging data, and the meteorological and hydrological processes that generate large floods (within the range of variability for the zone), it can be argued that a reasonable design flood discharge for stream valley infrastructure is a value that has an even chance of falling both short and exceeding a flood magnitude; this central tendency of large floods is the expected flood potential discharge. Overall, there is an insignificant difference between the Q_{efp} and the 100-year discharge (Q_{100}; 1% chance of occurrence; Yochum et al., 2019), though variability between Q_{efp} and Q_{100} may likely exist with respect to zone and watershed size, with systematic differences in some areas.

All streamgages with 40 or more years of data are generally required to be included in flood potential analyses (to minimize bias). Detailed information on the procedure used to develop the flood potential zones is provided in Appendix C. For the contiguous United States extent, more than 8200 streamgaged watersheds were utilized to quantify 206 flood potential zones (average R^2 = 0.93).

A flood potential plot for the Southern Rocky Mountains (zone 3) is provided (Figure 16), as an example. These plots provide key results of the flood potential analyses performed for each zone, as well as frequency plots by month for seasonality. These regression lines quantify Q_{efp}, while the upper 90% prediction limit indicates the Q_{mlf}. Floods greater than the maximum likely flood potential discharge are extreme. Prediction equations for Q_{efp} and Q_{mlf}, for both the area only and two-variable (area and secondary watershed characteristic) predictions, are provided in these plots. These are the algorithms used in the FPP, with the two-variable predictions preferentially utilized where they are available. The flood potential index (P_f), number of records (n), year and month of extreme events, and explained variance (R^2) are also provided. For R^2, the 2nd value is for the two-variable regression. Where they are present, high and low outliers are also plotted, for reference. The FPP provides a version of these plots as described in the Zone Information section, with examples provided in Appendix A.

Of interest is the situation of (possibly) unique watersheds and how they may respond during large flood events. These aberrations fall into two groups: a watershed that repeatedly produces greater flood magnitudes than expected (compared to other watersheds in a zone); and a watershed that has yet (or may never) produce a flood of a magnitude similar to the scale expected. The former can be known by available data and compensated for by utilizing streamgage analysis results, rather than flood potential, index flood-frequency, or regional regression flood-frequency results, while the latter may very well be unknowable. With the latter case, it is prudent to assume that such low outliers are aberrations, and that a flood of expected magnitude will eventually occur. History has provided examples of such circumstances (Eleven Point River example).

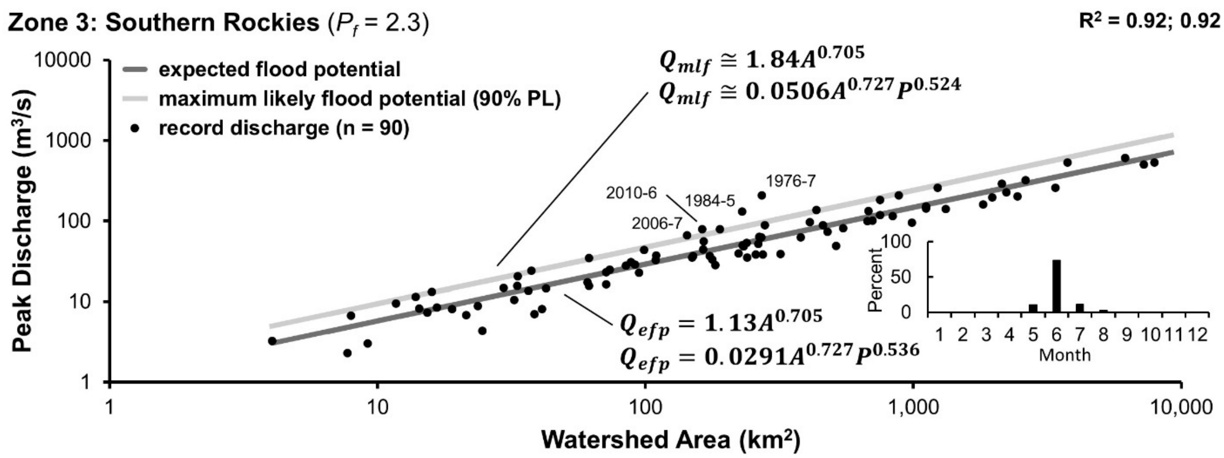


Figure 16: Flood potential plot for the Southern Rocky Mountains (zone 3), with prediction equations for Q_{efp} and Q_{mlf} and a seasonality plot. The equations are in the SI unit system.

Example: Eleven Point River Aberration

Consider the Ozarks floods of 2017 and the Eleven Point River, Missouri, with two analyses performed using data from only before as well as including this event. The Eleven Point River streamgage (USGS ID: 07071500), in zone 59S, had 96 years of data through 2016 with a maximum recorded discharge of 49,800 cfs (12/30/1982). Using standard procedures (IACWD, 1982; England et al., 2018), a log-Pearson frequency analysis yields Q_{100} = 66,000 cfs; with 96 years of record and the tradition in flood hydrology to assume that streamgage data at a site with a long record is most valuable for selecting design flood discharges near a streamgage, infrastructure designs would have likely utilized this as a design flood discharge. However, the flood potential method using data from this same period provides a different perspective – with Q_{efp} = 142,000 cfs for this site (more than twice the Q_{100}), it is clear that this watershed had experienced substantially lesser magnitude floods than neighboring watersheds (in zone 59S). Either this watershed was unique compared to its neighbors, or a much larger flood could have been expected. When a large storm system impacted the Ozarks in March 2017, this streamgage experienced a flood of 122,000 cfs, a value similar to the expected flood potential discharge. The 2017 event represents a larger flood mode that occurs in this zone, and that this streamgaged watershed (and zone) has a mixed (bimodal) population of annual peak flood events. Inclusion of the high 2017 value within an additional log-Pearson analysis with 100-years of data increases the Q_{100} (76,800 cfs), but still underestimates flood risk due to the log-Pearson distribution not accounting for a bimodal flood regime at this long record site. The flood potential method is valuable for informing selection of the most appropriate design flood discharges for such circumstances.

An example in the analysis examples section (Eleven Point River, Missouri) provides details on performing a watershed analysis for this Eleven Point River outlet point.

For additional information on the impacts of bimodal flood regimes on streamgage analyses using log-Pearson distributions, see Appendix G.

Index Flood-Frequency

The index flood-frequency method, introduced by the U.S. Geological Survey (Dalrymple, 1960), is a widely used flood-frequency analysis methods for prediction at ungaged locations. For presentation as flood-frequency results within the Flood Potential Portal, L-moments based index-flood analysis (Hosking and Wallis 1993, 1997) were performed using annual peak discharge data within flood potential zones.

Hosking and Wallis (1993) suggested an index flood procedure using L-moments to undertake regional flood-frequency analysis by assuming that all sites within a homogeneous region have the same distributions except for the scale or index-flood parameter; this is the approach utilized within the FPP, for each flood potential zone. L-moments are estimated by linear combinations of order statistics, which is more robust compared to conventional moments in terms of presenting outliers and avoids sample size-related bounds (Hosking 1990).

The index-flood method as applied within the FPP consists of two primary steps. First, a dimensionless frequency curve, also known as the regional growth curve, was developed to represent the ratio between flooding of any frequency and an index flood. The mean annual flood is used as the scale or index-flood parameter, as suggested by Hosking and Wallis (1997). Second, relationships between the geomorphologic characteristics of watersheds and the mean annual flood were developed that enables estimation of the mean annual flood at any point. A regional frequency curve is formed by combining the mean annual flood with the dimensionless frequency curve.

In a given flood potential zone, if annual flood data are available at N sites, with a duration of n_i year at site i, flood with a return period T at site i (Q_T^i) is expressed as:

Equation 1

$$Q_T^i = q_T u_i \qquad i = 1,2, \ldots\ldots, N$$

where u_i denotes the mean annual flood at site i, and q_T is the dimensionless regional frequency distribution, which remains the same throughout a zone for each return period.

The ratios between annual peak flows and mean annual flood at site i, $q_{ij} = \frac{Q_{ij}}{\hat{u}_i}$ $j = 1,2, \ldots., n_i \; and \; i = 1,2, \ldots\ldots, N$, are the basis for estimation of q_T (Hosking and Wallis 1993). In order to estimate q_T, first annual peak discharge data from streamgages in a given flood potential zone were used to estimate at-site generalized extreme value distribution (GEV) parameters based on the L-moment approach. The at-site estimates were combined to give regional estimates:

Equation 2

$$\theta_k^{(R)} = \frac{\sum_{i=1}^{N} n_i \, \theta_k^{(i)}}{\sum_{i=1}^{N} n_i}$$

where $\theta_k^{(i)}$ is the site i estimate of θ_k and $\theta_k^{(R)}$ is a weighted average, with the site i parameter estimate given weight proportional to n_i. In this fashion GEV ξ (location), α (scale), and k (shape) regional parameters and subsequently q_T were estimated in each flood potential zone for different return period of T=1.5, 2, 5, 10, 25, 50, 100, 200, and 500. Only the streamgages used in each flood potential analysis were utilized in the index flood analysis to provide consistency of results and accounting for data quality issues like streamgage length and outliers.

Multiple linear regression analysis were then carried out to link the natural logarithm of the mean annual flood (i.e., index-flood) to the watershed area, and sometimes with another watershed characteristic (e.g., slope, elevation, annual or monthly precipitation) in a given flood potential zone. Consequently u_i was defined as:

Equation 3

$$u_i = a \, A_i^b \, B_i^c$$

where A_i denotes site i watershed area and B_i represents the second watershed characteristic.

Appendix F provides an example of the development of index flood-frequency equations for a flood potential zone; see this appendix for additional information.

Updates to this method include providing for prediction intervals in results and a check for statistical significance of secondary predictor variables (watershed characteristics) prior to their inclusion in the index flood estimation equation (WY2024 end year and newer).

USGS Regional Regression Flood-Frequency

The U.S. Geological Survey provides a service of developing and publishing regional regression equations for predicting flood-frequency estimates at ungaged locations on a state-by-state basis across the United States (Miller, 2003; Kenney et al., 2007; Waltemeyer, 2008; Capesius and Stephens, 2009; Kohn et al., 2016). Generally, the development process has been for hydrologists to fit log-Pearson distributions (IACWD, 1982; England et al., 2018) to streamgage data across regions of streamgages with similar response to flood events and develop regression equations for each standard recurrence interval (percent chance of exceedance) from these fitted distributions. These regression equations are then embedded within the USGS StreamStats application (Ries et al., 2017), for providing flood magnitude predictions alongside of predictions of a variety of other flow characteristics.

The FPP has been integrated with web services that support the StreamStats website to perform watershed delineation and then extract the regional regression results for flood-frequency estimates at that ungaged location. This includes watershed delineation and watershed characteristics calculated by the StreamStats Web Services and the National Stream Statistics (NSS) Web Services for regional regression locations, metrics, and calculation of the flow statistics. These results are then presented alongside other flood magnitude prediction results within the FPP.

USGS regional regression results may be biased in some areas due to the impact of bimodal flood data (from mixed populations of flood-producing mechanisms) within log-Pearson frequency distributions. For additional information on the impacts of mixed flood populations on streamgage flood-frequency analyses, see Appendix G.

Units

Summary information and analysis results can be presented in either Imperial or SI unit systems. On the bottom of the left panel (red oval in Figure 17) the ***Units*** toggle allows users to select between desired unit systems. The default is Imperial.

Analysis

This section provides specific information on performing a ***Watershed Analysis*** within the Flood Potential Portal.

Note: *When initiating a new Flood Potential Portal session, there is a delay before the Mapping, Cross-Section Analysis, Watershed Analysis, and Streamgage Analysis modules can be used, due to data being downloaded. An initial mapping download of a coarser map is shown until the high resolution map is downloaded. A "High Resolution Map Loading" note and loading icon is shown while this information is downloaded.*

Generally, the following steps are recommended when performing a watershed analysis to determine peak discharge:

1. Review zone flooding characteristics, in Mapping and Cross-Section Analysis modules
2. Zoom in to <1:10,000 and select point of interest
3. Delineate watershed
4. Check watershed boundary, using various base layers
5. Run watershed analysis
6. Record results
7. Select peak flood discharges

Detailed information on each of these steps are as follows:

1. **Review zone flooding characteristics, in Mapping and Cross-Section Analysis modules.** Practitioners should become familiar with the following characteristics for the area they are working in:
    a. General characteristics:
        i. zone boundaries and neighboring zones
        ii. indices
        iii. cut a cross section across region, to observe orographic effects
    b. Flood status:
        i. Flood Potential Index (P_f)
        ii. Watershed Scale Ratio (R_f)
        iii. Beard Flashiness Index (F)
        iv. Richards-Baker Flashiness Index (R-B)
        v. Bimodality Index (B_i)
        vi. Flood Variability Index (V_f)
        vii. Flood Hazard Index (H_f)
        viii. Flood potential plot
        ix. Flood seasonality (dominant flooding months)
        x. Regional flood potential comparison
        xi. Regional flood hazard comparison
        xii. Extreme floods
    c. Flood trends:
        i. Largest 5% flood magnitudes: ≥ 20-year return interval
        ii. Largest quarter flood magnitudes (Q4): ≥ 4-year return interval
        iii. Moderate quarter flood magnitudes (Q3): 4 to 2-year return interval
        iv. ~Bankfull quarter flood magnitudes (Q2): 2 to 1.33-year return interval
        v. <Bankfull quarter flood magnitudes (Q1): < 1.33-year return interval
        vi. Annual flood-frequency (one event counted per year)

vii. Event flood-frequency (multiple events counted each year)
viii. Flashiness (Richards-Baker flashiness index)

2. **Zoom in to <1:10,000 and select point of interest**
   a. Choose the desired unit system for the analysis results (red oval in Figure 17). Note: If the unit system is changed after the analysis results have been provided, the results will be converted.
   b. Select an outlet point (point of interest, pour point), by picking a point on the map using the tool outlined by the green circle (Figure 17) while zoomed to a scale <1:10,000, or by entering latitude and longitude coordinates (in decimal degrees) at the location outlined by the orange oval.
   c. The initial step of a watershed analysis is to produce a watershed boundary for the outlet point, such as at a bridge or culvert crossing of a stream where a design is being developed for a new or modified infrastructure, or where floodplain extents are being computed. The FPP determines watershed boundaries by utilizing a selected outlet point of a watershed. The user selects this point of interest, while adjusting base layers to best see the characteristics of the area. The National Hydrography Dataset can also toggled on, to utilize while selecting the outlet point of the watershed.

Figure 17: Select Watershed Outlet step within the Watershed Analysis tab, for the Eleven Point River at the US-160 crossing in Missouri. The USGS Imagery Topo base layer is being used, with the National Hydrography Dataset turned off.

3. **Delineate watershed**
   a. click the Delineate Watershed button
   b. A “Running…” notice is provided below the location information, to inform users that the FPP is working on the process to delineate the watershed.
   c. An initial check is performed, to assess if the clicked point has a watershed area appropriate for application of the flood potential method. This step avoids the selection of sites on rivers with excessively large contributing areas. This check buffers the user specified watershed outlet point by 500 m and uses this region to search for nearby NHD stream segments (https://hydro.nationalmap.gov/arcgis/rest/services/nhd/MapServer). It identifies the nearest stream to the selected outlet location and references its corresponding total drainage area (TotDASqKM) for an estimate of the drainage area associated with an outlet along this segment (https://pubs.usgs.gov/of/2019/1096/ofr20191096.pdf). If this drainage area is

larger than 15,000 km^2, a warning is provided to the user that: "Watershed delineation was not performed. The watershed size exceeds the upper limit of the flood potential method." If no nearby stream segments are found, in cases of small watersheds, this upper-limit check is not performed. After this initial check, the FPP uses TauDEM algorithms (see below) to delineate the watershed.

4. **Check watershed boundary, using various base layers**
   a. Once this delineation has been performed, a red watershed boundary is shown on the map (Figure 18), which is resized to the watershed extent. Inspect this boundary for accuracy, changing the base layer and, perhaps, toggling on the National Hydrography Dataset (Figure 19), as needed for this inspection.

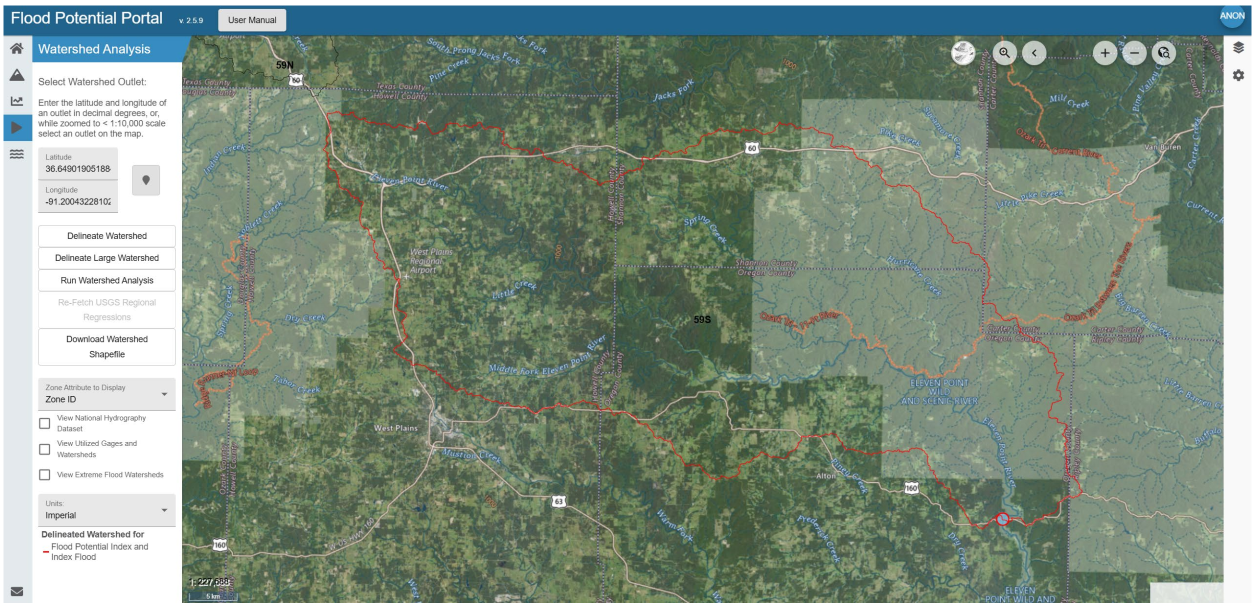


Figure 18: Check watershed boundaries step within the Watershed Analysis tab, for the Eleven Point River at the US-160 crossing in Missouri. The USGS Imagery Topo base layer is being used.

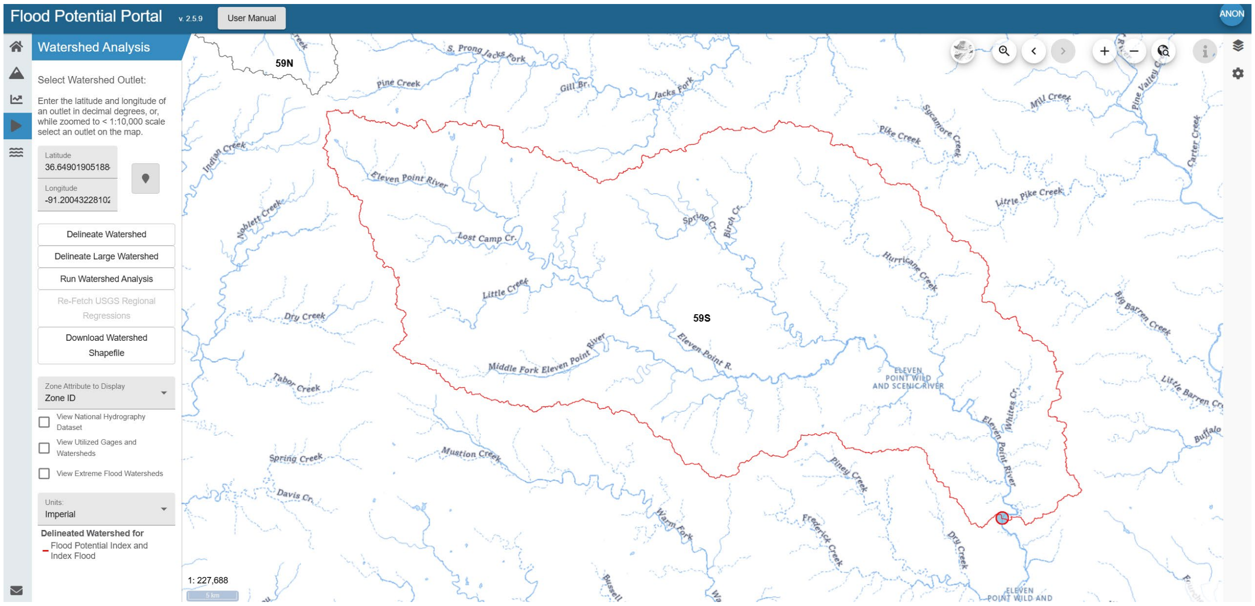


Figure 19: Check watershed boundaries step within the Watershed Analysis tab, for the Eleven Point River at the US-160 crossing in Missouri. The USGS Hydro-NHD base layer is being used.

b. The red boundary is used for the flood potential and index flood analyses.

c. This watershed boundary is computed using TauDEM, a terrain analysis program for watershed delineation leveraging the GDAL library of geoprocessing tools. Within the FPP, watersheds are initially delineated assuming that they are smaller than the HUC8 scale of watersheds with a 30 meter resolution DEM and the user provided stream outlet is snapped-to the nearest stream segment using a combination of snap-distance, 5 meters, and the Strahler order of the stream reach (to avoid defaulting to snapping to small tributaries). As a result, in certain areas of complex stream networks, repeated adjustment of the outlet location may be necessary to delineate the 'right' watershed.

d. If the check determines that the watershed is larger than the HUC8 scale, but smaller than the upper limit of the flood potential analysis in the zone(s), a user can use the "Delineate Large Watershed" option to delineate a larger watershed. This process will re-delineate the watershed using the same methodology (DEM size, 30 meters, and stream outlet snap-to) logic as described above, but adjusts the allowable watershed size to the HUC6 scale, to allow generation of much larger watersheds. This step will take substantially longer to run due to the additional data being processed.

5. **Run watershed analysis**

a. Once an accurate watershed has been obtained, click ***Run Watershed Analysis*** to proceed with the processes that will provide flood potential, index flood-frequency, and regional regression flood-frequency analysis results.

b. A "***Running…***" notice is provided below the location information, to inform users that the FPP is working on the processes to perform these analyses.

c. Initially, the flood potential and index flood-frequency results are provided in a Calculations table displayed below a resized map (Figure 20). At this point the process to obtain regional regression results from StreamStats is still being performed, with the "***Running…***" icon still showing and the note "*USGS Regional Regressions are loading*" provided.

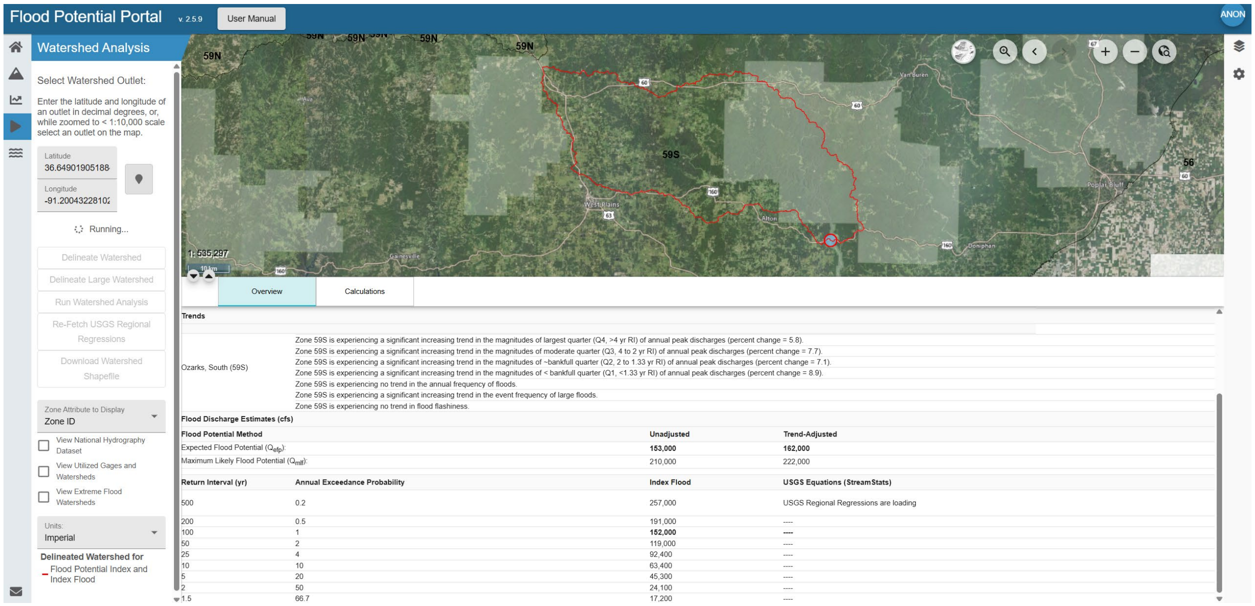


Figure 20: Initial flood potential and index flood-frequency results, for the Eleven Point River at the US-160 crossing in Missouri.

d. After an additional period of time, the regional regression results (from StreamStats) are also provided within the Calculations table (Figure 21). If an error is encountered by the StreamStats API during this step, clicking ***ReFetch USGS Regional Regressions*** will attempt to resubmit the user's outlet location to the StreamStats API for assessment. This re-fetch button allows re-analysis for situations when there is an outage to the StreamStats service due to maintenance or excessive load on the system that prevents previously requested analyses from properly returning results. However, be aware that some states have not yet developed the StreamStats application for accessing USGS regional regression equations; analyses in these states will not have any results provided.

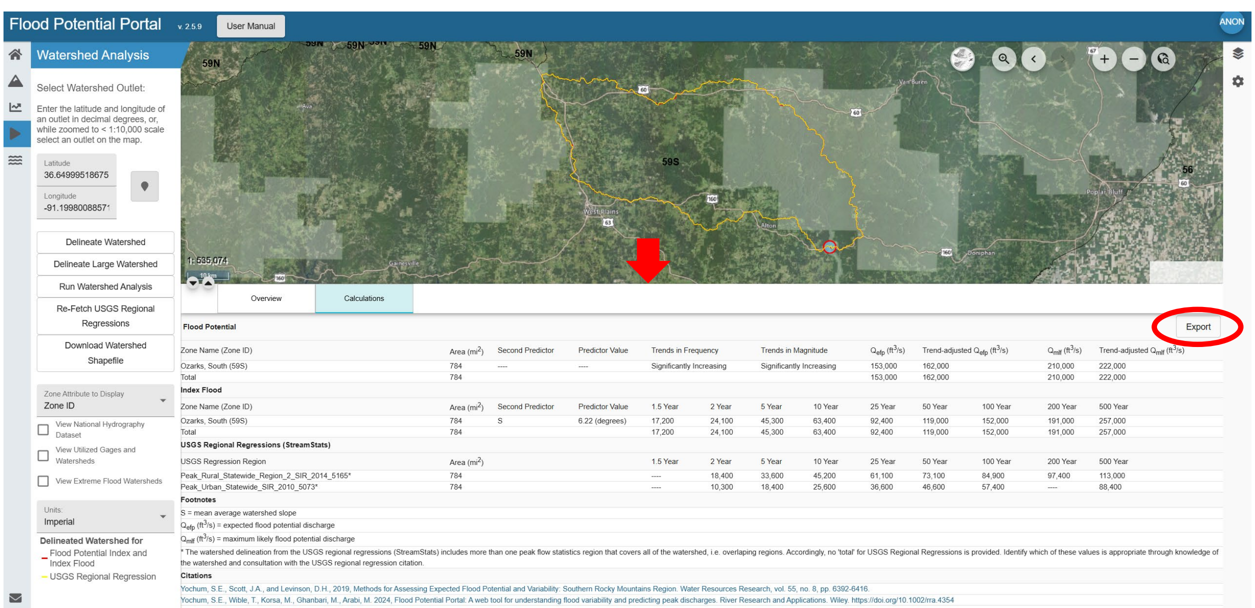


Figure 21: Flood potential, index flood-frequency, and USGS regional regression results, as displayed by the Calculations tab for the Eleven Point River at the US-160 crossing in Missouri. The 90% prediction intervals for the Index results are provided for zones that have been analyzed with an analysis end date of 2024 or later.

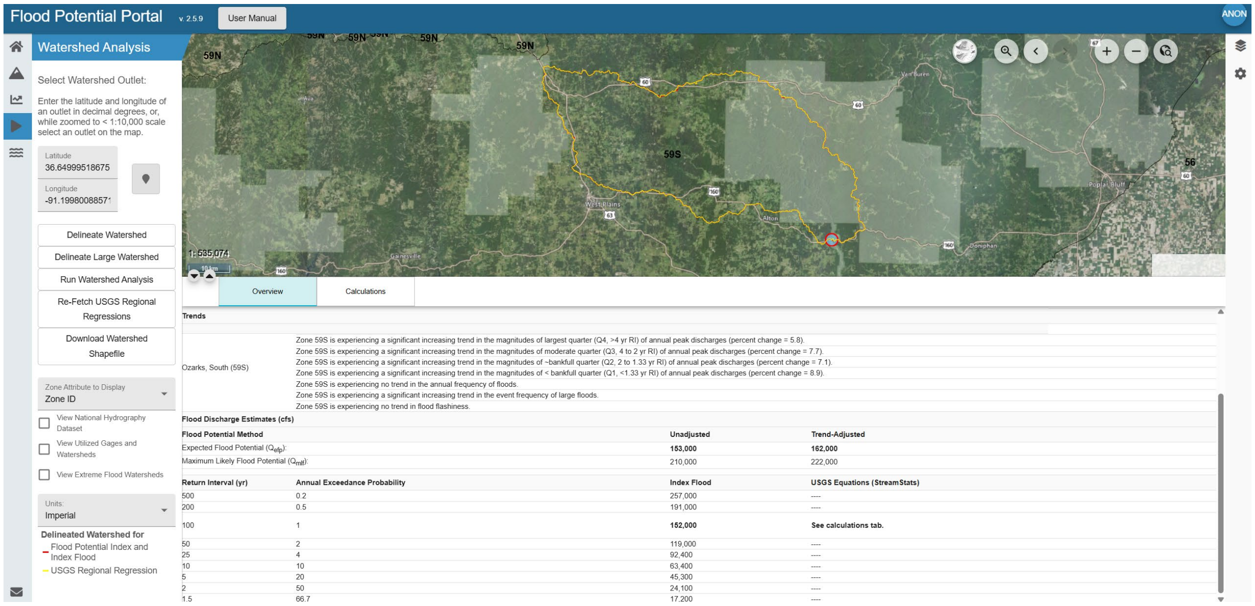


Figure 22: Flood potential, index flood-frequency, and USGS regional regression results, as displayed by the Overview tab for the Eleven Point River at the US-160 crossing in Missouri.

e. A second watershed delineation (in yellow) is also plotted within the map (Figure 21; Figure 22). This yellow boundary is the watershed delineated by the StreamStats application. The user needs to inspect the FPP delineation (red) and the StreamStats delineation (yellow) for consistency and to assure that both properly represent the watershed extent for the point of interest. It can be helpful to use the national hydrography dataset to confirm the extent, either by toggling on the NHD or changing the base layer. If they are not consistent, a new (slightly adjusted) outlet point will need to be chosen, repeating the process. The user is responsible for ensuring that the delineated watersheds are appropriate for the point of interest.

f. If there are substantial differences between the two delineated watershed boundaries, the following warning may be provided as a pop up: "*The watershed delineation for the flood potential and index methodologies is substantially different from the delineation for the USGS regional regressions (from StreamStats). Review the outlet location and confirm the correct delineation.*" The criteria for this warning is whether the watersheds delineated by the FPP and StreamStats have a watershed size that differs by 10%. This helps identify situations where, for example, one method delineates a stream and the other delineates a nearby gully that are vastly different sizes. If the watershed sizes are similar enough, a second check for similarity is made to compare the spatial extent of each watershed. If there is not a 90% overlap in the spatial extent of the two watersheds, a separate warning is provided: *"The watershed delineation for flood potential and index methodologies does not align/overlap well with the delineation from the USGS regional regressions (from StreamStats). Review the outlet location and confirm the correct delineation."* A separate and final warning message, *"The watershed delineation from the USGS regional regressions (from StreamStats) is an invalid geometry in GeoJSON and does not obey the right-hand-rule for orientation of polygon coordinates. Please contact StreamStats support for help with this location"* will be shown in a pop up if issues are encountered deciphering the watershed geometry from StreamStats.

g. Results are provided within two tabs: ***Calculations*** (Figure 21) and ***Overview*** (Figure 22). The proportion of the display showing the map and tables can be adjusted by dragging the boundary (red arrow in Figure 21).

6. **Record results**
    a. Results can be exported to Excel, pdf, and Word formats using the Export button (red circle in Figure 21). The Excel export is recommended, for greater utility.
        i. Example results from an Excel export are provided (Figure 23)
    b. Download watershed shapefile. The shapefile of this boundary can be obtained by clicking the "Download Watershed Shapefile" button, which will prompt a "Save As" window for downloading a zip file with the shapefile.
    c. Take a screenshot of the map

Flood Potential Watershed Analysis: Results Overview

Date Generated: 11/04/2025 Latitude: 36.64999519
Version: 2.5.9 Longitude: -91.19980089

Indices -- Watershed Flooding Characteristics	Value	Percentile [Range]
Flood Potential Index (P_f)	43.4	94.0th [0.25 - 164.7]
Watershed Scale Ratio (R_f)	0.87	51.0th [0 - 5.79]
Beard Flashiness Index (F)	0.85	62.0th [0.37 - 2.82]
Richards-Baker Flashiness Index (R-B)	0.455	67th [0.039 - 1.621]
Bimodality Index (Bi)	6.9	58.0th [2.1344 - 182.8173]
Flood Variability Index (V_f)	1.38	11.0th [1.15 - 2.86]
Flood Hazard Index (H_f)	37.1	92.0th [0.1 - 164.7]

Trends

Ozarks, South (59S)

Zone 59S is experiencing no trend in the magnitudes of largest (5%) of annual peak discharges.
Zone 59S is experiencing a significant increasing trend in the magnitudes of largest quarter (Q4, >4 yr RI) of annual peak discharges (percent change = 5.8).
Zone 59S is experiencing a significant increasing trend in the magnitudes of moderate quarter (Q3, 4 to 2 yr RI) of annual peak discharges (percent change = 7.7).
Zone 59S is experiencing a significant increasing trend in the magnitudes of ~bankfull quarter (Q2, 2 to 1.33 yr RI) of annual peak discharges (percent change = 7.1).
Zone 59S is experiencing a significant increasing trend in the magnitudes of < bankfull quarter (Q1, <1.33 yr RI) of annual peak discharges (percent change = 8.9).
Zone 59S is experiencing no trend in the annual frequency of floods.
Zone 59S is experiencing a significant increasing trend in the event frequency of large floods.
Zone 59S is experiencing no trend in flood flashiness.

Flood Discharge Estimates (cfs)	Unadjusted	Trend-Adjusted
Expected Flood Potential (Q_{efp})	153,000	162,000
Maximum Likely Flood Potential (Q_{mlf})	210,000	222,000

Return Interval (yr)	Annual Exceedance Probability	Index Flood	USGS Equations (StreamStats)
500	0.2	257,000	----
200	0.5	191,000	----
100	1	152,000	See calculations tab.
50	2	119,000	----
25	4	92,400	----
10	10	63,400	----
5	20	45,300	----
2	50	24,100	----
1.5	66.7	17,200	----

: directly comparable

Figure 23: Watershed analysis overview results (generated using the Excel export option) for the Eleven Point River at US-160, Missouri example. Since Q_{efp} is, on average, insignificantly different than Q_{100}, gray-highlighted cells are directly comparable for decision making. However, substantial variability between Q_{efp} and Q_{100} in some zones and at some watershed sizes can exist. Ensemble decision making is utilized to decide the most appropriate design flood discharge.

    d. The url can be bookmarked for future reference through the unique token.
    e. The ***Calculations*** tab (Figure 21) indicates contributions to the total flood potential and index peak flow estimates by each zone present within the watershed. The watershed area and information on the second predictor(s) used within the regressions are also provided. Variables are defined in the Footnotes section of this tab. More information on the specific prediction equations for both flood potential and index methods can be found within the [Mapping tool](), for the relevant zone(s)
        i. For flood potential and index analyses, contributing watersheds to the point of interest that include multiple zones are computed by area-weighing contributions from each zone.
        ii. In zones where trends in either the largest 5% flood magnitudes or largest quarter of flood magnitudes (Q4) have been detected as significant (p-value ≤ 0.05) or possible (0.05> p-value ≤ 0.15), a trend-adjusted value is provided for the flood potential results. Percent change computed by a comparison of the last 30 years of utilized record to the entire data

record for each zone (within the delineated watershed) is used to compute these trend-adjusted results. This adjustment addresses observed changes in flood magnitudes, due to such non-stationarity mechanisms as climate change and reservoir attenuation.

Additional information on the trend analyses is available in Appendix E

f. The ***Overview*** tab (Figure 22) has three sections:

i. Indices for the point of interest, as well as percentiles to place these values within context compared to the entire analysis extent. These indices can be used to compare flooding characteristics between any watersheds, including information on the general size of floods (flood potential index, P_f), on whether larger or smaller sized watersheds experience larger floods (watershed scale ratio, R_f), the variability of floods in space and time (V_f), the flashiness of floods (Beard *F*; Richard-Baker flashiness index, *R-B*), and the degree of bimodality present (B_i). More information on these indices is provided in Appendix B.

ii. Observed trends in large floods (for each zone); specifically, trends in flood magnitudes, annual flood-frequency, event flood-frequency, and flashiness. More information on flood trend detection is provided in Appendix E.

iii. Peak flood magnitude estimates, including flood potential results (expected flood potential discharge, Q_{efp}; maximum likely flood potential discharge, Q_{mlf}), and flood-frequency as determined from an index analysis and USGS regression equations (StreamStats). Results are provided for return intervals of 1.5-, 2-, 5-, 10-, 25-, 50-, 100-, 200-, and 500-year (percent change of occurrence or exceedance of 66.7, 50, 20, 10, 4, 2, 1, 0.5, and 0.2).

7. Select peak flood discharges

a. Interpretation of results needs to be performed by a qualified professional.

b. The Flood Potential Portal includes three approaches for prediction within the Watershed Analysis module: (a) the flood potential method; (b) an index flood method that utilizes flood potential zones, and (c) U.S. Geological Survey regional regression equations. Methods (b) and (c) provide flood-frequency distributions. These three results are utilized together, for ensemble decision making.

c. The Streamgage Analysis module within the FPP provides results from standard frequency analyses of streamgage data (Bulletins 17B & 17C), where a streamgage is present. These streamgage analysis results should be combined with results from the Watershed Analysis module for ensemble decision making.

d. The Q_{efp} has been found to be, on average, insignificantly different from the 100-year return interval discharge (Yochum et al., 2019), though variability between Q_{efp} and Q_{100} may likely exist with respect to zone and watershed size, with systematic differences in some areas. Generally, Q_{efp} and Q_{100} estimates are directly comparable when making interpretations.

e. Inspection of results from at least three analysis methods can highlight the most appropriate flood discharge values, to identify a method that is providing unreasonably large or small flood discharge estimates for a site of interest and deference given to results where multiple methods are providing consistent flood predictions. Where there is agreement between flood magnitude predictions, a professional can be reasonably assured of an appropriate selection of a design flood discharge. In situations where there are substantial differences, agreement between the results of two or more approaches can be used to identify the most appropriate value. Where there is not consistency between at least two results, use of a median solution may be best. Use of an average is not recommended.

f. Where increasing trends are present, use of the trend-adjusted value may be warranted. Percent increases are manually applied to index and regional regression flood-frequency results, if the practitioner chooses to account for the observed trend in the design flood discharge selection.
g. Where decreasing trends are present, it may not be appropriate (insufficiently conservative) to utilize the trend-adjusted values for selecting design flood discharges. However, it may be appropriate to utilize a trend reduction where there are large numbers of flood control reservoirs throughout the zone and the watershed of interest, due to such programs as the PL-556 program (NRCS, 2014). This program was widely implemented in portions of some states (such as Kansas and Oklahoma). Professional knowledge of the setting as is required
h. Familiarity with the beginning of the Watershed Analysis section and the Appendix can be valuable for these interpretations.
i. Examples are provided in the Analysis Examples section below. These examples can assist new users with developing the expertise in using an ensemble approach to peak discharge prediction for selecting design flood discharge and base flood discharge estimates.

Limitations

To prevent excessive extrapolation of the flood potential and index flood results, limits are provided on analyses within the Flood Potential Portal. Results are not provided where computations within a zone are for a point with a watershed area >1.1 or <0.10 times the maximum and minimum watershed areas (respectively) of the streamgages utilized to derive the flood potential and index flood regressions. In these situations, the following note is provided:

> *Computations not performed since watershed size is well beyond the limits of the source streamgage data*.

USGS regional regression results are still provided**.** These limits vary by zone, though an overall upper limit of 3860 mi^2 (10,000 km^2) is embedded within the flood potential method.

In watersheds with multiple zones where the upstream zone is >1.1*maximum watershed area limit but the overall watershed area is <1.1*maximum watershed area of the downstream (or predominant) zone, an advanced analysis option is offered. In such situations, this upstream area limitation can be bypassed by having the module compute peak discharge estimates based on only the downstream (or predominant) watershed area. When the proper criteria are met, an Advanced Analysis option is presented in both the overview and calculations tabs (Figure 24). The results from this analysis are provided in an additional Advanced Analysis tab.

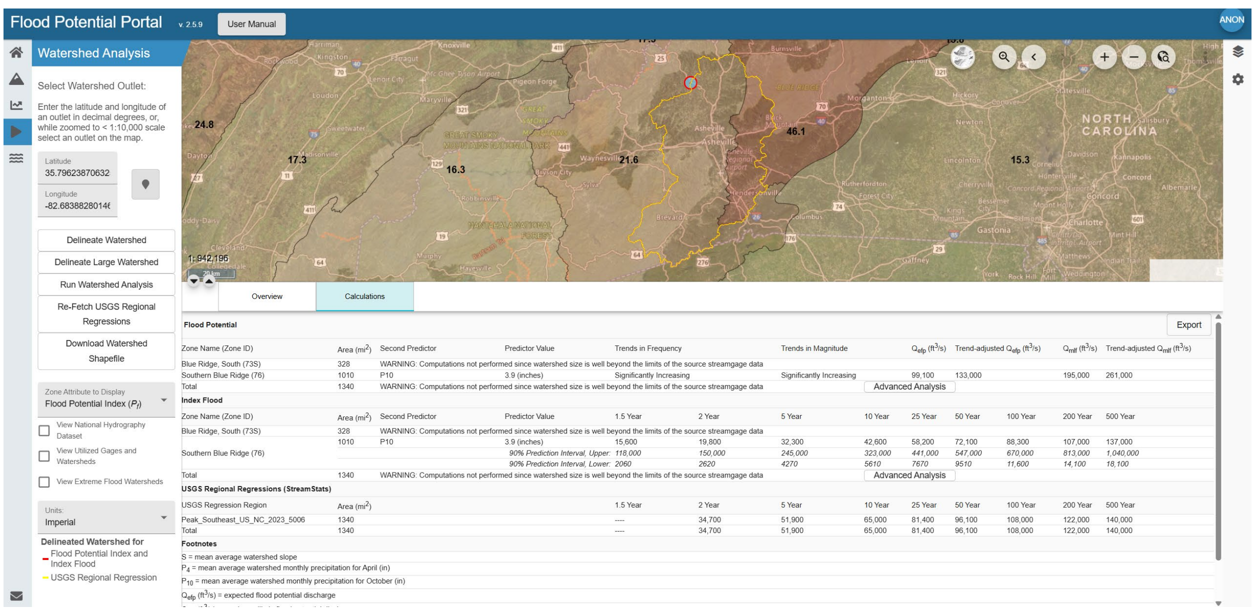


Figure 24: Watershed Analysis for the French Broad River at Marshall, NC, showing the Advanced Analysis button for performing watershed analysis computations using only the downstream (predominant) zone algorithms.

Some areas have insufficient information available for determining flood potential and index analyses; too few streamgages exist in these areas to develop relationships. When an analysis is performed that includes (in substantial part) one of these areas, the following note is provided:

> *Computations not performed since the watershed includes an area where too few streamgage data exist to develop flood potential estimates.*

In these situations, only USGS regional regression results are provided (where available).

Finally, multiple results from the USGS are provided for some regional regression areas, accounting for such differences as flood control attenuation and urbanization. In these situation, the following popup is provided:

> *The watershed delineation from the USGS regional regressions (StreamStats) includes more than one peak flow statistics region that covers all of the watershed, i.e. overlaping regions. Accordingly, no 'total' for USGS Regional Regressions is provided. Identify which of these values is appropriate through knowledge of the watershed and consultation with the USGS regional regression citation.*

Streamgage Analysis

The Flood Potential Portal has the capability to perform streamgage flood-frequency analyses as defined in Bulletin 17B (IACWD, 1982) and Bulletin 17C (England et al., 2018). Users can create an area of interest within the streamgage analysis module, fetch available streamgaging stations within this area that have available annual peak discharge data, select a specific gage from the map or a list, plot annual peak discharge data within a figure, enter or have automatically populated a generalized skew coefficient and variance, unselect low and high outlier years from the analysis, and view and export predictions and confidence intervals. Analyses are performed using the station skew and a weighted generalized skew. Return intervals for the results range from 1.05 to 500-years (95% to 0.20% chance of annual occurrence). Streamgages with at least 10 years of annual peak discharge data are available for computations, although visualization of annual peak discharge data for streamgages with less than 10 years of data is allowed, as well as data addition by the user. These streamgage analysis results should then be compared to results computed within the Watershed Analysis module for ensemble decision making. Rainfall-runoff analyses results can also be generated using other software, for additional comparisons.

Note: *When initiating a new Flood Potential Portal session, there is a delay before the Mapping, Cross-Section Analysis, Watershed Analysis, and Streamgage Analysis modules can be used, due to data being downloaded. An initial mapping download of a coarser map is shown until the high resolution map is downloaded. A "High Resolution Map Loading" note and loading icon is shown while this information is downloaded.*

It should not be assumed that a streamgage analysis provides the most appropriate design flood discharges ($Q_{100,\ gage}$), since this single gage analysis may produce a biased result due to the nature of the record (see Appendix G). A streamgage record may be missing a larger scale flood magnitude that neighboring (zonal) streamgaged watersheds indicate as being expected or have a longer record with insufficient representation of larger floods that should be designed to safely pass, resulting in underprediction. Alternatively, a streamgage may have recorded a preponderance of larger flood magnitudes within a shorter record, resulting in overprediction. An inspection of streamgage annual peak flow data for a short record length, bimodal flood magnitudes (that indicate mixed populations of flood-producing mechanisms), a lack of larger (expected) flood magnitudes in the record (flood magnitude similar to Q_{efp}), or the existence of an extreme flood in the record (as defined using the flood potential method) can all indicate if a particular streamgage analysis may be biased.

General Procedure

Streamgage analyses can be initiated as the first step in an evaluation, after which a watershed analysis is performed, or this module can be used after a watershed analysis. In the procedure described below, a streamgage analysis is initially performed. For this situation, the following steps are recommended when performing a streamgage analysis to determine a peak discharge:

1. Review zone flooding characteristics, in Mapping and Cross-Section Analysis modules
2. Create a filter (fence) around the area of interest, and fetch stations
3. Select a streamgage
4. Plot annual peak discharges, and inspect record
5. Review data for Bulletin 17B analysis
6. Perform Bulletin 17B analysis, and review results
7. Review data for Bulletin 17C analysis
8. Perform Bulletin 17C analysis, and review results
9. Export streamgage analysis data and results
10. Perform watershed analysis, and export results

11. Select peak flood discharges for design

It is recommended that both Bulletin 17B and 17C analyses be performed, using both station and weighted generalized skews, to provide multiple analysis results from which a practitioner can make a most informed decision on peaks discharge estimates at the streamgaged site. Details on the specifics regarding the statistics of log-Pearson flood-frequency analyses are available in IACWD (1982) and England et al. (2018), as well as in Appendix G.

Streamgage analyses should start by reviewing general flood characteristics of the zone(s) that the streamgaged watershed is within. Practitioners should become familiar with the following characteristics:

- General characteristics:
  - Zone boundaries and neighboring zones
  - Indices
  - Cross section cut across region, to observe orographic effects
- Flood status:
  - Flood Potential Index (P_f)
  - Watershed Scale Ratio (R_f)
  - Beard Flashiness Index (F)
  - Richards-Baker Flashiness Index (R-B)
  - Bimodality Index (B_i)
  - Flood Variability Index (V_f)
  - Flood Hazard Index (H_f)
  - Flood potential plot
  - Flood seasonality (dominant flooding months)
  - Regional flood potential comparison
  - Regional flood hazard comparison
  - Extreme floods
- Flood trends:
  - Largest 5% flood magnitudes: ≥ 20-year return interval
  - Largest quarter flood magnitudes (Q4): ≥ 4-year return interval
  - Moderate quarter flood magnitudes (Q3): 4 to 2-year return interval
  - ~Bankfull quarter flood magnitudes (Q2): 2 to 1.33-year return interval
  - <Bankfull quarter flood magnitudes (Q1): < 1.33-year return interval
  - Annual flood-frequency (one event counted per year)
  - Event flood-frequency (multiple events counted each year)
  - Flashiness (Richards-Baker flashiness index)

Streamgages available for analysis within the Flood Potential Portal are those from the USGS National Water Information System (NWIS) with annual peak streamflow data. Streamgage locations, within a user defined area of interest, are dynamically queried using NWIS web services each time users access the Flood Potential Portal’s Streamgage Analysis section. This ensures the most up-to-date list of monitoring locations directly from USGS without the need to host any streamgage information directly in the Flood Potential Portal.

An area of interest can be selected using a geometric shape (Figure 25), a user-supplied shapefile, as well as through selection of known political (county, city, etc.) or hydrologic (USGS HUC-8, HUC10, HUC12 watershed) boundary. After defining an area of interest, NWIS web services are leveraged to provide a list of streamgages. Subsequently, the peak flow dataset for each streamgage is fetched. These data are cached temporarily (<24 hours) in the Flood Potential Portal to assist with later data steps, reducing the need to repeatedly access the NWIS web services. A flood-frequency analysis is permitted for a specific gage if there are sufficient data present (≥10 years).

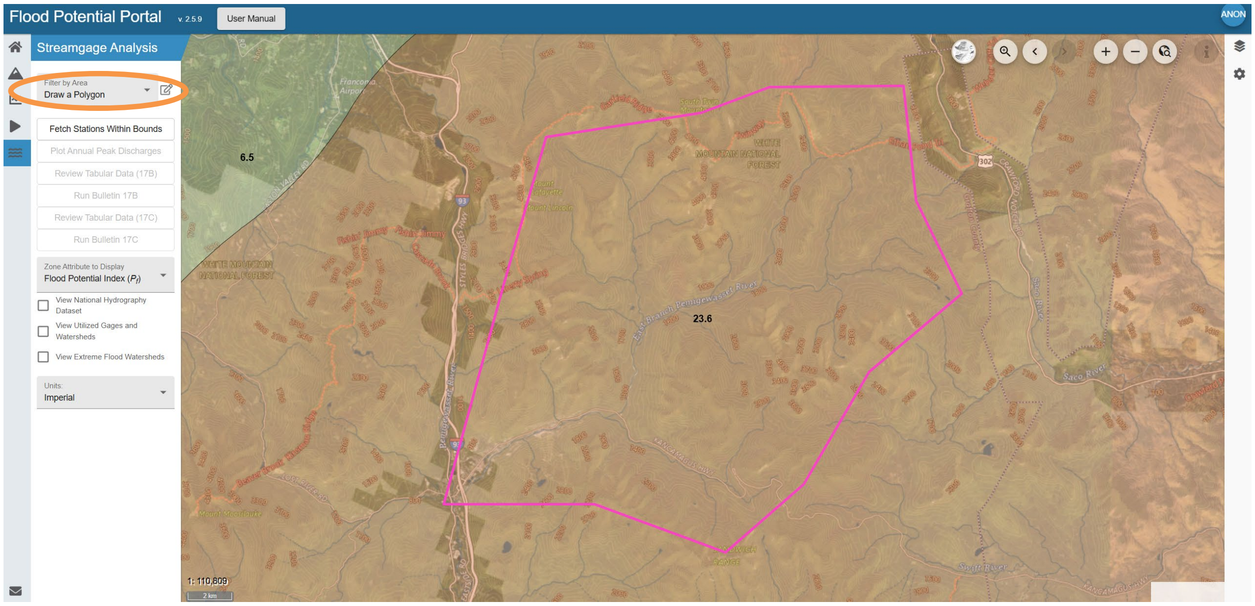


Figure 25: Polygon drawn to define an area of interest in the Streamgage Analysis module, for the E.B. Pemigewasset River, NH, in zone 106. The orange circle indicates the tool for drawing a geometric shape to define this area. A pull down is provided that allows users to adjust the zone attribute to display within the map, with the flood potential index selected.

After this geometric shape is created, the user presses the "Fetch Stations Within Bounds" button to activate a search for all streamgages with relevant data within this area. Streamgages are shown on the resulting map, and a table is provided with the gage locations (Figure 26). Attributes provided in the table include the station ID, station name, the source database and organization, and the number of available annual peak discharge events. Streamgages with any annual peak discharge records are provided, though a flood-frequency analysis requires at least 10 values. A zoom to link is also provided, to automatically zoom in to a streamgage of interest.

The user clicks on the map to select a streamgage for analysis (shifting the point from gold to green), or selects a row in the table. Only one gage can be selected at a time.

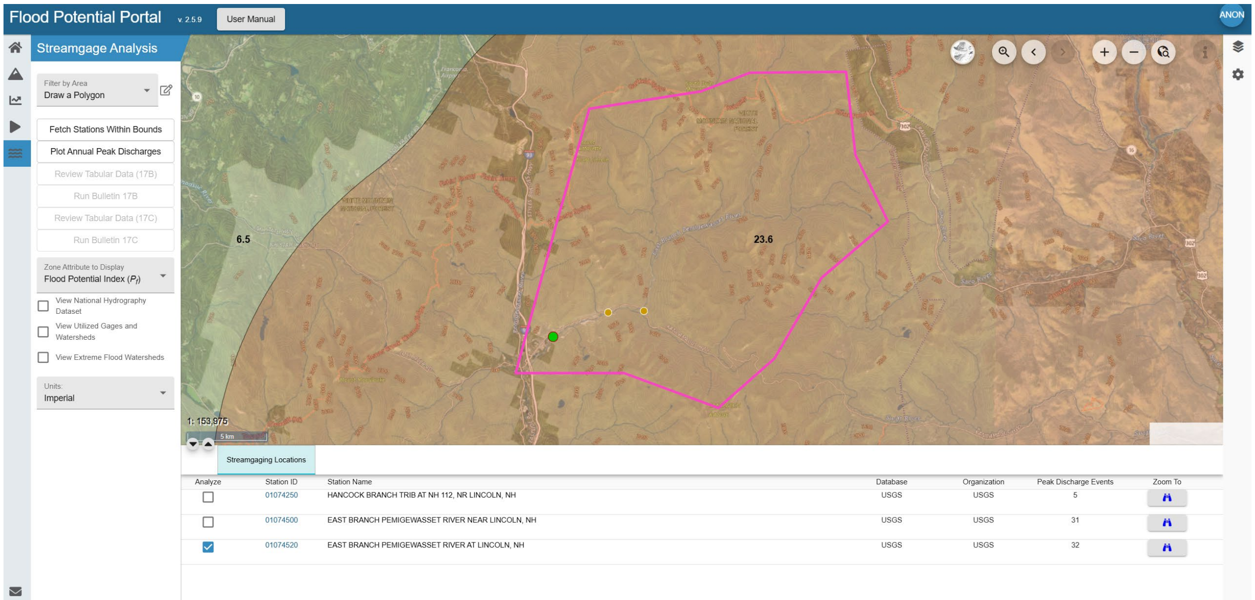


Figure 26: Available and selected streamgage, for the E.B. Pemigewasset River, NH. Streamgage 01074520 (EAST BRANCH PEMIGEWASSET RIVER AT LINCOLN, NH) is selected.

Next, the user clicks the “Plot Annual Peak Discharges” to inspect the flood variability and period of record (Figure 27). Close inspection of these data should occur, to inspect for higher and low flood modes, trends, etc. Use on-hover to inspect each point, to see details on each flood. By dragging a window within the plot, the user can zoom to a portion of the graphic to inspect a subset of the data. This graphic can be exported using the tool in the upper-right portion of the plot (green circle).

If additional data are available beyond what is provided through the USGS, annual peak discharges can be added to the record for inclusion in the flood-frequency analyses. To add data, click the pencil-write button on the top-left portion of the plot. This opens up an Add Peak Discharge Data entry box for adding user-provided data.

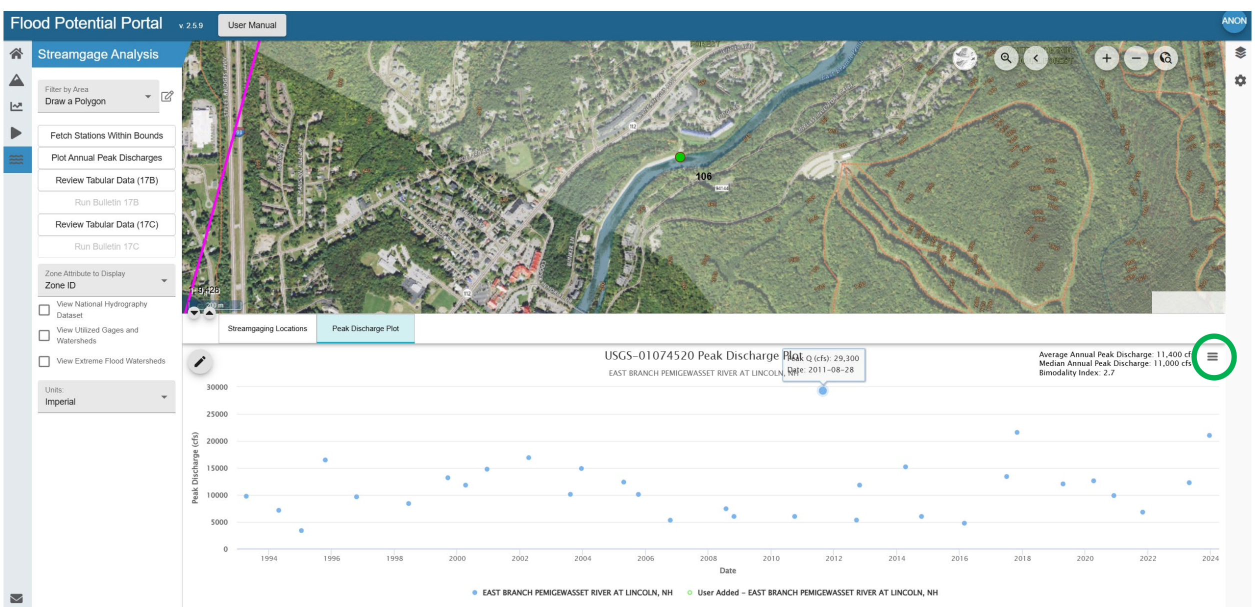


Figure 27: Peak discharge plot for the E.B. Pemigewasset River, NH streamgage (01074520). On-hover information is shown for the largest measured discharge: 29,300 cfs on 8/28/2011 (Hurricane Irene).

Bulletin 17B

To perform a Bulletin 17B computation, click “Review Tabular Data (17B)” to inspect each of the annual peak discharge values, dates, and the presence of high and low outliers (Figure 28). The user can uncheck any datapoint to exclude from the flood-frequency analysis, to address (for example) a detected outlier. (High outliers should be typically retained within an analysis, since these points can be most valuable for understanding the flood hazard of a site.) The generalized skew coefficient (and variance) is also set at the top of this table, to perform a weighted generalized skew flood-frequency analysis, in addition to the station skew analysis. The user can manually enter this information, or rely on state-focused resources or the national map (Bulletin 17B: Plate 1) by pressing the button for one of these options to populate the values. Use of the State Map is generally preferred.

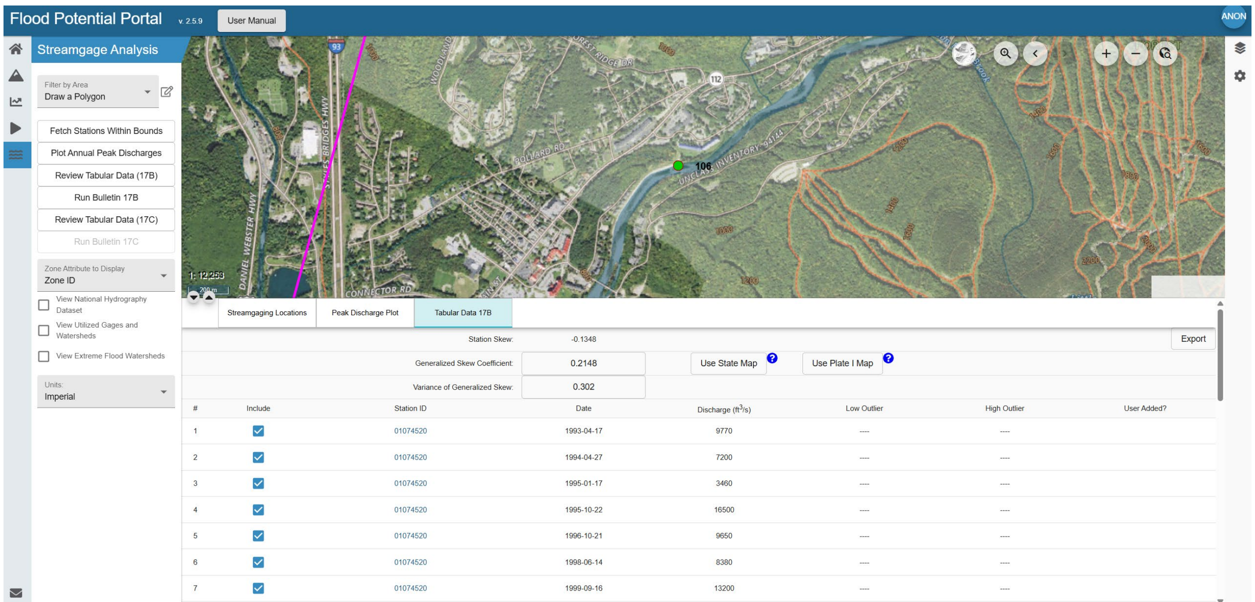
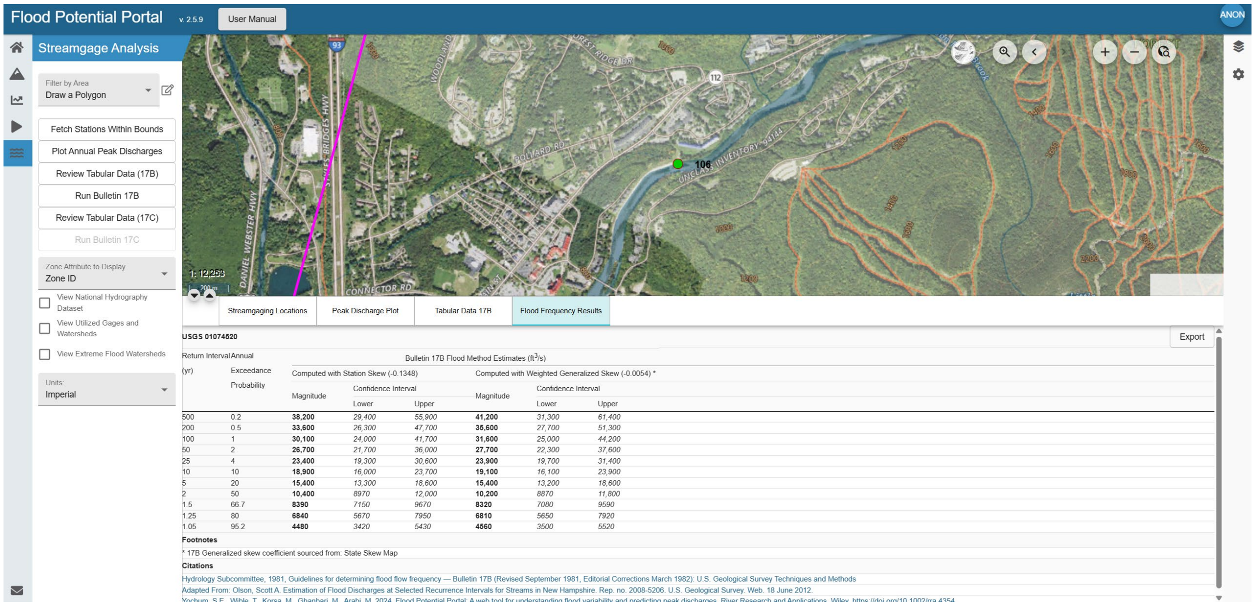


Figure 28: Tabular 17B data of annual peak discharges for the E.B. Pemigewasset River, NH streamgage (01074520), with options to exclude data for being a high or low outlier, and entering generalized skew and variance values.

After reviewing the tabular data and entering/reviewing the other parameters, press “Run Bulletin 17B” to perform the streamgage flood-frequency analysis (Figure 29). Analysis results using the station skew are presented, followed by results using a weighted generalized skew. Changing the units (in the left panel) will convert results between the SI (cms) and Imperial (cfs) unit systems.



Return Interval (yr)	Annual Exceedance Probability	Bulletin 17B Flood Method Estimates (ft^3/s): Computed with Station Skew (-0.1348)			Computed with Weighted Generalized Skew (-0.0054) *		
		Magnitude	Confidence Interval Lower	Confidence Interval Upper	Magnitude	Confidence Interval Lower	Confidence Interval Upper
500	0.2	**38,200**	*29,400*	*55,900*	**41,200**	*31,300*	*61,400*
200	0.5	**33,600**	*26,300*	*47,700*	**35,600**	*27,700*	*51,300*
100	1	**30,100**	*24,000*	*41,700*	**31,600**	*25,000*	*44,200*
50	2	**26,700**	*21,700*	*36,000*	**27,700**	*22,300*	*37,600*
25	4	**23,400**	*19,300*	*30,600*	**23,900**	*19,700*	*31,400*
10	10	**18,900**	*16,000*	*23,700*	**19,100**	*16,100*	*23,900*
5	20	**15,400**	*13,300*	*18,600*	**15,400**	*13,200*	*18,600*
2	50	**10,400**	*8970*	*12,000*	**10,200**	*8870*	*11,800*
1.5	66.7	**8390**	*7150*	*9670*	**8320**	*7080*	*9590*
1.25	80	**6840**	*5670*	*7950*	**6810**	*5650*	*7920*
1.05	95.2	**4480**	*3420*	*5430*	**4560**	*3500*	*5520*

Figure 29: Streamgage flood-frequency analysis results using the 17B procedure, for the E.B. Pemigewasset River, NH (01074520), with confidence intervals.

Bulletin 17C

The implementation of the Bulletin 17C procedure, as detailed in England et al. (2018), utilizes the expected moments algorithm. The coding used in the Flood Potential Portal (PeakfqSA, v. 0.998) is the same as used in other available software for utilizing the 17C procedure, from the USGS (PeakFQ) and the Army Corps of Engineers (HEC-SSP). Input is similar to using the 17B methodology, with the addition of flow intervals and perception thresholds. Click "Review Tabular Data (17C)" to inspect each of the annual peak discharge values, dates, and the presence of high and low outliers, as well as to set flow intervals and perception thresholds (Figure 30). A perception threshold plot is provided at the top of the screen, followed by perception thresholds to be used in the expected moments algorithm analysis. The user can uncheck any data point to exclude it from the flood-frequency analysis. The generalized skew coefficient (and variance) is set immediately above the data table. Like in a Bulletin 17B analysis, the user can manually enter this information or rely on state-focused resources or the national map (Bulletin 17B: Plate 1) by pressing the button for one of these options to populate the values.

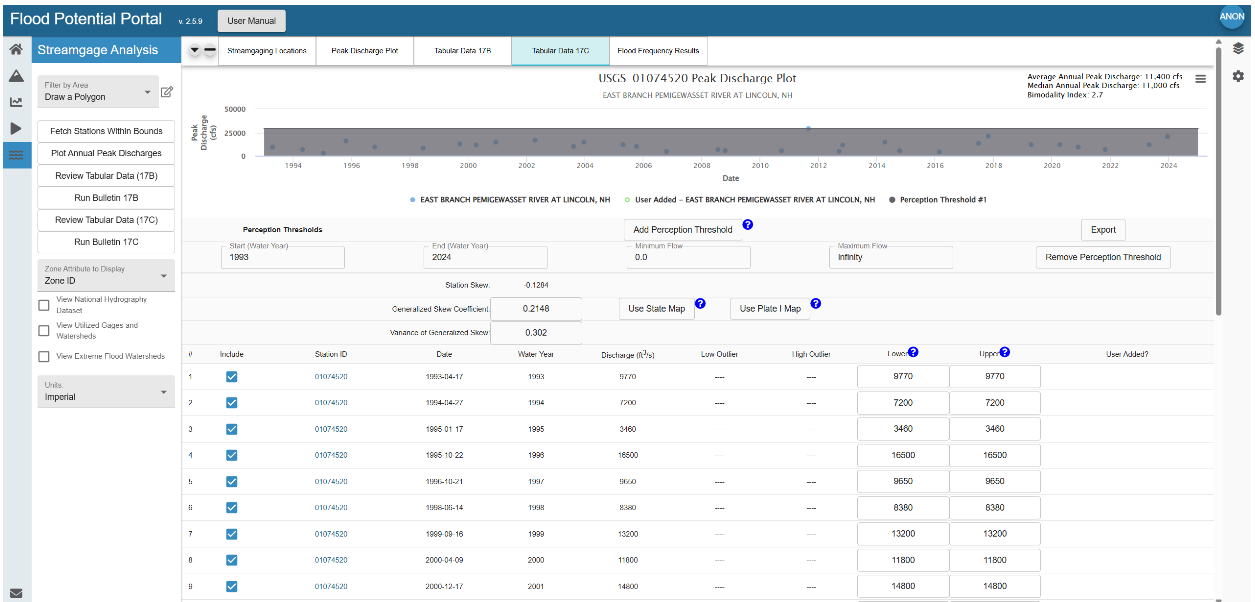


Figure 30: Tabular 17C data of annual peak discharges for the E.B. Pemigewasset River, NH streamgage (01074520), with options to exclude data, enter generalized skew and variance values, as well as change interval values and modify perception thresholds from defaults. The top of this tab is a graphical representation of perception thresholds to be utilized in the expected moments algorithm analysis.

Guidance for selecting flow intervals is provided in England et al. (2018). Key information is provided in the quote below, which is also available by pressing the query button next to the Upper and Lower interval headers (Figure 30). Default interval values are provided by the FPP that are equivalent to the provided annual peak discharges.

As quoted from England et al. (2018):

> For each year Y, the magnitude of Q_Y is characterized as a flow interval ($Q_{Y,lower}$, $Q_{Y,upper}$). A lower estimate $Q_{Y,lower}$ and upper estimate $Q_{Y,upper}$ (an interval) are made based on observations, written records, or physical evidence. For the majority of floods, such as those from a gaging station, the discharge is nearly "exactly" known (for all practical purposes), and $Q_{Y,lower} = Q_{Y,upper} = Q_Y$. Floods that are described by intervals or ranges currently address the following two situations: (1) a flood that is known to exceed some level, with no upper estimate (binomial-censored data); and (2) floods that are known to fall within a large range (interval data). In the binomial case, one only

> knows the lower estimate $Q_{Y,lower}$; the upper estimate $Q_{Y,upper}$ ~= +∞. Flow intervals are used to describe, in some cases, the largest flood magnitudes that are estimated from historical and paleoflood records, and sometimes indirect measurements or field estimates at a gage, which have large uncertainty (> 25 percent). Flow intervals ($Q_{Y,lower}$, $Q_{Y,upper}$) are not used to provide ranges on gaged flows and reflect measurement uncertainties that are within 5–25 percent…For unobserved historical floods whose magnitudes are only known to be less than some perception threshold (T_h), the lower estimate $Q_{Y,lower}$ = 0, and the upper estimate $Q_{Y,upper}$ corresponds to the perception threshold for that year, such as $Q_{Y,lower}$ or $Q_{Y,upper}$. For crest-stage gages, flow intervals are determined with consideration of equipment recording limits of stage. There is usually a base (minimum) discharge Q_b established; this may vary each year.

Perception thresholds also need to be defined for a 17C analysis (Figure 30). Results can be highly sensitive to the appropriate selection of these thresholds. Defaults are automatically populated for the entire record and for data gap years. Specifics on this input is provided in the quote below, which is also available by pressing the query button next to the Add Perception Threshold button.

As quoted from England et al. (2018):

> Perception thresholds ($T_{Y,lower}$, $T_{Y,upper}$) are used to describe the knowledge in each year *Y* within the flood record, for which the value of Q_Y would have been observed or recorded. The lower bound ($T_{Y,lower}$) represents the smallest peak flow that would result in a recorded flow; the upper bound ($T_{Y,upper}$) represents the largest peak flow that could be observed or recorded. The interval ($T_{Y,lower}$, $T_{Y,upper}$) defines the range of "perceptible values"— the range of potentially measurable flood discharges. These perception thresholds reflect the range of flows whose magnitude would have been recorded had they occurred, and are a function of the type of data collected at or near a gaging station and the physical characteristics of the river. In other words, the perception thresholds represent the "observable range" of floods. It is important to note that the perception thresholds T_Y do not depend on the actual peak discharges Q_Y that have occurred.
>
> Lower and upper perception thresholds T_Y need to be estimated for each and every year of the record. The lower bound $T_{Y,lower}$ represents the smallest annual peak flow that would result in a permanent record. For systematic (gaging) records, this is typically represented by the "gage base discharge," which is typically 0 (zero). At crest-stage gages, Q_b > 0, and may vary. For historical floods, $T_{Y,lower}$ is typically estimated to be equal to a historical flood discharge threshold T_h. For most sites with a systematic, continuous gaging record, $T_{Y,upper}$ is assumed to be infinite; larger floods typically get recorded. At crest-stage gages and for historical and paleoflood periods, $T_{Y,upper}$ needs to be estimated based on the CSG recording range, historical information (such as markers, bridges or buildings), or from geologic or botanical evidence. For periods where the gage has been discontinued (broken record) or ceased operation, the observation thresholds are both set to infinity if there is no other information such as a gage base or historical information. By setting $T_{Y,lower} = T_{Y,upper} = \infty$, this means that there is no information about that particular year. If there is historical information that is used for record extension of the largest floods during broken record periods, $T_{Y,lower}$ can be set to a historical flood discharge threshold T_h. In some situations, flood datasets need to be represented by multiple perception thresholds. This means more than one perception threshold is required to describe the data at hand.

After this information has been entered and checked, press "Run Bulletin 17C" to perform this streamgage flood-frequency analysis. Results from the Bulletin 17C analysis are presented alongside the results of the Bulletin 17B analysis (Figure 31).

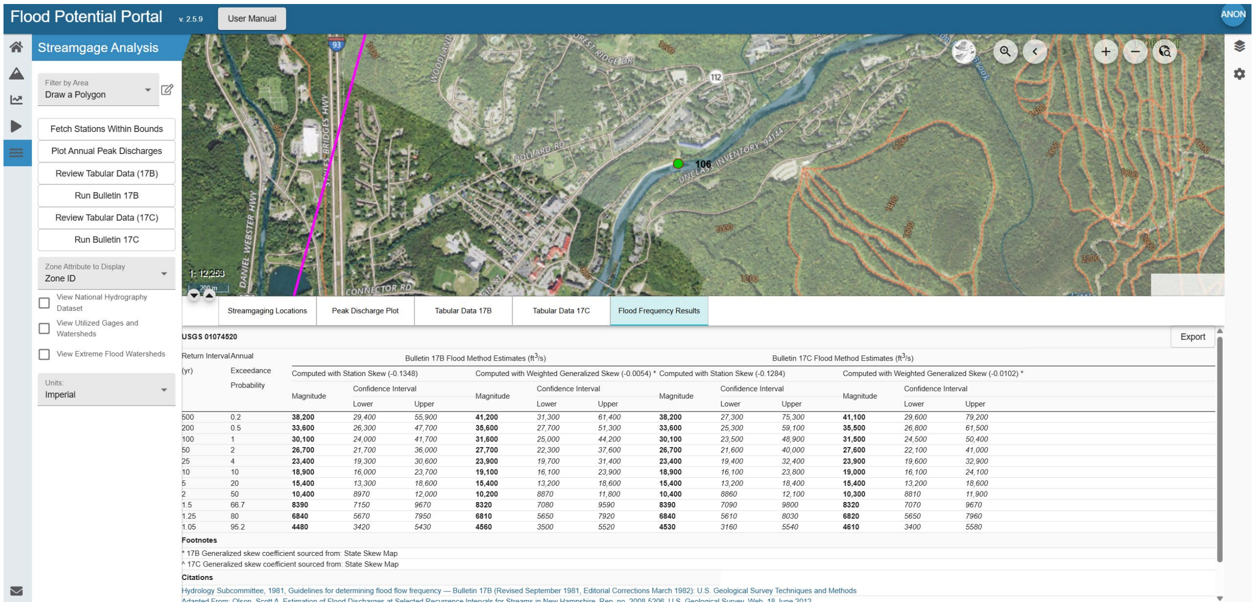


Figure 31: Streamgage flood-frequency analysis results using both the 17B and 17C procedures, for the E.B. Pemigewasset River, NH (01074520), with confidence intervals.

Results Summary

The export button in the top-right portion of the results panel will allow the user to export the results in Excel, pdf, or Word formats (Excel is recommended). The annual peak flow values are provided with the flood-frequency analysis results (Figure 32).

Flood Potential Portal Streamgage Analysis: Flood Frequency Results

Date Generated: 11/04/2025
Version: 2.5.9

USGS 01074520

Return Interval (yr)	Annual Exceedance Probability	Bulletin 17B Flood Method Estimates (cfs)					
		Computed with Station Skew (-0.1348)			Computed with Weighted Generalized Skew (-0.0054) *		
		Magnitude	Confidence Interval		Magnitude	Confidence Interval	
			Lower	Upper		Lower	Upper
500	0.2	**38,200**	29,400	55,900	**41,200**	31,300	61,400
200	0.5	**33,600**	26,300	47,700	**35,600**	27,700	51,300
100	1	**30,100**	24,000	41,700	**31,600**	25,000	44,200
50	2	**26,700**	21,700	36,000	**27,700**	22,300	37,600
25	4	**23,400**	19,300	30,600	**23,900**	19,700	31,400
10	10	**18,900**	16,000	23,700	**19,100**	16,100	23,900
5	20	**15,400**	13,300	18,600	**15,400**	13,200	18,600
2	50	**10,400**	8,970	12,000	**10,200**	8,870	11,800
1.5	66.7	**8,390**	7,150	9,670	**8,320**	7,080	9,590
1.25	80	**6,840**	5,670	7,950	**6,810**	5,650	7,920
1.05	95.2	**4,480**	3,420	5,430	**4,560**	3,500	5,520

Return Interval (yr)	Annual Exceedance Probability	Bulletin 17C Flood Method Estimates (cfs)					
		Computed with Station Skew (-0.1284)			Computed with Weighted Generalized Skew (-0.0102) ^		
		Magnitude	Confidence Interval		Magnitude	Confidence Interval	
			Lower	Upper		Lower	Upper
500	0.2	**38,200**	27,300	75,300	**41,100**	29,600	79,200
200	0.5	**33,600**	25,300	59,100	**35,500**	26,800	61,500
100	1	**30,100**	23,500	48,900	**31,500**	24,500	50,400
50	2	**26,700**	21,600	40,000	**27,600**	22,100	41,000
25	4	**23,400**	19,400	32,400	**23,900**	19,600	32,900
10	10	**18,900**	16,100	23,800	**19,000**	16,100	24,100
5	20	**15,400**	13,200	18,400	**15,400**	13,200	18,600
2	50	**10,400**	8,860	12,100	**10,300**	8,810	11,900
1.5	66.7	**8,390**	7,090	9,800	**8,320**	7,070	9,670
1.25	80	**6,840**	5,610	8,030	**6,820**	5,650	7,960
1.05	95.2	**4,530**	3,160	5,540	**4,610**	3,400	5,580

Footnote

* Generalized skew coefficient sourced from: State Skew Map
^ Generalized skew coefficient sourced from: State Skew Map

Citations

Adapted From: Olson, Scott A. Estimation of Flood Discharges at Selected Recurrence Intervals for Streams in New Hampshire. Rep. no. 2008-5206. U.S. Geological Survey. Web. 18 June 2012.

England, J.F., Jr., Cohn, T.A., Faber, B.A., Stedinger, J.R., Thomas, W.O., Jr., Veilleux, A.G., Kiang, J.E., and Mason, R.R., Jr., 2019, Guidelines for determining flood flow frequency — Bulletin 17C (ver. 1.1, May 2019): U.S. Geological Survey Techniques and Methods, book 4, chap. B5, 148 p., https://doi.org/10.3133/tm4B5.

Hydrology Subcommittee, 1981, Guidelines for determining flood flow frequency — Bulletin 17B (Revised September 1981, Editorial Corrections March 1982): U.S. Geological Survey Techniques and Methods

Yochum, S.E., Wible, T., Korsa, M., Ghanbari, M., Arabi, M. 2024, Flood Potential Portal: A web tool for understanding flood variability and predicting peak discharges. River Research and Applications. Wiley. https://doi.org/10.1002/rra.4354

Figure 32: Flood Potential Portal Streamgage Analysis module results using the Bulletin 17B and 17C procedures exported in Excel format, for the E.B. Pemigewasset River, NH streamgage (01074520).

The Watershed Analysis module is then implemented to compare these streamgage flood-frequency results with flood potential, index, and regional regression results (Figure 33), for the selection of the most appropriate design flood discharge and flood-frequency magnitudes.

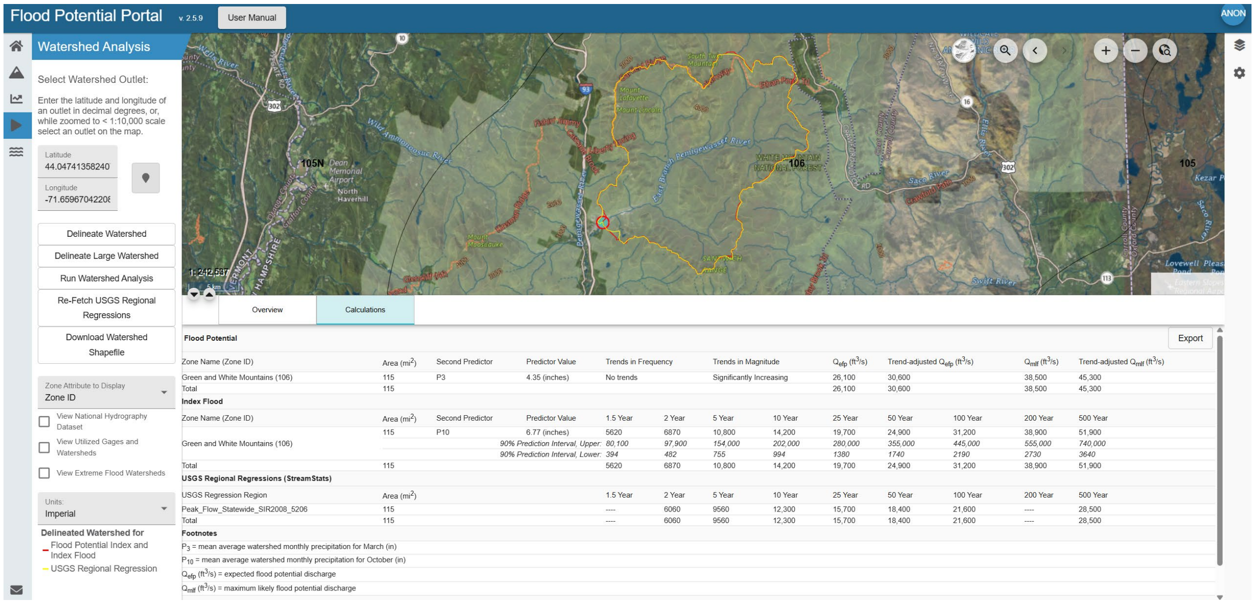


Figure 33: Watershed analysis results using the 17B procedure for the E.B. Pemigewasset River, NH streamgage (01074520).

In this example, the watershed analysis module suggests a Q = 26,100 cfs (median prediction: Q_{efp}). The Q_{100} from the streamgage analysis Bulletin 17C weighted generalized skew results is conservative (31,500 cfs) and is essentially identical to the index Q_{100} (**31,200 cfs**) – this result is likely most appropriate as the trend unadjusted design flood discharge. A practitioner can consider an adjustment of this value to account of observed increasing trends in large floods in zone 106 (largest 5% annual peak discharges: +17.5%; largest quarter annual peak discharges: +13.2%), with use of the +17.5% resulting in an adjusted design flood discharge $Q_{design} = Q_{100}[1+ (\% \text{ change})/100]$ = 31,500 cfs * 1.175 = **37,000 cfs**.

Analysis Examples

Examples are provided to illustrate the use of the Watershed Analysis and Streamgage Analysis modules of the Flood Potential Portal, for selection of design flood and base flood discharges for infrastructure design and floodplain management, as well as for stream and riparian ecological management. Good practice for use of the FPP in the selection of a design flood discharge is to initially explore flooding characteristics within the Mapping tool, before making an ensemble discharge prediction. This is detailed in step 1 of the Watershed Analysis section. Step 8 provides information on decision making for selecting peak discharges, with this section providing examples to illustrate decision making.

Eleven Point River, Missouri

The Eleven Point River in the Ozarks of Missouri (Figure 17 through Figure 23), shown in Figure 34, has a watershed entirely within zone 59S. Zone 59S flooding characteristics are initially reviewed by the practitioner, noting key findings:

- z59S encompasses the southern Ozarks, with the northern Ozarks being within z59N
- z59S has a high flood potential (P_f = 43.4), at the 94th percentile compared to zones within the United States. Only 6% of zones have higher flood potential. The northern Ozarks have lower flood potential (P_f = 30.9), with floods in z59S being, on average, 43.4/30.9 = 1.40 times larger than in z59N.
- This zone experiences relatively high flashiness, with a Richard-Baker flashiness of R-B = 0.46 (67th percentile).
- Bimodality across the zone, on average, is a bit above normal (B_i = 6.9, 58th percentile).
- Increasing observed trends exists in this zone for all quarters of annual peak discharges:
  - Q4 (> 4-year return interval): significant increasing trend, +5.8% (Figure 35)
  - Q3 (4- to 2-year return interval): significant increasing trend, +7.7%
  - Q2 (~bankfull, 2- to 1.33-year return interval): significant increasing trend, +7.1%
  - Q1 (< 1.33-year return interval): significant increasing trend, +8.9%
- Significant increasing trend in event flood-frequency (event trends account for multiple flood peaks occurring during each water year, while annual trends account for only the annual peak)

Figure 34: Eleven Point River (2018-5), on the Mark Twain National Forest, Missouri.

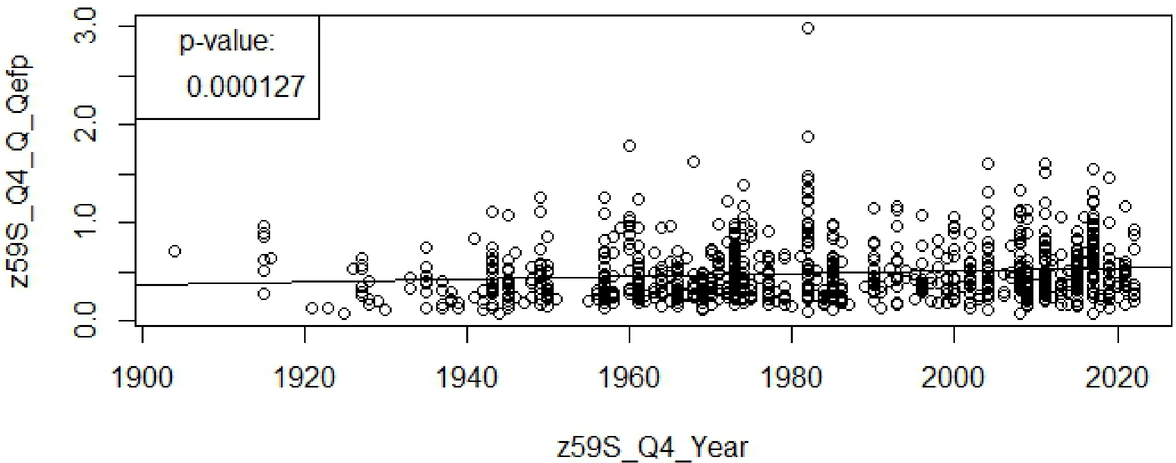


Figure 35: Significantly increasing trend for zone 59S in the largest quarter of annual peak discharges (Q4; >4-year return interval).

The analysis results (Figure 23) for this 784 mi^2 watershed, for the unadjusted values (for trends), are 84,900 cfs (Q_{100}: USGS regional regression), 152,000 cfs (Q_{100}: Index), and 153,000 cfs (Q_{efp}). A streamgage is located at this site (07071500), with a Q_{100} = 73,600 cfs. (This result is the Q_{100} value from a Bulletin 17B analysis with a weighted generalized skew. The Bulletin 17C analysis provides a lower value: 68,900 cfs.) The largest flood on record at this site is 122,000 cfs, on 4/30/2017, with a downstream streamgage having experienced an additional high mode flood in 1982. The regional regression equations and this site's streamgage frequency analysis appear to be underestimating flood magnitudes at this site, and are inadvisable for use in quantifying the design flood discharge (since they are not sufficiently conservative). Flood data across the Ozarks show bimodal characteristics (B_i = 6.9 for zone 59S), with most streamgages having datasets with one or two high mode events mixed in with smaller, more typical flood scales, due to mixed populations of flood-producing mechanisms. This streamgage has a higher bimodality (B_i = 13.5) than the average for zone 59S. Such data bimodalities can be poorly addressed with both at-a-station log-Pearson streamgage analyses and within regional regression analyses (see Example: Eleven Point River and Appendix G).

Additionally, trends in the largest quarter (Q4) of annual peak discharges indicate a 5.8% increase across zone 59S. Due to a lack of other known non-stationarity mechanisms that may be inducing this systematic change across the zone, it is reasonable to assume that this increase is due to climate change and could be accounted for in the selection of the design flood discharge. Given these results, it is most reasonable to utilize the lower of the two higher predictions, specifically $Q_{100\ index}$. This yields a result of:

$$Q_{design} = Q_{100\ index} = \underline{152{,}000\ cfs}$$

Alternatively, the designer could apply a manual application of the observed 5.8% trend adjustment, with the design flood discharge then being:

$$Q_{design} = Q_{100\ index}[1+ (\%\ change)/100] = 152{,}000*1.058 = \underline{161{,}000\ cfs}.$$

Both of these possible design flood discharge may be considered unusually high, but these values likely best represent the high mode floods that have occurred in most streamgaged watersheds across this flood-prone interior highlands zone.

Tygart Valley River, West Virginia

The Tygart Valley River, at Dailey, West Virginia (Figure 36) has a streamgage at the US-219 crossing (USGS 03050000), from a 187 mi^2 watershed. This watershed is in zone 95 (Allegheny Mountains).

Figure 36: Tygart Valley River at Dailey, West Virginia.

Zone 95 Summary:

- This Allegheny Mountains zone is composed of the western edge of the Appalachians in West Virginia, Western Maryland, and Western Pennsylvania.
- This zone has relatively high flood potential (P_f = 19.6), at the 71st percentile compared to zones across the contiguous United States. Twenty nine percent of zones have higher flood potential. Floods are smaller to the west, north, and east of this zone, while floods to the southeast in the Valley and Ridge (zone 72N, P_f = 34.8) are substantially larger (34.8/19.6 = 1.8 times larger, on average). Floods to the south (zone 71, P_f = 25.6), just south of the Tygart Valley River watershed boundary, are also substantially larger.
- This zone has low to moderate flashiness, as quantified using Beard F (0.55, 26th percentile) and Richards-Baker (0.38, 59th percentile).
- Bimodality is moderate (5.2, 42nd percentile), on average.
- Decreasing trends in flood magnitudes have been observed in this zone:
    - Q4 (>4-year return interval): significant decreasing trend, -7.6%
    - Q3 (2- to 4-year return interval): significant decreasing trend, 0%
    - Q2 (bankfull-scale floods; 1.33 to 2-year return interval): significant decreasing trend, -1.3%
    - Q1 (<bankfull-scale floods; <1.33-year return interval): significant decreasing trend, -4.0%
- No trends have been observed in flood-frequency and flashiness.

To select a design flood discharge and flood-frequency relationship at this location, a streamgage flood-frequency analysis is performed, followed by a watershed analysis. Streamgages within the Tygart Valley are initially searched for through a polygon created for the area, and “Fetch Stations Within Bounds” is clicked to show the available stations (Figure 37). The streamgage of interest is selected.

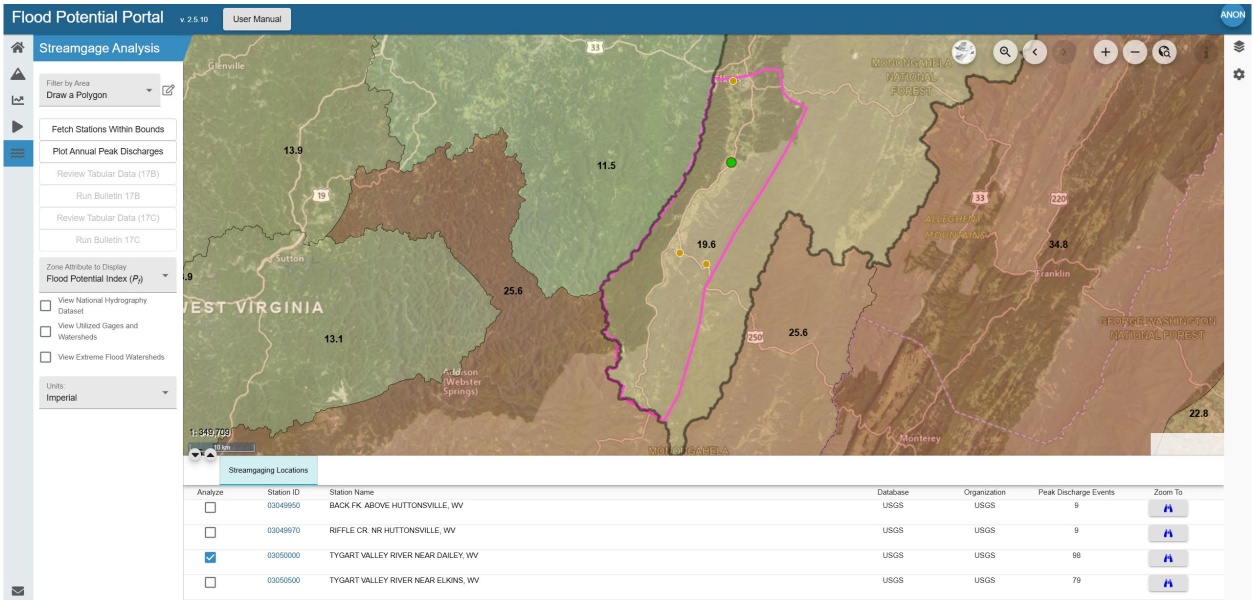


Figure 37: Finding and selecting the streamgage of interest (03050000) for the Tygart Valley River at Dailey, West Virginia.

Next, annual peak discharges are plotted for the streamgage. The user should inspect these records, noting the period of record, the maximum recorded discharge (22,000 cfs on 11/5/1985), the data gaps from 1977 to 1985, and 1987 and 1988, and the relatively similar-scale annual peak discharges (lesser bimodality). The lowest measured annual peak discharge (in 2023) of 2730 cfs may also be of interest.

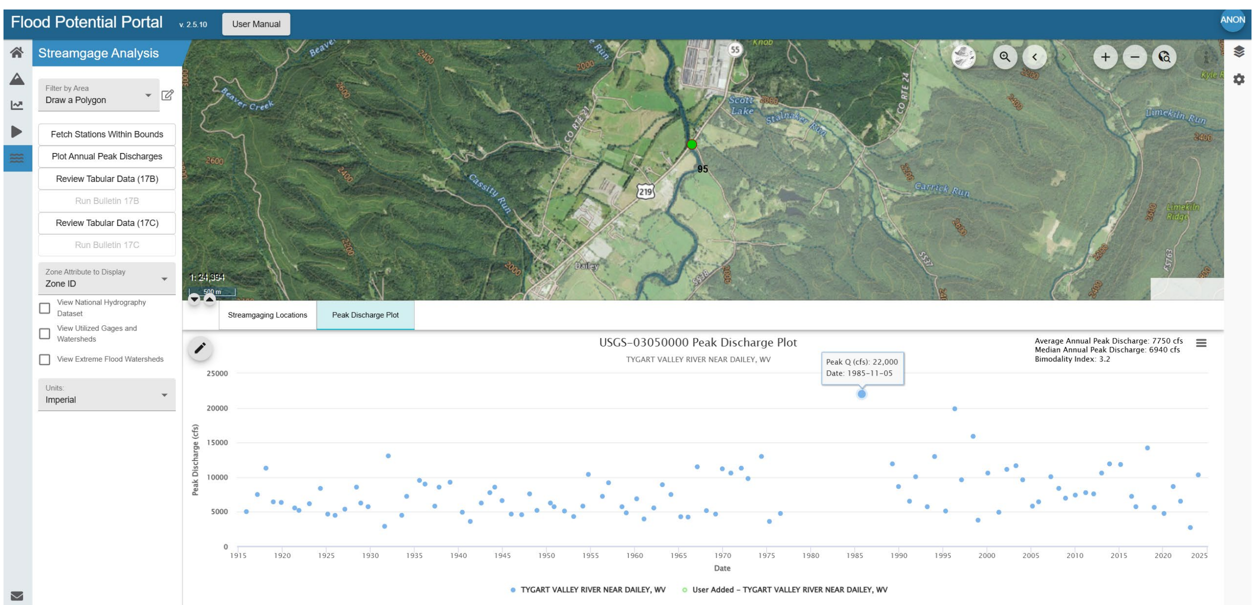


Figure 38: Annual peak discharge plot for the Tygart Valley River at Dailey, West Virginia. On-hover information for the flood of record on 11/5/1985 is shown.

Flood-frequency analysis using both the Bulletin 17B (IACWD, 1982) and Bulletin 17C (England et al., 2018) procedures are performed. To perform the 17B analysis, "Review Tabular Data (17B)" button is pressed and tabular data are reviewed (Figure 39). The peak discharges and dates are reviewed, and possible outliers are inspected to see if any have been detected.

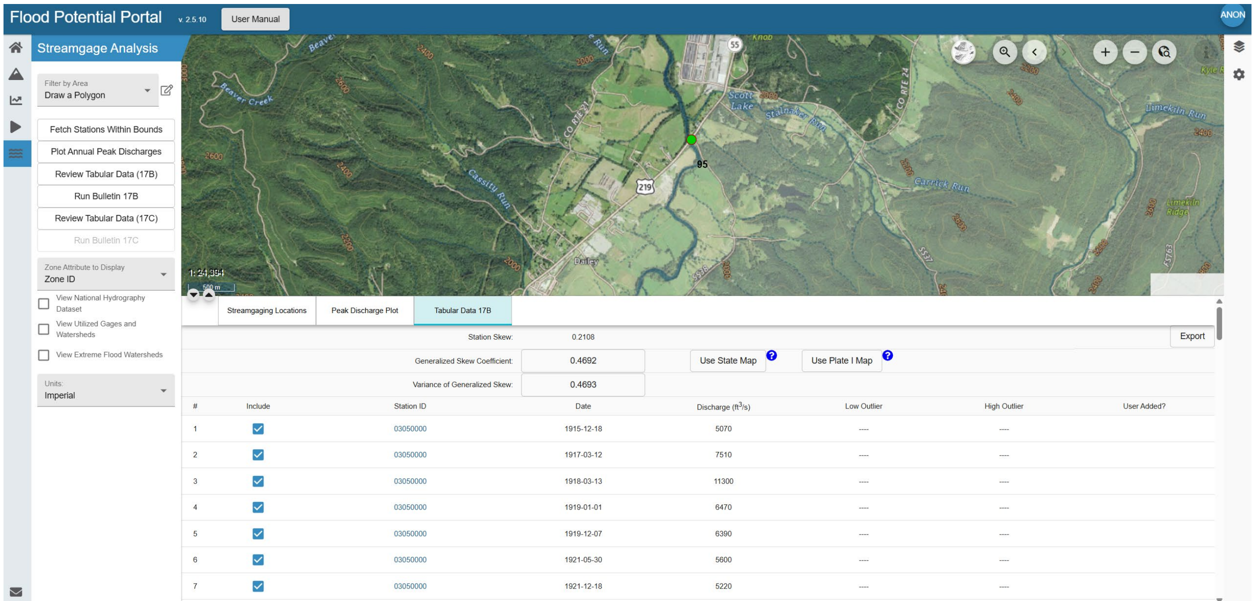


Figure 39: Tabular annual peak discharge data, high and low outlier detection, and generalized skew and variance input for the Tygart Valley River at Dailey, West Virginia.

The user can unselect any data year(s) they wish, though generally high outliers should be retained in an analysis. The generalized skew and variance should be populated, to compare results computed using the station skew and a weighted generalized skew. The user can do this manually, or have this populated from available state or national guidance. In this example, the state analysis is used (the State Map). Clicking the "?" balloon next to the Use State Map button will show the utilized state map (Figure 40), and the source reference (Atkins et al., 2008).

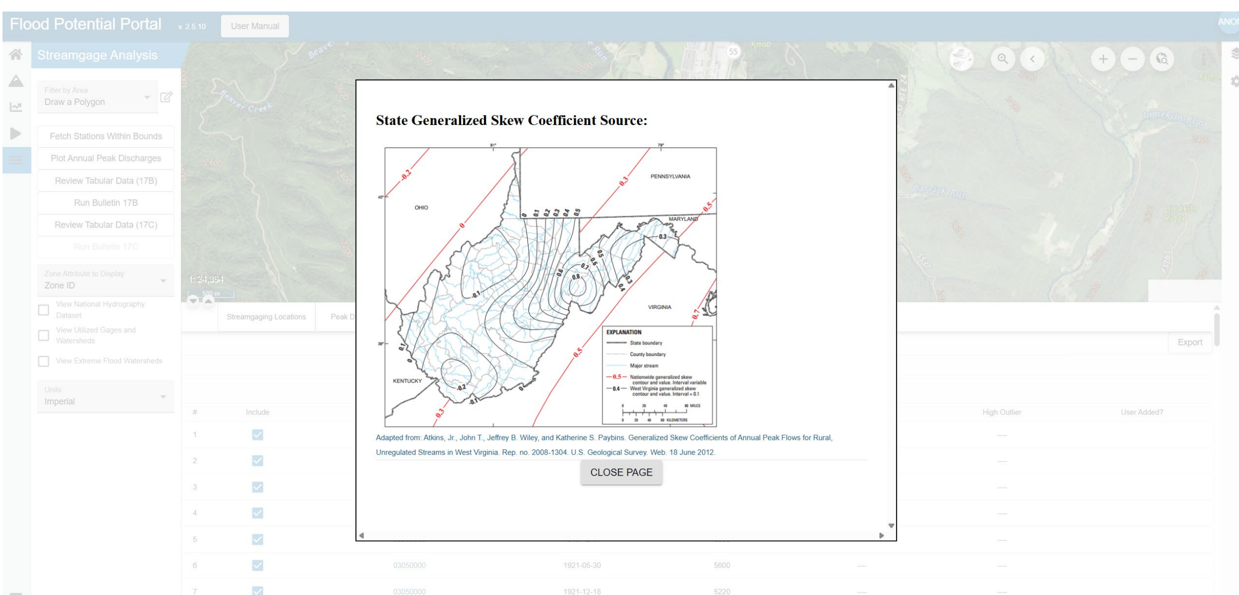


Figure 40: Skew map for West Virginia.

"Run Bulletin 17B" is pressed to perform the streamgage flood-frequency analysis (Figure 41). Key results include the Q_{100} from the station skew (19,500 cfs) and the Q_{100} weighted generalized skew (19,700 cfs), which are essentially identical at this site.

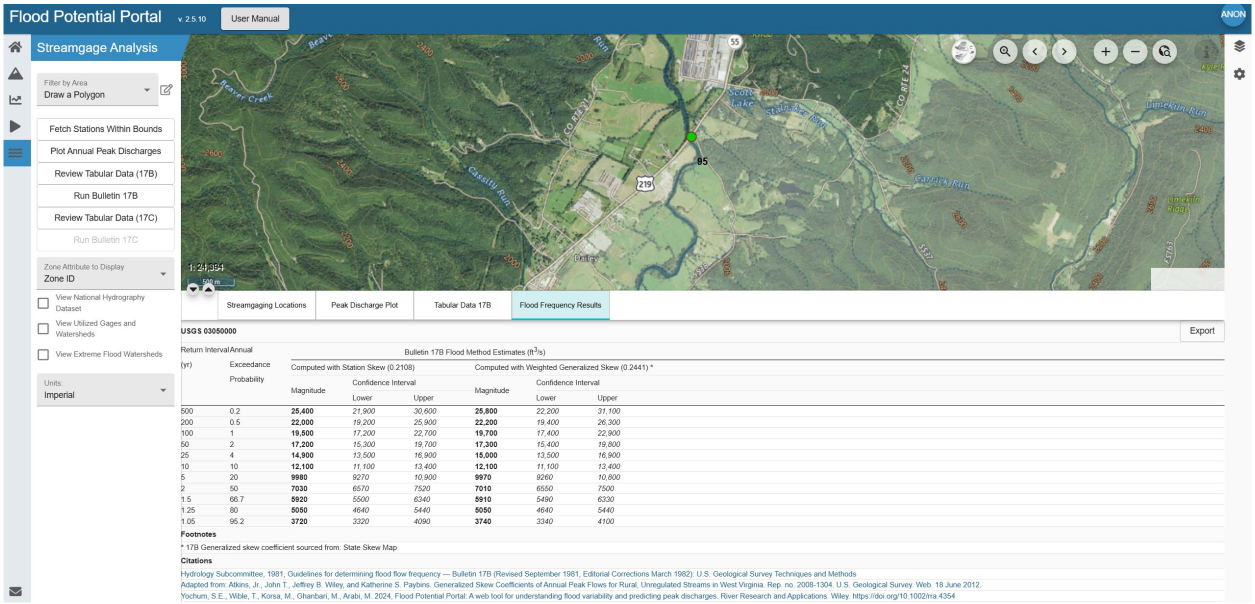


Figure 41: Streamgage food frequency analysis Bulletin 17B results for the Tygart Valley River at Dailey, West Virginia (03050000).

Next, a Bulletin 17C analysis is performed. Press the “Review Tabular Data (17C)” button. The resulting tab shows the tabular data, observed outliers, discharge intervals, perception thresholds, and a perception threshold annual peak discharge plot (Figure 42). The query buttons to the immediate right of the perception threshold button and intervals header explain this required input. Default perception thresholds are populated for the entire analysis period and the gap years – analyses can be very sensitive to these perception thresholds. Additionally, default intervals are also provided. These defaults can be adjusted by the user. The user must check the inputs for appropriateness per the Bulletin 17C guidance (England et al., 2018). The generalized skew coefficient (and variance) also need to be populated, to perform a weighted generalized skew analysis. After all needed parameters are chosen, the user presses the “Run Bulletin 17C” button to obtain these additional results (Figure 43).

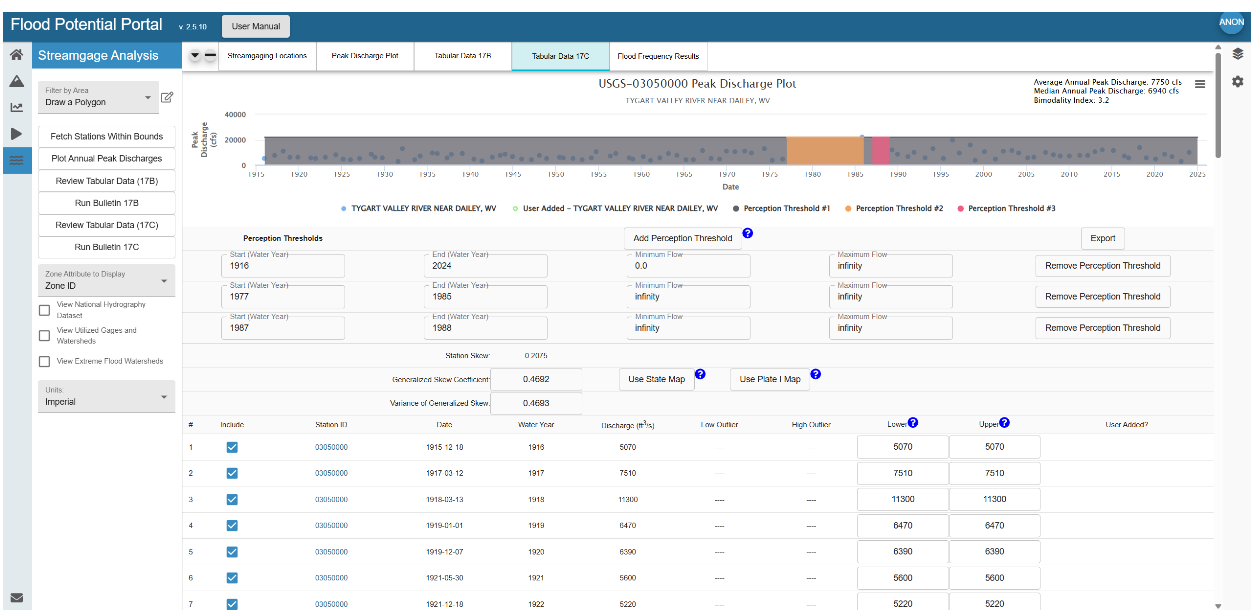
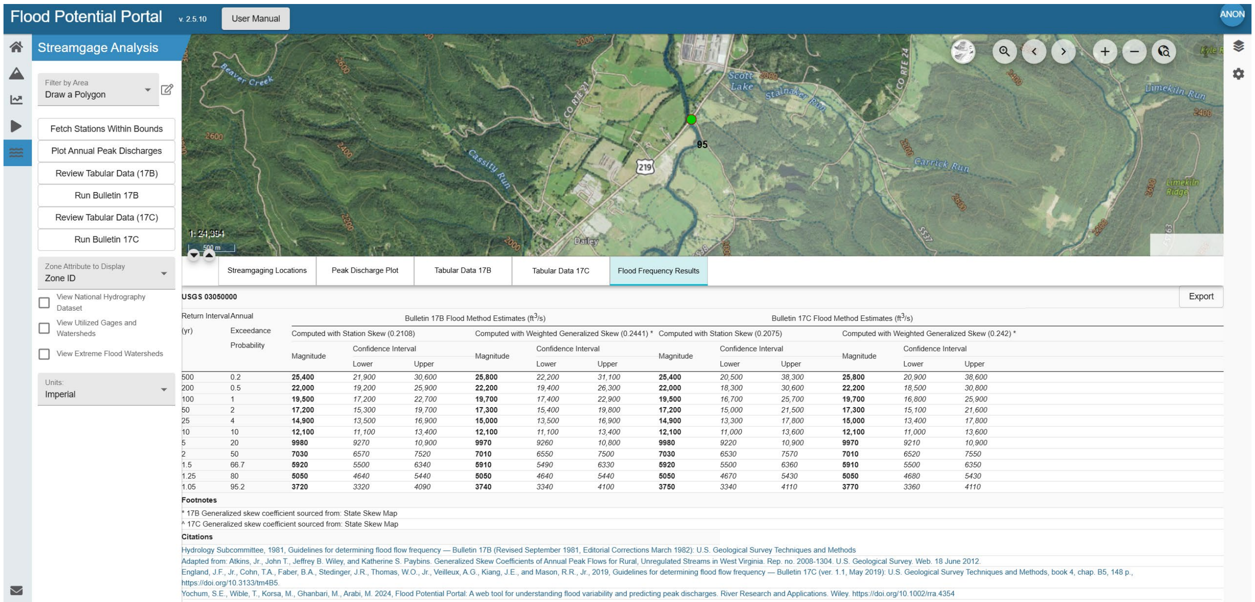


Figure 42: Bulletin 17C data and calculation parameters for the Tygart Valley River at Dailey, West Virginia streamgage.



Return Interval (yr)	Annual Exceedance Probability	Bulletin 17B Flood Method Estimates (ft³/s): Computed with Station Skew (0.2108) Magnitude	Lower	Upper	Computed with Weighted Generalized Skew (0.2441) * Magnitude	Lower	Upper	Bulletin 17C Flood Method Estimates (ft³/s): Computed with Station Skew (0.2075) Magnitude	Lower	Upper	Computed with Weighted Generalized Skew (0.242) * Magnitude	Lower	Upper
500	0.2	**25,400**	*21,900*	*30,600*	**25,800**	*22,200*	*31,100*	**25,400**	*20,500*	*38,300*	**25,800**	*20,900*	*38,600*
200	0.5	**22,000**	*19,200*	*25,900*	**22,200**	*19,400*	*26,300*	**22,000**	*18,300*	*30,600*	**22,200**	*18,500*	*30,800*
100	1	**19,500**	*17,200*	*22,700*	**19,700**	*17,400*	*22,900*	**19,500**	*16,700*	*25,700*	**19,700**	*16,800*	*25,900*
50	2	**17,200**	*15,300*	*19,700*	**17,300**	*15,400*	*19,800*	**17,200**	*15,000*	*21,500*	**17,300**	*15,100*	*21,600*
25	4	**14,900**	*13,500*	*16,900*	**15,000**	*13,500*	*16,900*	**14,900**	*13,300*	*17,800*	**15,000**	*13,400*	*17,800*
10	10	**12,100**	*11,100*	*13,400*	**12,100**	*11,100*	*13,400*	**12,100**	*11,000*	*13,600*	**12,100**	*11,000*	*13,600*
5	20	**9980**	*9270*	*10,900*	**9970**	*9260*	*10,800*	**9980**	*9220*	*10,900*	**9970**	*9210*	*10,900*
2	50	**7030**	*6570*	*7520*	**7010**	*6550*	*7500*	**7030**	*6530*	*7570*	**7010**	*6520*	*7550*
1.5	66.7	**5920**	*5500*	*6340*	**5910**	*5490*	*6330*	**5920**	*5500*	*6360*	**5910**	*5500*	*6350*
1.25	80	**5050**	*4640*	*5440*	**5050**	*4640*	*5440*	**5050**	*4670*	*5430*	**5050**	*4680*	*5430*
1.05	95.2	**3720**	*3320*	*4090*	**3740**	*3340*	*4100*	**3750**	*3340*	*4110*	**3770**	*3360*	*4110*

Footnotes
* 17B Generalized skew coefficient sourced from: State Skew Map
^ 17C Generalized skew coefficient sourced from: State Skew Map

Citations
Hydrology Subcommittee, 1981, Guidelines for determining flood flow frequency — Bulletin 17B (Revised September 1981, Editorial Corrections March 1982): U.S. Geological Survey Techniques and Methods
Adapted from: Atkins, Jr., John T., Jeffrey B. Wiley, and Katherine S. Paybins. Generalized Skew Coefficients of Annual Peak Flows for Rural, Unregulated Streams in West Virginia. Rep. no. 2008-1304. U.S. Geological Survey. Web. 18 June 2012.
England, J.F., Jr., Cohn, T.A., Faber, B.A., Stedinger, J.R., Thomas, W.O., Jr., Veilleux, A.G., Kiang, J.E., and Mason, R.R., Jr., 2019, Guidelines for determining flood flow frequency — Bulletin 17C (ver. 1.1, May 2019): U.S. Geological Survey Techniques and Methods, book 4, chap. B5, 148 p., https://doi.org/10.3133/tm4B5.
Yochum, S.E., Wible, T., Korsa, M., Ghanbari, M., Arabi, M. 2024, Flood Potential Portal: A web tool for understanding flood variability and predicting peak discharges. River Research and Applications. Wiley. https://doi.org/10.1002/rra.4354

Figure 43: Streamgage food frequency analysis Bulletins 17B and 17C results for the Tygart Valley River at Dailey, West Virginia (03050000).

These results should be exported to an Excel file for documentation (Figure 44). Screenshots similar to Figure 38 and Figure 43 can also be saved. The 17C analysis method yields identical results as the 17B analysis at this site for the 100-year (1% chance of annual occurrence) event, with Q_{100} = 19,500 cfs using the station skew and the Q_{100} = 19,700 cfs using the weighted generalized skew.

A watershed analysis should also be performed (Figure 45), to provide more insight for the selection of the most appropriate design flood discharge value and flood-frequency relationship; the streamgage analysis should not be solely depended upon. The results from both the watershed analysis and the streamgage analysis are shown (Figure 46), using the 17C weighted generalized skew results.

The results of four methods for design flood discharge prediction are:

- $Q_{100,\ gage}$ = 19,700 cfs
- $Q_{100,\ regional\ regression}$ = 19,600 cfs
- Q_{efp} = 25,400 cfs
- $Q_{100,\ index}$ = 27,200 cfs

From a flood potential perspective, the streamgage analysis (with 98 years of record) may be underpredicting the Q_{100} in a zone that experiences relatively large events. Indeed, the 19,700 cfs discharge is less than two annual peak discharge events (22,000 cfs in November, 1985 and 19,900 cfs in May, 1996). Considering this:

$$Q_{design} = Q_{efp} = 25{,}400 \text{ cfs}$$

Reducing this value to account for the observed decreasing trend in Q4 (-7.6%) would be insufficiently conservative. While current data indicate that this zone is not experiencing increased flood severity but instead decreasing flood magnitudes, it should not be assumed that these trends will continue.

Flood Potential Portal Streamgage Analysis: Flood Frequency Results

Date Generated: 11/05/2025
Version: 2.5.10

USGS 03050000

Return Interval (yr)	Annual Exceedance Probability	Bulletin 17B Flood Method Estimates (cfs)					
		Computed with Station Skew (0.2108)			Computed with Weighted Generalized Skew (0.2441) *		
		Magnitude	Confidence Interval Lower	Confidence Interval Upper	Magnitude	Confidence Interval Lower	Confidence Interval Upper
500	0.2	**25,400**	21,900	30,600	**25,800**	22,200	31,100
200	0.5	**22,000**	19,200	25,900	**22,200**	19,400	26,300
100	1	**19,500**	17,200	22,700	**19,700**	17,400	22,900
50	2	**17,200**	15,300	19,700	**17,300**	15,400	19,800
25	4	**14,900**	13,500	16,900	**15,000**	13,500	16,900
10	10	**12,100**	11,100	13,400	**12,100**	11,100	13,400
5	20	**9,980**	9,270	10,900	**9,970**	9,260	10,800
2	50	**7,030**	6,570	7,520	**7,010**	6,550	7,500
1.5	66.7	**5,920**	5,500	6,340	**5,910**	5,490	6,330
1.25	80	**5,050**	4,640	5,440	**5,050**	4,640	5,440
1.05	95.2	**3,720**	3,320	4,090	**3,740**	3,340	4,100

Return Interval (yr)	Annual Exceedance Probability	Bulletin 17C Flood Method Estimates (cfs)					
		Computed with Station Skew (0.2075)			Computed with Weighted Generalized Skew (0.242) ^		
		Magnitude	Confidence Interval Lower	Confidence Interval Upper	Magnitude	Confidence Interval Lower	Confidence Interval Upper
500	0.2	**25,400**	20,500	38,300	**25,800**	20,900	38,600
200	0.5	**22,000**	18,300	30,600	**22,200**	18,500	30,800
100	1	**19,500**	16,700	25,700	**19,700**	16,800	25,900
50	2	**17,200**	15,000	21,500	**17,300**	15,100	21,600
25	4	**14,900**	13,300	17,800	**15,000**	13,400	17,800
10	10	**12,100**	11,000	13,600	**12,100**	11,000	13,600
5	20	**9,980**	9,220	10,900	**9,970**	9,210	10,900
2	50	**7,030**	6,530	7,570	**7,010**	6,520	7,550
1.5	66.7	**5,920**	5,500	6,360	**5,910**	5,500	6,350
1.25	80	**5,050**	4,670	5,430	**5,050**	4,680	5,430
1.05	95.2	**3,750**	3,340	4,110	**3,770**	3,360	4,110

Footnote

* Generalized skew coefficient sourced from: State Skew Map
^ Generalized skew coefficient sourced from: State Skew Map

Citations

Adapted from: Atkins, Jr., John T., Jeffrey B. Wiley, and Katherine S. Paybins. Generalized Skew Coefficients of Annual Peak Flows for Rural, Unregulated Streams in West Virginia. Rep. no. 2008-1304. U.S. Geological Survey. Web. 18 June 2012.

England, J.F., Jr., Cohn, T.A., Faber, B.A., Stedinger, J.R., Thomas, W.O., Jr., Veilleux, A.G., Kiang, J.E., and Mason, R.R., Jr., 2019, Guidelines for determining flood flow frequency — Bulletin 17C (ver. 1.1, May 2019): U.S. Geological Survey Techniques and Methods, book 4, chap. B5, 148 p., https://doi.org/10.3133/tm4B5.

Hydrology Subcommittee, 1981, Guidelines for determining flood flow frequency — Bulletin 17B (Revised September 1981, Editorial Corrections March 1982): U.S. Geological Survey Techniques and Methods

Yochum, S.E., Wible, T., Korsa, M., Ghanbari, M., Arabi, M. 2024, Flood Potential Portal: A web tool for understanding flood variability and predicting peak discharges. River Research and Applications. Wiley. https://doi.org/10.1002/rra.4354

Figure 44: Excel export of streamgage flood-frequency results for the Tygart Valley River at Dailey, West Virginia (03050000).

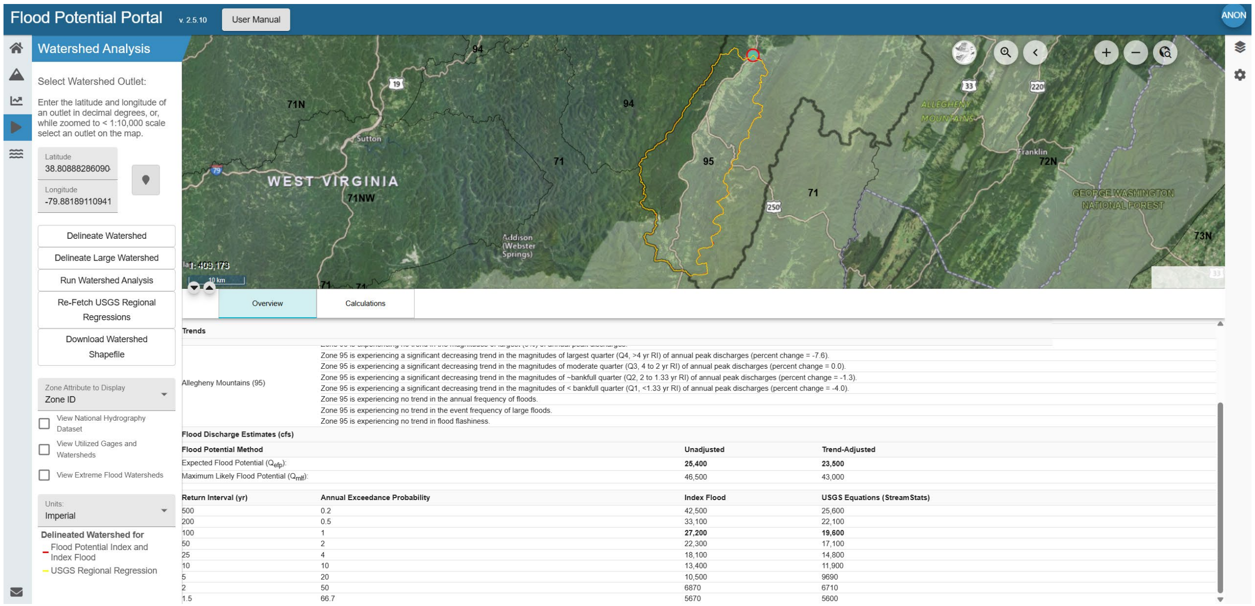


Figure 45: Watershed analysis results for the Tygart Valley River at Dailey, West Virginia.

Flood Potential Watershed Analysis: Results Overview

Date Generated: 11/05/2025   Latitude: 38.80888286
Version: 2.5.10   Longitude: -79.88189111

Indices -- Watershed Flooding Characteristics	Value	Percentile [Range]
Flood Potential Index (P_f)	19.6	71.0th [0.25 - 164.7]
Watershed Scale Ratio (R_f)	1.63	85.0th [0 - 5.79]
Beard Flashiness Index (F)	0.55	25.0th [0.37 - 2.82]
Richards-Baker Flashiness Index (R-B)	0.381	59.0th [0.039 - 1.621]
Bimodality Index (Bi)	5.2	42.0th [2.1344 - 182.8173]
Flood Variability Index (V_f)	1.92	86.0th [1.15 - 2.86]
Flood Hazard Index (H_f)	10.8	56.0th [0.1 - 164.7]

Trends

Allegheny Mountains (95)

Zone 95 is experiencing no trend in the magnitudes of largest (5%) of annual peak discharges.
Zone 95 is experiencing a significant decreasing trend in the magnitudes of largest quarter (Q4, >4 yr RI) of annual peak discharges (percent change = -7.6).
Zone 95 is experiencing a significant decreasing trend in the magnitudes of moderate quarter (Q3, 4 to 2 yr RI) of annual peak discharges (percent change = 0.0).
Zone 95 is experiencing a significant decreasing trend in the magnitudes of ~bankfull quarter (Q2, 2 to 1.33 yr RI) of annual peak discharges (percent change = -1.3).
Zone 95 is experiencing a significant decreasing trend in the magnitudes of < bankfull quarter (Q1, <1.33 yr RI) of annual peak discharges (percent change = -4.0).
Zone 95 is experiencing no trend in the annual frequency of floods.
Zone 95 is experiencing no trend in the event frequency of large floods.
Zone 95 is experiencing no trend in flood flashiness.

Flood Discharge Estimates (cfs)	Unadjusted	Trend-Adjusted
Expected Flood Potential (Q_{efp})	25,400	23,500
Maximum Likely Flood Potential (Q_{mlf})	46,500	43,000

Return Interval (yr)	Annual Exceedance Probability	Index Flood	USGS Equations (StreamStats)	Streamgage Analysis (17C, Weighted)
500	0.2	42,500	25,600	25,800
200	0.5	33,100	22,100	22,200
100	1	27,200	19,600	19,700
50	2	22,300	17,100	17,300
25	4	18,100	14,800	15,000
10	10	13,400	11,900	12,100
5	20	10,500	9,690	9,970
2	50	6,870	6,710	7,010
1.5	66.7	5,670	5,600	5,910

: directly comparable

Figure 46: Combined streamgage analysis and watershed analysis results, for determination of the most appropriate design flood discharge and the flood-frequency relationship for the Tygart Valley River at Dailey, West Virginia.

Yampa River, Colorado

Consider the Yampa River at Craig, Colorado (Figure 47). This 1820 mi^2 watershed (Figure 48) is within two zones (7 and 3). A watershed analysis is to be performed for this ungaged location.

Zone 3 Summary:

- This zone is composed of core portions of the Southern Rocky Mountains, from southern Wyoming through much of the Colorado high country.
- This zone has relatively low flood potential (P_f = 2.3), at the 13th percentile compared to zones across the contiguous United States. Only 13 percent of zones have lesser flood potential.
- This zone has low flashiness, as quantified using both Beard F (0.54, 23rd percentile) and Richards-Baker (0.10, 8th percentile).
- Bimodality is relatively low (4.6, 36th percentile).
- Increasing observed trends exists in this zone for three (of five) flood magnitude tests:
  - Largest 5% (>20-year return interval): possibly increasing trend, +12.8%
  - Q4 (> 4-year return interval): significant increasing trend, +1.4%
  - Q2 (bankfull-scale floods; 1.33 to 2-year return interval): significant increasing trend, +6.0%
- No trends in flood-frequency or flashiness observed.

Zone 7 Summary:

- This zone is composed of mountains in Northwest Colorado, in the Yampa River basin, and the Uinta Mountains in Utah.
- This zone also has relatively low flood potential (P_f = 4.7), at the 27th percentile compared to zones across the contiguous United States. However, on average floods in zone 7 are 4.7/2.3 = 2.0 times larger than in zone 3.
- This zone has low flashiness, as quantified using both Beard F (0.49; 14th percentile) and Richards-Baker (0.10, 8th percentile).
- Bimodality is low (3.3, 17th percentile); floods are consistent, with the largest events (on average) being 3.3 times larger in magnitude than typical (median) annual peak discharges.
- Increasing observed trends exist for three flood magnitude tests:
  - Largest 5% (>20-year return interval): +11.5%
  - Q4 (> 4-year return interval): significant increasing trend, +7.8%
  - Q3 (2- to 4-year return interval): significant increasing trend, +5.8%
- Possibly increasing trend in annual flood-frequency.

Figure 47: Yampa River (2021-5) near Craig, Colorado.

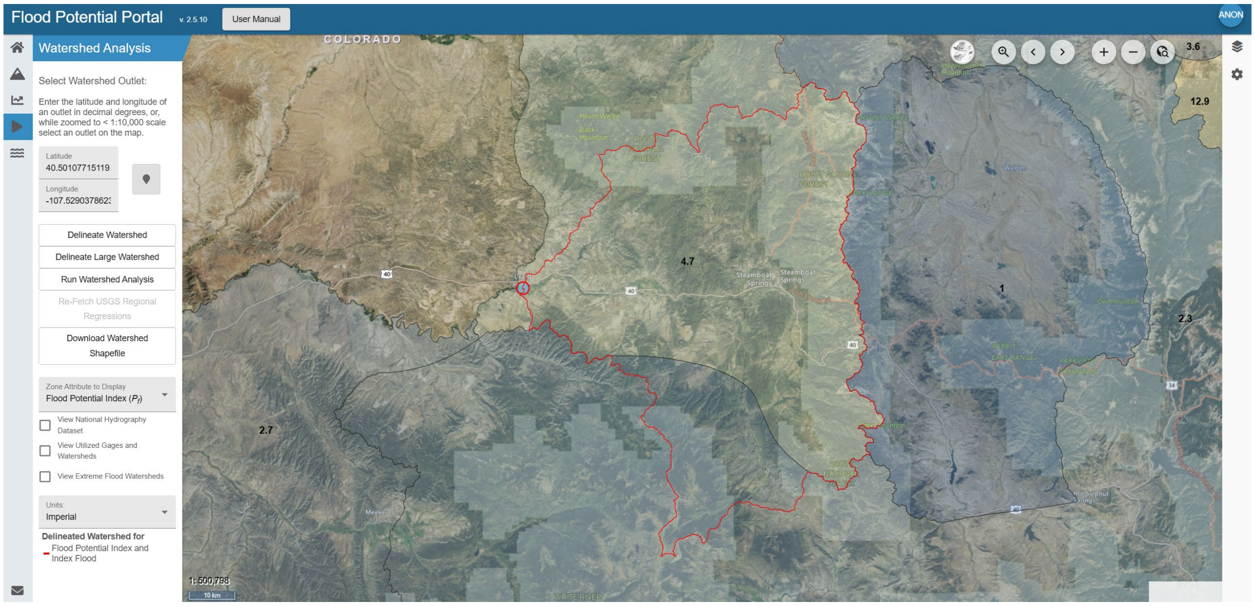


Figure 48: Watershed delineation (red polygon) for the Yampa River at Craig, Colorado.

These snowmelt dominated zones are experiencing trends that are likely the result of climate change, due to increased snowpack, and/or a warmer spring season and increased dust-on-snow events increasing the rate of snowmelt and the magnitude of annual peak discharges. This Yampa River watershed is largely uncontrolled by reservoirs; these zone patterns of increasing trends are applicable to design flood discharges for this river.

The watershed analysis Excel export is provided in Figure 49. The comparable analysis results are 20,100 cfs (Q_{100}: Index), 17,900 cfs (Q_{efp}), and 14,300 cfs (Q_{100}: USGS regional regression). These are the unadjusted values for the observed trends. It would be reasonable for a hydrologist to select a design flood discharge using either the Index Q_{100} result (manually-computed to include the increasing trends), which is most conservative at this site, or the trend-adjusted expected flood potential discharge (Q_{efp}). The lowest comparable value at this site (regional regression Q_{100}) should not be used, due to its less conservative nature.

The trend adjusted $Q_{100,\ Index}$, using contributing values for each zone from the calculations tab of the results (Figure 50), can be combined with the largest observed trends in large flood magnitudes (zone 7 largest 5%: +11.5%; zone 3 largest 5%: +12.8%) could be used for selecting the design flood discharge and is computed as:

$$Q_{design} = \Sigma(Q_{100\ index,\ zone\ x}[1+(\%\ change)/100]) = 15{,}000*1.115+5090*1.128 = \underline{22{,}500\ cfs}.$$

However, the median value can often be best for use as the design flood discharge (to avoid both underestimation and overestimation), specifically the Q_{efp}:

$$Q_{design} = \underline{18{,}000\ cfs}$$

If it is deemed by the practitioner that the trend-adjusted value should be used, this value is computed by the Flood Potential Portal:

$$Q_{design} = \underline{20{,}200\ cfs}$$

, and can be manually computed as:

$$Q_{design} = 13{,}300*1.115+4770*1.128 = \underline{20{,}200\ cfs}$$

Additionally, if freeboard is included in the design, from a discharge perspective this freeboard has no need to pass peak flows in excess of the maximum likely flood potential discharge (Q_{mlf}), in this case the trend-adjusted value (Q_{mlf} = 29,500 cfs). Magnitudes in excess of the maximum likely flood potential are systematically defined as extreme; it is inappropriate to design most stream valley infrastructure to pass extreme floods. Designing to this level would be a waste of limited available funding for many geomorphic settings. A check should be performed on the discharge associated with the utilized freeboard.

Flood Potential Watershed Analysis: Results Overview

Date Generated: 11/05/2025
Version: 2.5.9
Latitude: 40.50107715
Longitude: -107.5290379

Indices -- Watershed Flooding Characteristics

	Value	Percentile [Range]
Flood Potential Index (P_f)	4.24	24.0th [0.25 - 164.7]
Watershed Scale Ratio (R_f)	0.483	22.0th [0 - 5.79]
Beard Flashiness Index (F)	0.5	14.0th [0.37 - 2.82]
Richards-Baker Flashiness Index (R-B)	0.0976	6.0th [0.039 - 1.621]
Bimodality Index (Bi)	3.6	20.0th [2.1344 - 182.8173]
Flood Variability Index (V_f)	1.42	16.0th [1.15 - 2.86]
Flood Hazard Index (H_f)	2.09	15.0th [0.1 - 164.7]

Trends

Southern Rocky Mountains (3)

Zone 3 is experiencing a possible increasing trend in the magnitudes of largest (5%) of annual peak discharges (percent change = 12.8).
Zone 3 is experiencing a significant increasing trend in the magnitudes of largest quarter (Q4, >4 yr RI) of annual peak discharges (percent change = 1.4).
Zone 3 is experiencing no trend in the magnitudes of moderate quarter (Q3, 4 to 2 yr RI) of annual peak discharges.
Zone 3 is experiencing a significant increasing trend in the magnitudes of ~bankfull quarter (Q2, 2 to 1.33 yr RI) of annual peak discharges (percent change = 6.0).
Zone 3 is experiencing no trend in the magnitudes of < bankfull quarter (Q1, <1.33 yr RI) of annual peak discharges.
Zone 3 is experiencing no trend in the annual frequency of floods.
Zone 3 is experiencing no trend in the event frequency of large floods.
Zone 3 is experiencing no trend in flood flashiness.

Northwest Mountains (7)

Zone 7 is experiencing a significant increasing trend in the magnitudes of largest (5%) of annual peak discharges (percent change = 11.5).
Zone 7 is experiencing a significant increasing trend in the magnitudes of largest quarter (Q4, >4 yr RI) of annual peak discharges (percent change = 7.8).
Zone 7 is experiencing a significant increasing trend in the magnitudes of moderate quarter (Q3, 4 to 2 yr RI) of annual peak discharges (percent change = 5.8).
Zone 7 is experiencing no trend in the magnitudes of ~bankfull quarter (Q2, 2 to 1.33 yr RI) of annual peak discharges.
Zone 7 is experiencing no trend in the magnitudes of < bankfull quarter (Q1, <1.33 yr RI) of annual peak discharges.
Zone 7 is experiencing a possible increasing trend in the annual frequency of floods.
Zone 7 is experiencing no trend in the event frequency of large floods.
Zone 7 is experiencing a possible decreasing trend in flood flashiness.

Flood Discharge Estimates (cfs)

	Unadjusted	Trend-Adjusted
Expected Flood Potential (Q_{efp})	18,000	20,200
Maximum Likely Flood Potential (Q_{mlf})	26,300	29,500

Return Interval (yr)	Annual Exceedance Probability	Index Flood	USGS Equations (StreamStats)
500	0.2	24,500	16,900
200	0.5	22,100	15,500
100	1	20,100	14,300
50	2	18,200	12,800
25	4	16,300	10,800
10	10	13,500	10,200
5	20	11,300	8,500
2	50	7,880	6,340
1.5	66.7	6,410	----

: directly comparable

Figure 49: Watershed analysis overview results (generated using the Excel export option) for the Yampa River at Craig, Colorado.

Flood Potential - Calculations

Date Generated: 11/05/2025
Version: 2.5.9
Latitude: 40.50107715
Longitude: -107.5290379

Flood Potential

Zone Name (Zone ID)	Area (mi^2)	Second Predictor	Predictor Value	Trends in Frequency	Trends in Magnitude	Q_{efp} (cfs)	Trend-Adjusted Q_{efp} (cfs)	Q_{mlf} (cfs)	Trend-Adjusted Q_{mlf} (cfs)
Southern Rocky Mountains (3)	351.0	P	26.5 (inches)	No trends	Significantly Increasing	4,770	5,390	7,670	8,650
Northwest Mountains (7)	1,480.0	----	----	Possibly Increasing	Significantly Increasing	13,300	14,800	18,700	20,800
Total	1,830.0					18,000	20,200	26,300	29,500

Index Flood Frequency

Zone Name (Zone ID)	Area (mi^2)	Second Predictor	Predictor Value	1.5 Year	2 Year	5 Year	10 Year	25 Year	50 Year	100 Year	200 Year	500 Year
	351.0	P_{11}	2.53 (inches)	1,380	1,740	2,630	3,220	3,970	4,530	5,090	5,660	6,410
	1,480.0	P	30.1 (inches)	5,030	6,140	8,690	10,300	12,300	13,700	15,000	16,400	18,100
Total	1,830.0			6,410	7,880	11,300	13,500	16,300	18,200	20,100	22,100	24,500

USGS Regional Regression Flood Frequency (StreamStats)

USGS Regression Region	Area (mi^2)	Return Interval	1.5 Year	2 Year	5 Year	10 Year	25 Year	50 Year	100 Year	200 Year	500 Year
Mountain_Region_Peak_Flow	1,840.0		----	6,340	8,500	10,200	10,800	12,800	14,300	15,500	16,900
Total	1,840.0		----	6,340	8,500	10,200	10,800	12,800	14,300	15,500	16,900

Footnotes

P = mean average watershed annual precipitation (in)
P_{11} = mean average watershed monthly precipitation for November (in)
Q_{efp} = expected flood potential discharge
Q_{mlf} = maximum likely flood potential discharge

* The peak flow estimates from the USGS regional regressions (StreamStats) include a warning: One or more of the parameters is outside the suggested range. Estimates were extrapolated with unknown errors.

Citations

Capesius, J.P., and Stephens, V. C., 2009, Regional Regression Equations for Estimation of Natural Streamflow Statistics in Colorado: U. S. Geological Survey Scientific Investigations Report 2009-5136, 32 p.
Yochum, S.E., Scott, J.A., and Levinson, D.H., 2019, Methods for Assessing Expected Flood Potential and Variability: Southern Rocky Mountains Region. Water Resources Research, vol. 55, no. 8, pp. 6392-6416.
Yochum, S.E., Wible, T., Korsa, M., Ghanbari, M., Arabi, M. 2024, Flood Potential Portal: A web tool for understanding flood variability and predicting peak discharges. River Research and Applications. Wiley. https://doi.org/10.1002/rra.4354

Figure 50: Watershed analysis calculations results (generated using the Excel export option) for the Yampa River at Craig, Colorado.

Roosevelt Creek, California

Roosevelt Creek is a small stream on the Los Padres National Forest, west of King City, California. This 2.3 mi^2 watershed is a tributary to Arroyo Seco (Figure 51), in zone 25 (California Coast Ranges). The analysis point is at the crossing with Indian Road, which hypothetically requires a replaced structure. A watershed analysis is to be performed at this ungaged location.

Zone 25 Summary:

- This zone is composed primarily of the windward side of the California Coastal Ranges.
- This zone has relatively high flood potential (P_f = 31.4), at the 90th percentile compared to zones across the United States. Only 10 percent of zones have higher flood potential. Flood potential is substantially larger on this windward side of these mountains than the leeward side (zone 24, P_f = 13.4), with flood magnitudes, on average, being 31.4/13.4 = 2.3 times larger.
- This zone has moderate to high flashiness, as quantified using both Beard F (0.81, 58th percentile) and Richards-Baker (0.40, 60th percentile).
- Bimodality is relatively low (4.5, 36th percentile).
- Significantly decreasing observed trends exists for all four quarters of annual peak discharges:
  - Q4 (> 4-year return interval): significant decreasing trend, -7.3%
  - Q3 (2- to 4-year return interval): significant decreasing trend, -7.0%
  - Q2 (bankfull-scale floods; 1.33 to 2-year return interval): significant decreasing trend, -2.6%
  - Q1 (<bankfull-scale floods; <1.33-year return interval): significant decreasing trend, -1.6%
  - Trend analyses performed on data collected through WY2023.
- Significant decreasing trend in event flood-frequency observed.
- Possible decreasing trend in flashiness.

There are no pervasive increasing trends due to climate variability or change, or other non-stationarity mechanisms across this flood potential zone. These decreasing trends are likely heavily influenced by large flood events that occurred across this zone in 1964 and 1955. Similar-scale flooding has not yet reoccurred.

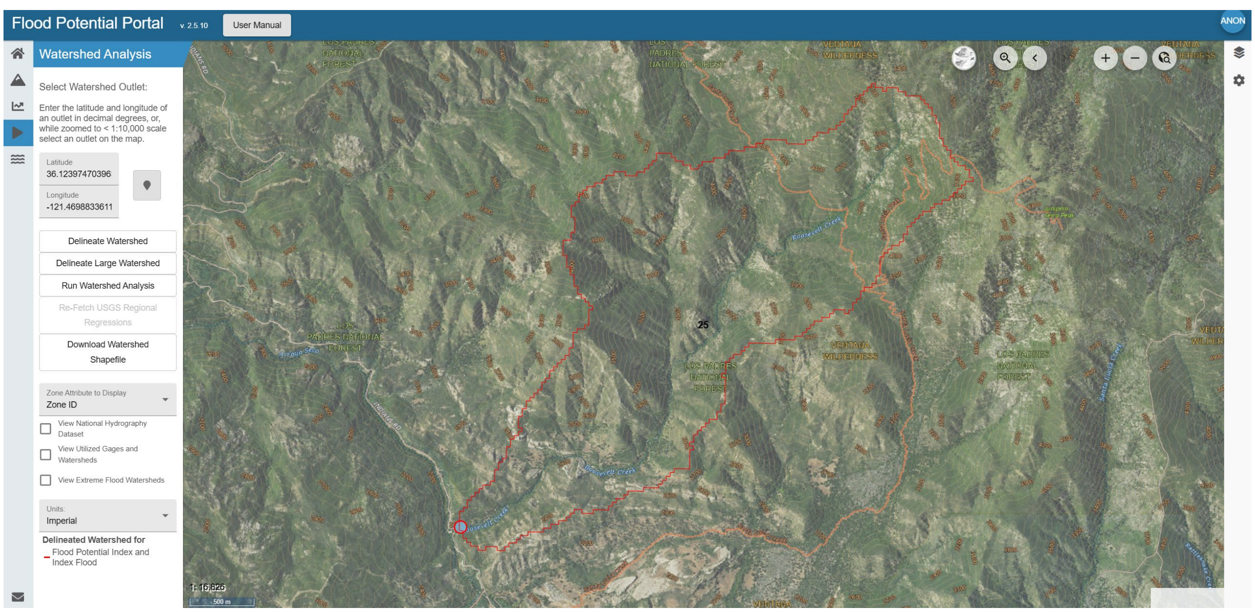


Figure 51: Watershed delineation (red polygon) for Roosevelt Creek, California, on the Los Padres National Forest.

For the selection of a design flood discharge, the comparable analysis results for this site are 896 cfs (Q_{100}: Index), 831 cfs (Q_{efp}), and 772 cfs (Q_{100}: USGS regional regression; Figure 52); the results are fairly consistent, providing some certainty in the selection of the design flood discharge. A design flood discharge of 830 cfs is recommended for this structure (rounded to two significant digits), since this value is the median of the comparable values.

$$Q_{design} = Q_{efp} = \underline{830\ cfs}$$

It would also be reasonable to select the $Q_{100,index}$ = 900 cfs (rounded to two significant digits) as the design flood discharge, if the watershed setting and local knowledge supports greater conservativeness.

Flood Potential Watershed Analysis: Results Overview

Date Generated: 11/05/2025 | Latitude: 36.1239747
Version: 2.5.10 | Longitude: -121.4698834

Indices -- Watershed Flooding Characteristics

	Value	Percentile [Range]
Flood Potential Index (P_f)	31.4	90.0th [0.25 - 164.7]
Watershed Scale Ratio (R_f)	2.48	95.0th [0 - 5.79]
Beard Flashiness Index (F)	0.81	58.0th [0.37 - 2.82]
Richards-Baker Flashiness Index (R-B)	0.397	60.0th [0.039 - 1.621]
Bimodality Index (Bi)	4.5	35.0th [2.1344 - 182.8173]
Flood Variability Index (V_f)	1.55	43.0th [1.15 - 2.86]
Flood Hazard Index (H_f)	25.4	85.0th [0.1 - 164.7]

Trends

CA Coast Ranges & Western Klamath Mountains (25)

Zone 25 is experiencing no trend in the magnitudes of largest (5%) of annual peak discharges.
Zone 25 is experiencing a significant decreasing trend in the magnitudes of largest quarter (Q4, >4 yr RI) of annual peak discharges (percent change = -7.3).
Zone 25 is experiencing a significant decreasing trend in the magnitudes of moderate quarter (Q3, 4 to 2 yr RI) of annual peak discharges (percent change = -7.0).
Zone 25 is experiencing a significant decreasing trend in the magnitudes of ~bankfull quarter (Q2, 2 to 1.33 yr RI) of annual peak discharges (percent change = -2.6).
Zone 25 is experiencing a significant decreasing trend in the magnitudes of < bankfull quarter (Q1, <1.33 yr RI) of annual peak discharges (percent change = -1.6).
Zone 25 is experiencing no trend in the annual frequency of floods.
Zone 25 is experiencing a significant decreasing trend in the event frequency of large floods.
Zone 25 is experiencing a possible decreasing trend in flood flashiness.

Flood Discharge Estimates (cfs)

	Unadjusted	Trend-Adjusted
Expected Flood Potential (Q_{efp})	831	770
Maximum Likely Flood Potential (Q_{mlf})	1,270	1,180

Return Interval (yr)	Annual Exceedance Probability	Index Flood	USGS Equations
500	0.2	1,250	1,050
200	0.5	1,040	893
100	1	896	772
50	2	762	657
25	4	636	524
10	10	482	362
5	20	370	239
2	50	217	102
1.5	66.7	160	----

: directly comparable

Figure 52: Watershed analysis overview results (generated using the Excel export option) for Roosevelt Creek, California.

The decreasing trend (-7.3%) of the largest quarter of annual peak discharges suggest the possibility of adjusting the design flood discharge downward. This trend is possibly due to climate variability or climate change, since reservoir storage is not extensive across this zone. However, applying a 7.3% reduction for computation of the design flood discharge would be insufficiently conservative.

Additionally, if freeboard is included in the design, from a discharge perspective this freeboard has no need to pass peak flows in excess of the maximum likely flood potential discharge (Q_{mlf} = 1270 cfs). Magnitudes in excess of the maximum likely flood potential are systematically defined as extreme; it is typically inappropriate to design most stream valley infrastructure to pass extreme floods. In many geomorphic settings, designing to this level would be a waste of limited available funding. Calculating the discharge associated with the design freeboard should be performed.

In regard to other flood-frequency values, while Q_{100} is similar (896 cfs & 772 cfs) between the two flood-frequency relationships, there is greater (percent) divergence for frequent events (217 cfs vs. 102 cfs for the 2-year event). Additional information is needed to determine the more appropriate flood-frequency relationship for these frequent return intervals, such as the estimation of bankfull discharge and comparison with an assumed return interval of such an event.

N. Fork S. Branch Potomac River, West Virginia

The North Fork of the South Branch of the Potomac River, at Seneca Rocks, West Virginia (Figure 53), in zone 72N (Figure 54), has a contributing watershed area of 240 mi^2 within the states of West Virginia and Virginia. This site is on the Monongahela National Forest, in the Spruce Knob-Seneca Rocks National Recreation Area.

Zone 72N Summary:

- This zone is the highest flood potential portion of the Valley and Ridge physiographic province.
- This zone has high flood potential (P_f = 34.8), at the 92^{nd} percentile compared to zones across the contiguous United States. Only 8 percent of zones have higher flood potential. Floods are smaller in the Valley and Ridge to both the south (zone 72, P_f = 11.2) and the north (zone 98, P_f = 15.8); flood magnitudes are, on average, 34.8/11.2 = 3.1 times larger in this zone than in the Valley and Ridge to the south and 34.8/15.8 = 2.2 times larger than in the Valley and Ridge to the north. To the southeast, flood potential is lower in much of the Blue Ridge as well (zone 73, P_f = 23.4; zone 73N, P_f = 22.8), with the notable exception the Appalachian Front (zone 73F), which has been observed to experience some of highest flood potential within the contiguous United States (P_f = 57.0). Floods in zone 72N are, on average, more than a third less (34.8/57.0 = 0.61), on average, than floods in zone 73F.
- This zone has moderate flashiness, as quantified using both Beard F (0.70, 46^{th} percentile) and Richards-Baker (0.37, 55^{th} percentile).
- Bimodality is relatively high (9.6, 70^{th} percentile), on average. The largest floods tend to be almost 10 times larger than typical (median) scale floods.
- Trends in flood magnitudes are not detected, or are mixed:
  - Q4 (> 4-year return interval): significant decreasing trend, -10.0%
  - Q1 (<bankfull-scale floods; <1.33-year return interval): possibly increasing trend, +1.2%
- No trends have been observed in flood-frequency and flashiness.

Figure 53: N. Fork of the S. Branch of the Potomac River, at Seneca Rocks, West Virginia.

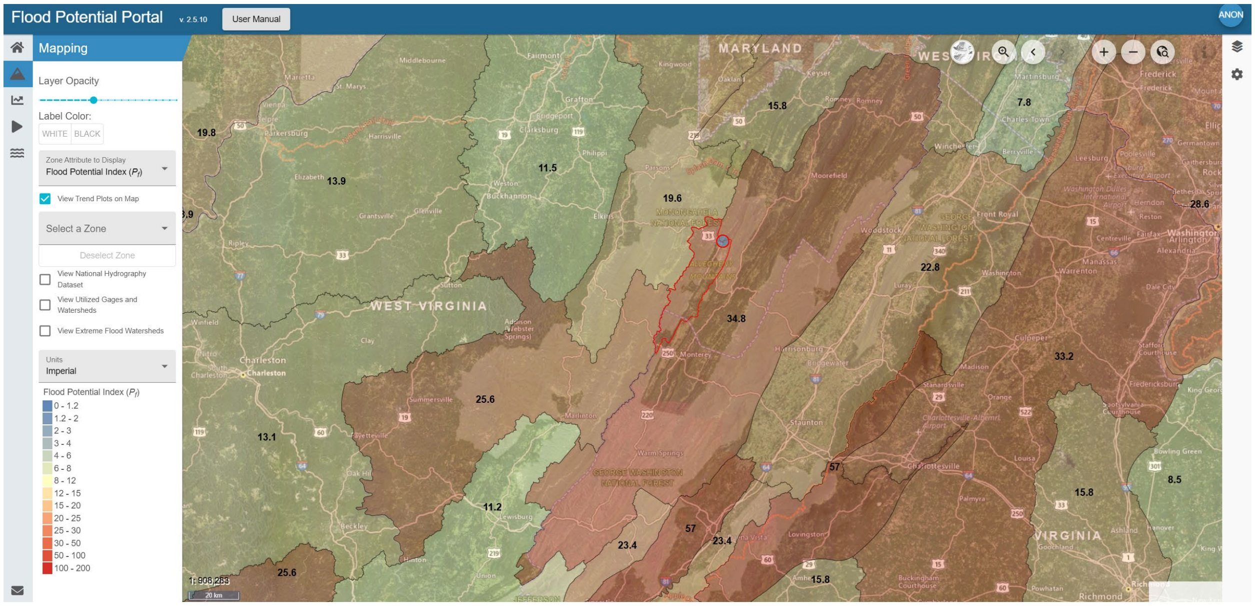


Figure 54: Zone 72N, Valley and Ridge, North, which envelopes the watershed for the point of interest (red polygon).

Key results of the watershed analyses are presented in the Excel export file (Figure 55), including indices that describing the fundamental flooding characteristics, trend results relevant for large floods, and flood discharge estimates.

For the selection of a design flood discharge, the comparable analysis results for this site are 66,000 cfs (Q_{efp}), 45,500 cfs (Q_{100}: Index), and 33,300 cfs (Q_{100}: USGS regional regression); these results show a substantial spread, with the USGS regional regressions Q_{100} being the lowest and the expected flood potential discharge being the largest. The median value is recommended for this structure:

$$Q_{design} = Q_{100,index} = \underline{45{,}500 \text{ cfs}}$$

The decreasing trend (-10.0%) of the largest quarter of annual peak discharges suggest the possibility of adjusting the design flood discharge downward. However, applying a 10.0% reduction for computation of the design flood discharge provides a result that would be insufficiently conservative.

Flood Potential Watershed Analysis: Results Overview

Date Generated:	11/05/2025	Latitude:	38.84278358
Version:	2.5.10	Longitude:	-79.37102927

Indices -- Watershed Flooding Characteristics

	Value	Percentile [Range]
Flood Potential Index (P_f)	34.8	92nd [0.25 - 164.7]
Watershed Scale Ratio (R_f)	2.14	92.0th [0 - 5.79]
Beard Flashiness Index (F)	0.7	46.0th [0.37 - 2.82]
Richards-Baker Flashiness Index (R-B)	0.374	57.0th [0.039 - 1.621]
Bimodality Index (Bi)	9.6	71.0th [2.1344 - 182.8173]
Flood Variability Index (V_f)	1.47	24.0th [1.15 - 2.86]
Flood Hazard Index (H_f)	24.5	83rd [0.1 - 164.7]

Trends

Valley and Ridge, North (72N)

Zone 72N is experiencing no trend in the magnitudes of largest (5%) of annual peak discharges.
Zone 72N is experiencing a significant decreasing trend in the magnitudes of largest quarter (Q4, >4 yr RI) of annual peak discharges (percent change = -10.0).
Zone 72N is experiencing no trend in the magnitudes of moderate quarter (Q3, 4 to 2 yr RI) of annual peak discharges.
Zone 72N is experiencing no trend in the magnitudes of ~bankfull quarter (Q2, 2 to 1.33 yr RI) of annual peak discharges.
Zone 72N is experiencing a possible increasing trend in the magnitudes of < bankfull quarter (Q1, <1.33 yr RI) of annual peak discharges (percent change = 1.2).
Zone 72N is experiencing no trend in the annual frequency of floods.
Zone 72N is experiencing no trend in the event frequency of large floods.
Zone 72N is experiencing no trend in flood flashiness.

Flood Discharge Estimates (cfs)

	Unadjusted	Trend-Adjusted
Expected Flood Potential (Q_{efp})	66,000	59,400
Maximum Likely Flood Potential (Q_{mlf})	94,900	85,400

Return Interval (yr)	Annual Exceedance Probability	Index Flood	USGS Equations
500	0.2	91,500	50,900
200	0.5	61,600	40,400
100	1	45,500	33,300
50	2	33,400	27,100
25	4	24,300	21,300
10	10	15,600	14,600
5	20	10,800	10,400
2	50	5,910	5,720
1.5	66.7	4,480	4,340

: directly comparable

Figure 55: Watershed analysis results for the N. Fork of the S. Branch of the Potomac River at Seneca Rocks, downstream of the Seneca Creek confluence.

Whiterock Creek, North Carolina

Whiterock Creek is a small stream on the Nantahala National Forest in North Carolina, in zone 76, south of Cherokee. The watershed size is 1.60 mi^2 at a road-stream crossing.

Zone 76 Summary:

- This zone is composed of the southern-most extent of the Southern Blue Ridge Mountains, straddling the boundaries between North Carolina, Tennessee, South Carolina, and Georgia. The Valley and Ridge physiographic province is to the west, with the Piedmont to the southeast.
- This zone has relatively high flood potential (P_f = 21.6), at the 75th percentile compared to zones across the contiguous United States. Twenty five percent of zones have higher flood potential. Floods are smaller in the Valley and Ridge to the west (zone 76W, P_f = 16.3) and Piedmont to the southeast (zone 74S, P_f = 15.3). However, floods are larger in a portion of the Blue Ridge to the northeast (zone 73S, P_f = 46.1), with some of the highest flood potential in the contiguous United States. Floods in zone 73S are, on average, 46.1/21.6 = 2.1 times larger than in zone 76.
- This zone has moderate to lower flashiness, as quantified using Beard F (0.60, 33rd percentile) and Richards-Baker (0.24, 35th percentile).
- Bimodality is moderate (5.7, 48th percentile), on average.
- Trends in all scales of flood magnitudes have been detected in this zone:
    - Trends in largest 5% of annual peak discharges: significant increasing trend, +33.8%
    - Q4 (>4-year return interval): significant increasing trend, +21.0%
    - Q3 (2- to 4-year return interval): significant increasing trend, +12.1%
    - Q2 (bankfull-scale floods; 1.33 to 2-year return interval): significant increasing trend, +9.2%
    - Q1 (<bankfull-scale floods; <1.33-year return interval): significant increasing trend, +5.5%
- Possibly increasing trends have been detected in annual flood-frequency.
- Significant increasing trends in event flood-frequency.

For the selection of a design flood discharge, the comparable analysis results for this site (Figure 56) are 773 cfs (Q_{efp}), 704 cfs (Q_{100}: Index), and 623 cfs (Q_{100}: USGS regional regression). The three results are somewhat consistent, with the median result (700 cfs, from the index flood-frequency method; rounded to two significant digits) providing the preferred value.

$$Q_{design} = Q_{100\ Index} = \underline{700\ cfs}$$

With increasing flood magnitudes being experienced across this zone, due to the impacts of Hurricane Helene on trend analyses (prior to 2024, there were no increasing trends observed for the largest flood magnitudes), increasing the design flood discharge to account for these trends would be reasonable:

$$Q_{design} = 704*1.338 = \underline{940\ cfs}$$

or

$$Q_{design} = 704*1.210 = \underline{850\ cfs}$$

However, inspection of the flood potential plot (Figure 57), which indicates a preponderance of 2024 record peak discharges in the algorithm computations, indicates that incorporating such observed increasing trends may be redundant since the 2024-updated algorithms are already heavily influenced by Hurricane Helene-induced flooding. It is essential to not underestimate flood magnitudes while selecting design flood discharges, but overestimation is also problematic.

Flood Potential Watershed Analysis: Results Overview

Date Generated:	11/05/2025	Latitude:	35.23123114
Version:	2.5.10	Longitude:	-83.19227974

Indices -- Watershed Flooding Characteristics	Value	Percentile [Range]
Flood Potential Index (P_f)	21.6	74.0th [0.25 - 164.7]
Watershed Scale Ratio (R_f)	1.11	65.0th [0 - 5.79]
Beard Flashiness Index (F)	0.6	33.0th [0.37 - 2.82]
Richards-Baker Flashiness Index (R-B)	0.24	35.0th [0.039 - 1.621]
Bimodality Index (Bi)	5.7	48.0th [2.1344 - 182.8173]
Flood Variability Index (V_f)	2.06	93.0th [1.15 - 2.86]
Flood Hazard Index (H_f)	12.9	62.0th [0.1 - 164.7]

Trends

Southern Blue Ridge (76)

Zone 76 is experiencing a significant increasing trend in the magnitudes of largest (5%) of annual peak discharges (percent change = 33.8).
Zone 76 is experiencing a significant increasing trend in the magnitudes of largest quarter (Q4, >4 yr RI) of annual peak discharges (percent change = 21.0).
Zone 76 is experiencing a significant increasing trend in the magnitudes of moderate quarter (Q3, 4 to 2 yr RI) of annual peak discharges (percent change = 12.1).
Zone 76 is experiencing a significant increasing trend in the magnitudes of ~bankfull quarter (Q2, 2 to 1.33 yr RI) of annual peak discharges (percent change = 9.2).
Zone 76 is experiencing a significant increasing trend in the magnitudes of < bankfull quarter (Q1, <1.33 yr RI) of annual peak discharges (percent change = 5.5).
Zone 76 is experiencing a possible increasing trend in the annual frequency of floods.
Zone 76 is experiencing a significant increasing trend in the event frequency of large floods.
Zone 76 is experiencing no trend in flood flashiness.

Flood Discharge Estimates (cfs)	Unadjusted	Trend-Adjusted
Expected Flood Potential (Q_{efp})	773	1,030
Maximum Likely Flood Potential (Q_{mlf})	1,560	2,090

Return Interval (yr)	Annual Exceedance Probability	Index Flood	USGS Equations
500	0.2	1,090	913
200	0.5	854	746
100	1	704	623
50	2	575	509
25	4	464	397
10	10	339	277
5	20	258	194
2	50	158	99
1.5	66.7	124	----

: directly comparable

Figure 56: Watershed analysis overview results (generated using the Excel export option) for Whiterock Creek, North Carolina, on the Nantahala National Forest.

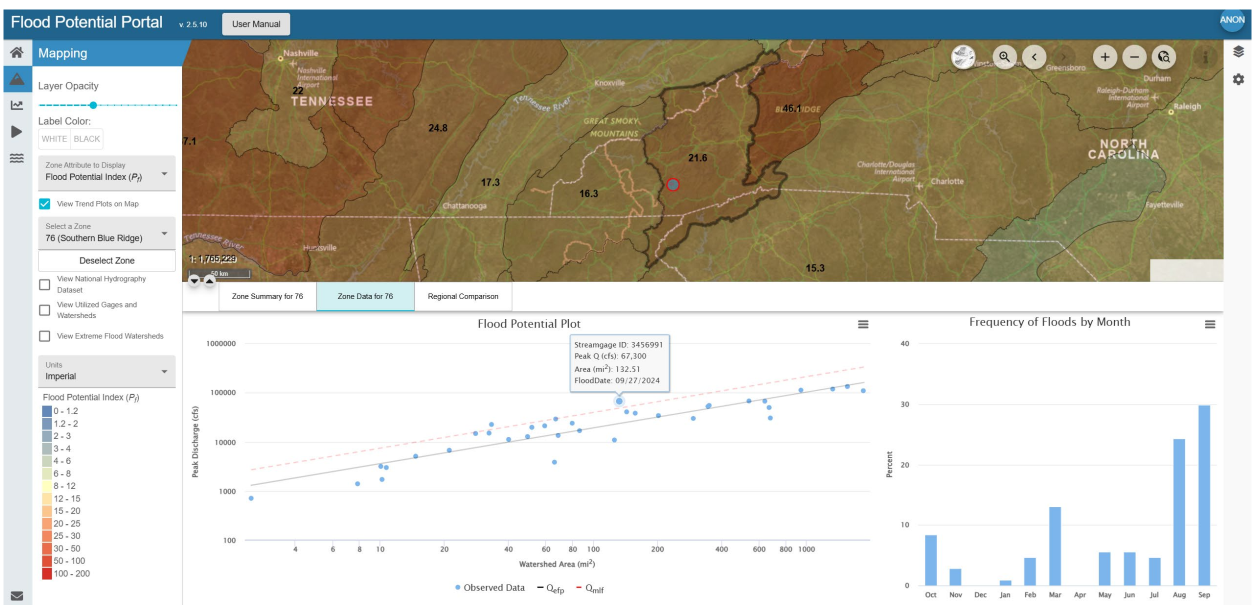


Figure 57: Flood potential plot in the Mapping Module for zone 76. With revised analyses performed after peak discharge data were made available by the U.S. Geological Survey from Hurricane Helene, inspection of the flood potential plot indicates the dominance of the 2024 flood in this zone's streamgages record peak discharges.

Mulberry River, Arkansas

The Mulberry River at the AR-108 crossing near Oark, Arkansas has had streamgage monitoring (USGS 07251790) from the 83 mi^2 watershed. To select a design flood discharge and flood-frequency relationship at this location (for a hypothetical bridge replacement), a streamgage analysis was performed followed by a watershed analysis. This watershed is in zone 59S (Ozarks, South).

Zone 59S Summary:

- z59S encompasses the southern Ozarks, with the northern Ozarks being within z59N
- z59S has a high flood potential (P_f = 43.4), at the 94th percentile compared to zones across the United States. Only 6% of zones have higher flood potential. The northern Ozarks have lower flood potential (P_f = 30.9), with floods in z59S being, on average, 43.4/30.9 = 1.40 times larger than in z59N.
- This zone experiences relatively high flashiness, with a Richard-Baker flashiness of *R-B* = 0.46 (67th percentile).
- Bimodality across the zone, on average, is a bit above normal (B_i = 6.9, 58th percentile).
- Increasing observed trends exists in this zone for all quarters of annual peak discharges:
  - Q4 (> 4-year return interval): significant increasing trend, +5.8% (Figure 35)
  - Q3 (4- to 2-year return interval): significant increasing trend, +7.7%
  - Q2 (~bankfull, 2- to 1.33-year return interval): significant increasing trend, +7.1%
  - Q1 (< 1.33-year return interval): significant increasing trend, +8.9%
- Significant increasing trend in event flood-frequency

Streamgages within the area of interest are initially searched by drawing a geometric shape and pressing "Fetch Stations Within Bounds" to show the available stations. The streamgage of interest is selected and annual peak discharges are plotted (press "Plot Annual Peak Discharges") for the streamgage (Figure 58). There are 17 years of record (1988 to 2004), a relatively short period. The maximum recorded discharge is 32,900 cfs (6/17/2000), with the next three largest floods being a bit more than 20,000 cfs, and the majority of annual peak discharges being <10,000 cfs. The lowest annual peak discharge occurred in 1991 (2400 cfs).

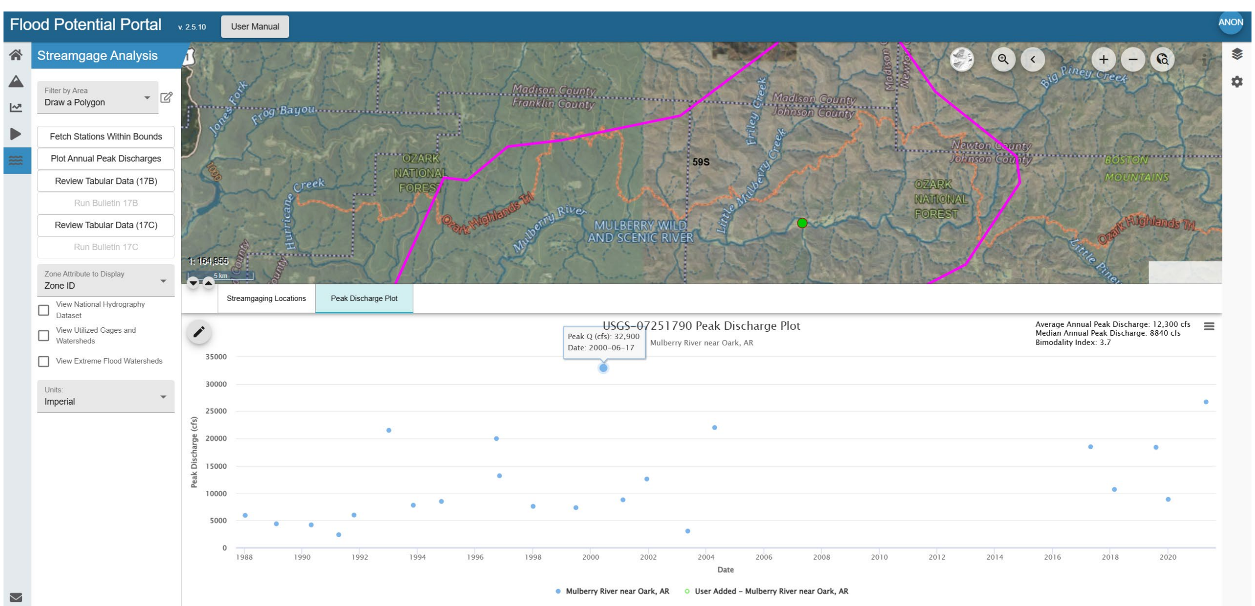


Figure 58: Annual peak discharge plot for the Mulberry River, Arkansas. On-hover information is provided for the flood of record, on 6/17/2000.

Tabular data for the Bulletin 17B analysis are reviewed after pressing the “Review Tabular Data (17B)” button. The peak discharges and dates are reviewed, and the data are inspected to see if outliers have been detected. The user can unselect any data year(s) they wish, though high outliers should typically be retained in an analysis. None of the peaks were indicated to be high or low outliers at this site. The generalized skew and variance should be populated, to compare results computed using only the station skew and the weighted generalized skew. The user can do this manually, or have this populated from available state or national guidance. In this example, the state analysis provides a generalized skew = -0.17. The station skew is -0.1717. “Run Bulletin 17B” is pressed to perform the streamgage flood-frequency analysis.

Tabular data and input parameters for the Bulletin 17C analysis are reviewed after pressing the “Review Tabular Data (17C)” button. The generalized skew is again populated, and the default discharge intervals and perception thresholds are inspected. The user must check the inputs for appropriateness per the Bulletin 17C guidance (England et al., 2018). “Run Bulletin 17C” is pressed to perform this streamgage flood-frequency analysis. Results from both the Bulletin 17B and Bulletin 17C analyses are provided (Figure 59), and should be exported (Excel is preferred).

Results from the 17B and 17C analyses are identical for the Q_{100}, with the Q_{100} using the station skew = 47,000 cfs and the Q_{100} using the weighted generalized skew = 47,100 cfs.

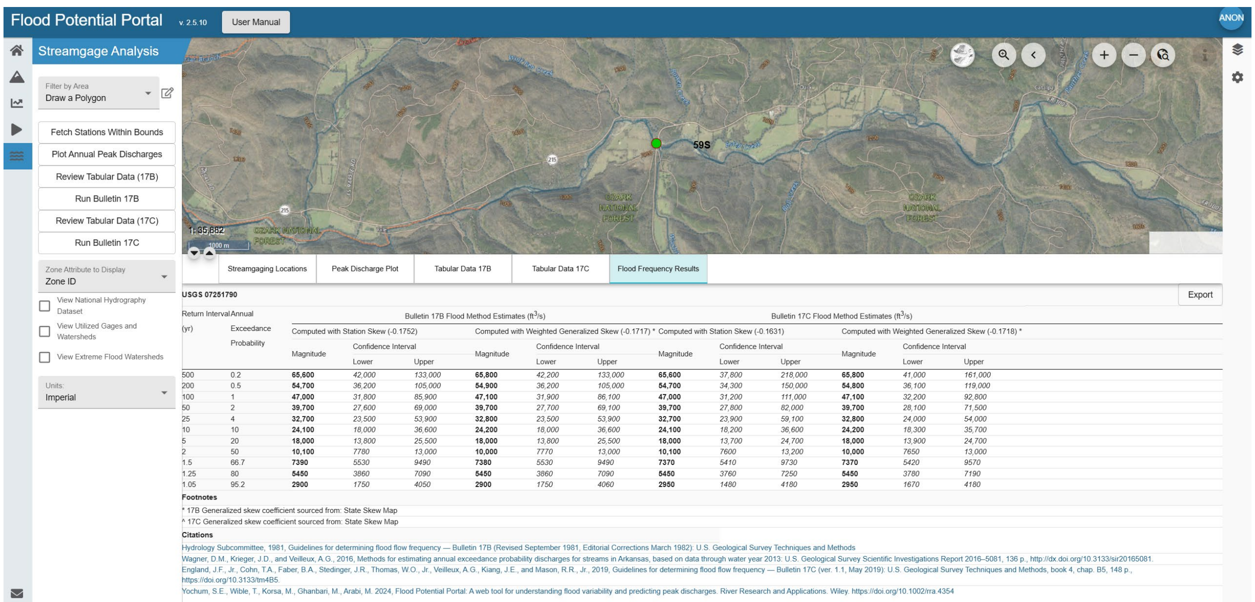


Figure 59: Streamgage food frequency analysis results for the Mulberry River, Arkansas (07251790).

A watershed analysis should also be performed (Figure 60), to provide more insight for the selection of the most appropriate design flood discharge value and flood-frequency relationships; a streamgage analysis should not be solely depended upon. The results from both the watershed analysis and the streamgage analysis are shown (Figure 61).

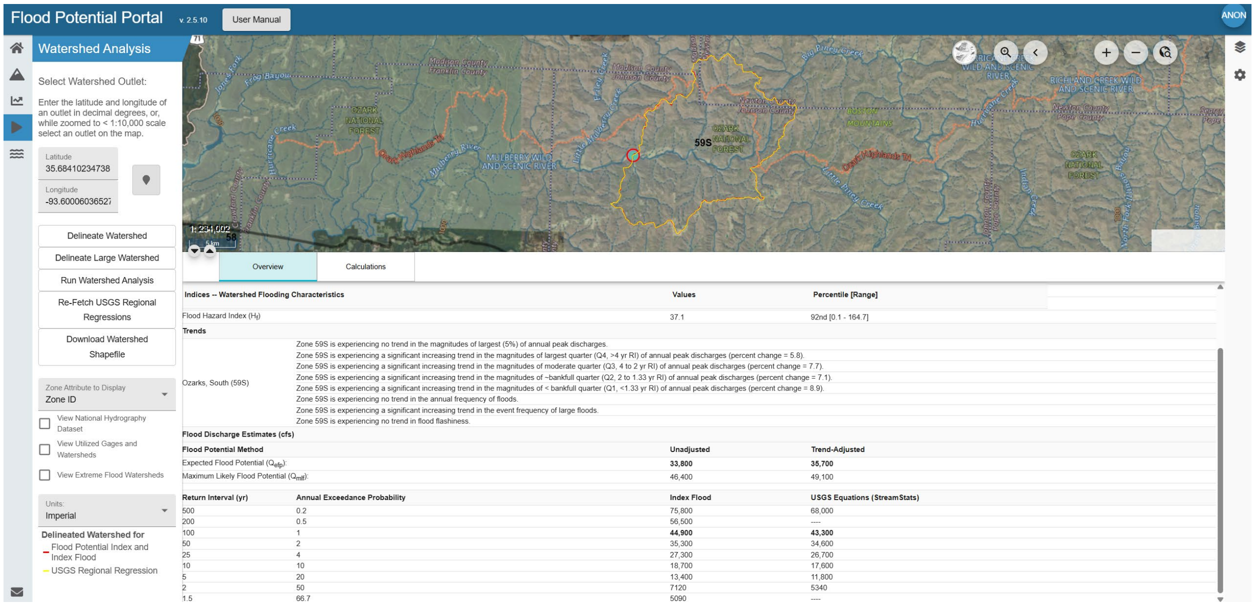


Figure 60: Watershed analysis results for the Mulberry River, Arkansas.

Flood Potential Watershed Analysis: Results Overview

Date Generated: 11/05/2025
Version: 2.5.10

Latitude: 35.68410235
Longitude: -93.60006037

Indices -- Watershed Flooding Characteristics	Value	Percentile [Range]
Flood Potential Index (P_f)	43.4	94.0th [0.25 - 164.7]
Watershed Scale Ratio (R_f)	0.87	50.0th [0 - 5.79]
Beard Flashiness Index (F)	0.85	62.0th [0.37 - 2.82]
Richards-Baker Flashiness Index (R-B)	0.455	67th [0.039 - 1.621]
Bimodality Index (Bi)	6.9	58.0th [2.1344 - 182.8173]
Flood Variability Index (V_f)	1.38	11.0th [1.15 - 2.86]
Flood Hazard Index (H_f)	37.1	92.0th [0.1 - 164.7]

Trends

Ozarks, South (59S)

Zone 59S is experiencing no trend in the magnitudes of largest (5%) of annual peak discharges.
Zone 59S is experiencing a significant increasing trend in the magnitudes of largest quarter (Q4, >4 yr RI) of annual peak discharges (percent change = 5.8).
Zone 59S is experiencing a significant increasing trend in the magnitudes of moderate quarter (Q3, 4 to 2 yr RI) of annual peak discharges (percent change = 7.7).
Zone 59S is experiencing a significant increasing trend in the magnitudes of ~bankfull quarter (Q2, 2 to 1.33 yr RI) of annual peak discharges (percent change = 7.1).
Zone 59S is experiencing a significant increasing trend in the magnitudes of < bankfull quarter (Q1, <1.33 yr RI) of annual peak discharges (percent change = 8.9).
Zone 59S is experiencing no trend in the annual frequency of floods.
Zone 59S is experiencing a significant increasing trend in the event frequency of large floods.
Zone 59S is experiencing no trend in flood flashiness.

Flood Discharge Estimates (cfs)	Unadjusted	Trend-Adjusted	Streamgage Analysis Results (17C)
Expected Flood Potential (Q_{efp})	33,800	35,700	
Maximum Likely Flood Potential (Q_{mlf})	46,400	49,100	

Return Interval (yr)	Annual Exceedance Probability	Index Flood	USGS Equations	Streamgage Analysis Results (17C)
500	0.2	75,800	68,000	65,800
200	0.5	56,500	----	54,800
100	1	44,900	43,300	47,100
50	2	35,300	34,600	39,700
25	4	27,300	26,700	32,800
10	10	18,700	17,600	24,200
5	20	13,400	11,800	18,000
2	50	7,120	5,340	10,000
1.5	66.7	5,090	----	7,370

: directly comparable

Figure 61: Combined streamgage analysis and watershed analysis results, for determination of the most appropriate design flood discharge and the flood-frequency relationship for the Mulberry River, Arkansas.

There are four sets of results to compare for the selection of the design flood discharge:

- Q_{efp} = 33,800 cfs
- $Q_{100\ regional\ regression}$ = 43,300 cfs
- $Q_{100\ index}$ = 44,900 cfs
- $Q_{100\ gage\ station}$ = 47,100 cfs

The flood potential (Q_{efp}) analysis appears to be underpredicting in this watershed. The USGS regional regression and the index analyses are providing similar predictions. The streamgage analysis is high in comparison, but the 22-year record is not unreasonably short. For this site, it may be best to use the streamgage analysis result:

$$Q_{design} = \underline{47{,}100 \text{ cfs}}.$$

Considering that floods are becoming more severe in this area, adjusting this value based on the observed increase in the largest quarter of annual peak discharges (+5.8%) may be warranted:

$$Q_{design} = Q_{100}[1+(\% \text{ change})/100] = 47{,}100*1.058 = \underline{49{,}800 \text{ cfs}}.$$

References

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Appendix A: Flood Potential Method Overview

The flood potential method (Yochum et al., 2019) quantifies the central tendency of large flood magnitudes across zones of similar flood response. It is similar to an approach proposed by Tipton (1937) for Colorado. This central tendency is the *expected flood potential*, a regression of the maximum recorded (record) discharges for streamgages within each zone. Floods of this size can reasonably be expected to occur at a stream valley point of interest, which (in concert with flood-frequency methods) makes these estimates valuable for stream valley infrastructure design and floodplain management. The expected flood potential discharge (Q_{efp}) has been found to not be statistically different from the flood-frequency derived 100-year discharge (Q_{100}; Yochum et al., 2019), though variability between Q_{efp} and Q_{100} may likely exist with respect to zone and watershed size, with systematic differences in some areas. The flood potential method has an advantage over flood-frequency methods for addressing bimodal peak flow magnitudes (heavy tails in statistical distributions) due to mixed populations, an acknowledged issue (England et al., 2018). This method also sidesteps issues stemming from varied streamgage lengths and periods of record. These advantages are important for the determination of design flood discharges. The 90% prediction limit of the regressions is the *maximum likely flood potential*. Floods with discharges (Q) greater than the maximum likely flood potential discharge (Q_{mlf}) are quantitatively defined as extreme, with the departure above this limit indicating the degree of extremity (see Appendix D). Hence, this method provides a systematic approach for identifying and ranking extreme floods, with ~10% of the record discharges being extreme. Each zone has flood potential plots that vary in scale (variability of flood magnitudes) and slope (variability of how watersheds of different sizes experience floods). Such characteristics are quantified and compared between zones through the use of indices. Finally, the flood potential method provides more statistical power in the assessment of trends in flood magnitudes and flood frequencies, through analyses that identify areas where, for example, floods are not experiencing trends in magnitudes but are increasing in frequency, or where flashiness is increasing but flood magnitudes and frequency is not changing. Where trends in flood magnitudes have been detected, percent change is quantified to adjust design flood discharges.

The flood potential method, and associated flood-hydrology techniques, are in need of additional development. Appendix I provides a list of research needs to further develop the field of flood hydrology, to increase understanding of large floods for more resilient infrastructure and informed floodplain management.

Contiguous United States Summary

Across the contiguous United States, 206 zones of similar flood response were delineated (Figure 62). These zone delineations, with attributes describing flooding characteristics, are available on the project webpage. These zones were developed using more than 8200 streamgaged watershed delineations with contributing areas less than 10,000 km^2. These streamgage locations and watershed delineations can be viewed within the mapping tool, with shapefiles available on the project webpage. Explained variance (R^2) of the regressions ranged from 99% to 69%, with an average (adjusted) R^2 of 0.93. Areas deemed to have insufficient data available for application of the flood potential method are also shown in Figure 62; these areas include the Central Valley of California, Flathead Valley of Montana, Snake River Plain of Idaho, western Utah, western New Mexico, Nebraska Sandhills, South Texas, the Louisiana Bayou, a portion of Michigan, and the New York City metropolitan area.

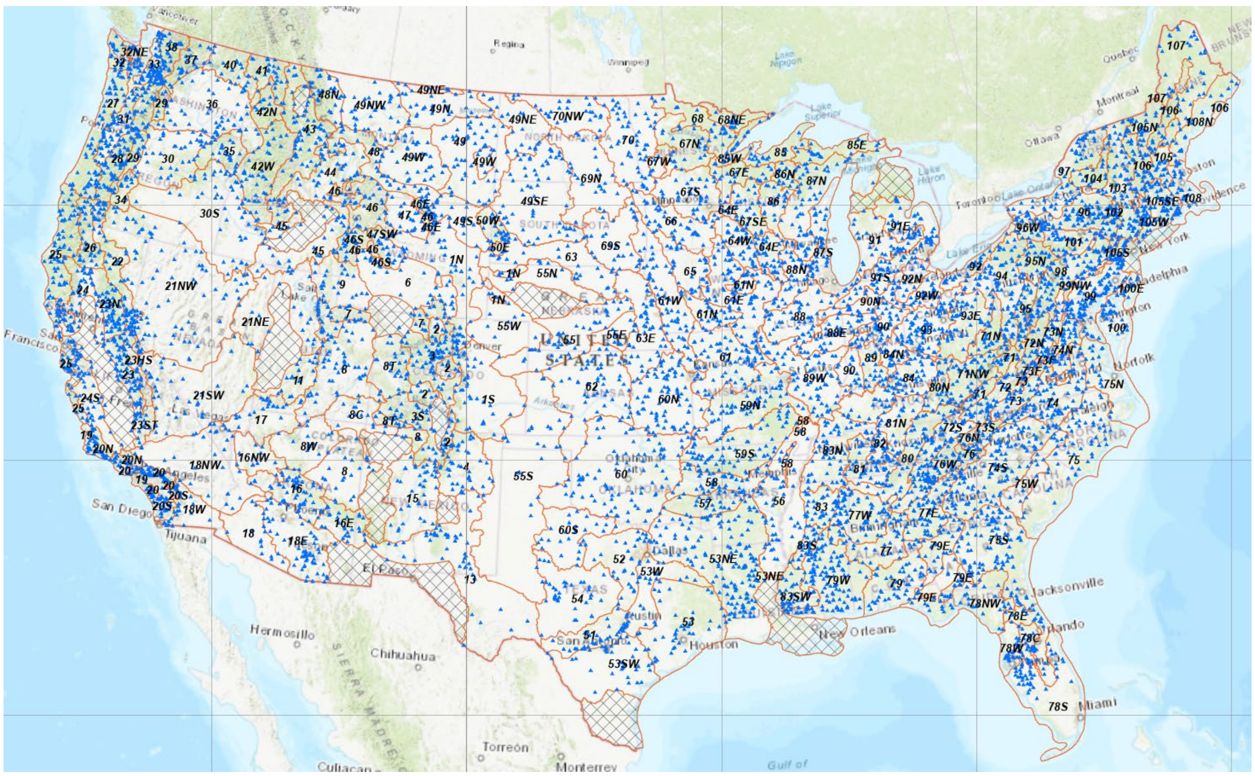


Figure 62: Flood Potential zone delineations, with identifications and utilized streamgages (blue triangles). Cross-hatched polygons indicate areas that have insufficient streamgage data for application of the flood potential method. Zone 2 is the reference zone for the flood potential index.

Flood Potential Index

To rank the average magnitudes of expected floods and compare how floods vary between any two zones, flood potential index (P_f) values were utilized (Figure 63; Appendix B). Consider the Ouachita Mountains (zone 57) of central Arkansas and Southeast Oklahoma (high flood potential), the Oregon and Washington Coast Ranges (zone 27; moderate flood potential), and the Mississippi River Headwaters, South (zone 67S; low flood potential). The Ouachitas experience some of the largest floods within the contiguous United States, as indicated by P_f = 54.3. Compared with the Oregon and Washington Coast Ranges (P_f = 18.8) and the Mississippi River Headwaters, South (P_f = 2.8), floods in the Ouachitas are, on average, 54.3/18.8 = 2.9 times larger than in the Oregon and Washington coastal ranges, and 54.3/2.8 = 19.4 times larger than in the southern headwaters of the Mississippi River. The flood potential method provides a simple approach for comparing how large floods inherently are across regions and continents, with the wide variability in P_f values highlighting the variability of flooding as detected through the nation's streamgaging network.

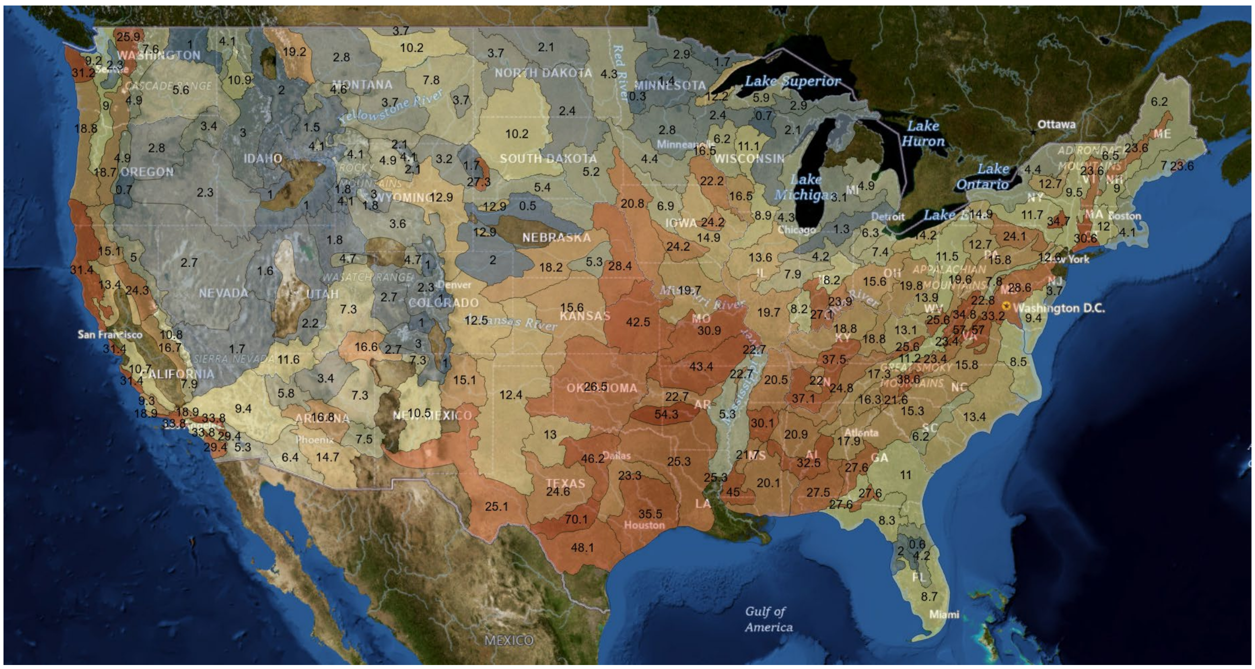


Figure 63: Flood potential index (P_f) variation across the United States. P_f values provide comparisons of flood magnitudes between zones. For example, the southern Ozarks of southern Missouri and northern Arkansas (P_f = 43.4) experiences floods that are 43.4/30.9 = 1.4 times larger than the northern Ozarks (P_f) = 30.9).

Flood Potential Plots

Example flood potential plots for the three zones presented in the above section are provided in Figure 65. A comparative flood potential plot for the three zones is shown in Figure 64, which illustrates how flood potential varies in magnitude between zones, as well how flood magnitudes vary by watershed scale within each zone.

A version of these flood potential plots are available as Zone Information in the Mapping tool. These plots show key results of the flood potential analyses performed for each zone, with the regressions being the expected flood potential, the central tendency of record floods experienced across each zone. Note the varying seasonality of these three zones, with large floods in the Ouachitas occurring almost every month of the year but with three separate seasonal peaks (May, December, March), while the Oregon and Washington Coast Ranges experiencing large floods in the winter (peaking in December), and Mississippi River Headwaters, South experiencing dual peaks (April and July). Where present, low outliers are streamgages where the periods of record apparently do not yet include a larger flood discharge that surrounding streamgaged watersheds across the zone indicate as being expected. The flood potential method assumes that these watersheds are not unique and that a larger event will eventually occur.

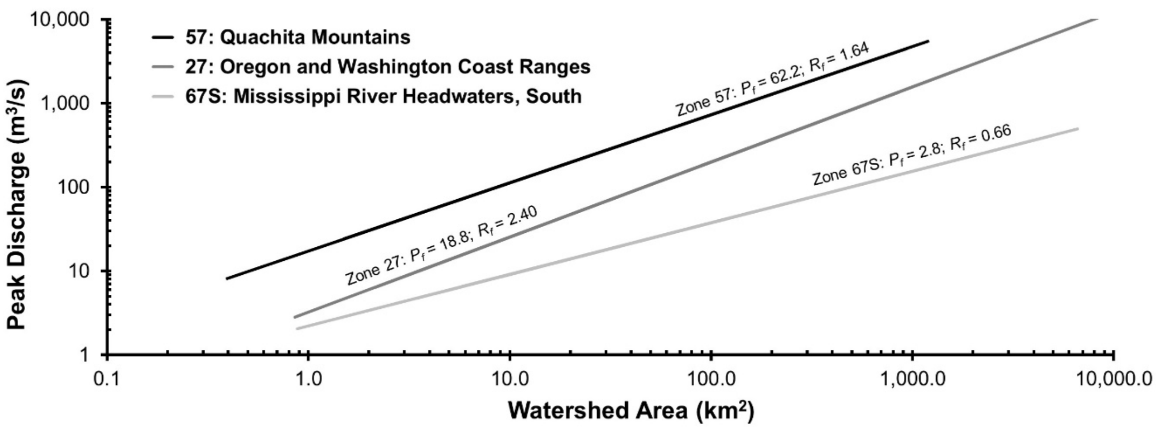


Figure 64: Comparative flood potential plots for zones 57, 27, and 67S. Expected flood potential regression lines are provided along with flood potential index (P_f) and watershed scale ratio (R_f) values.

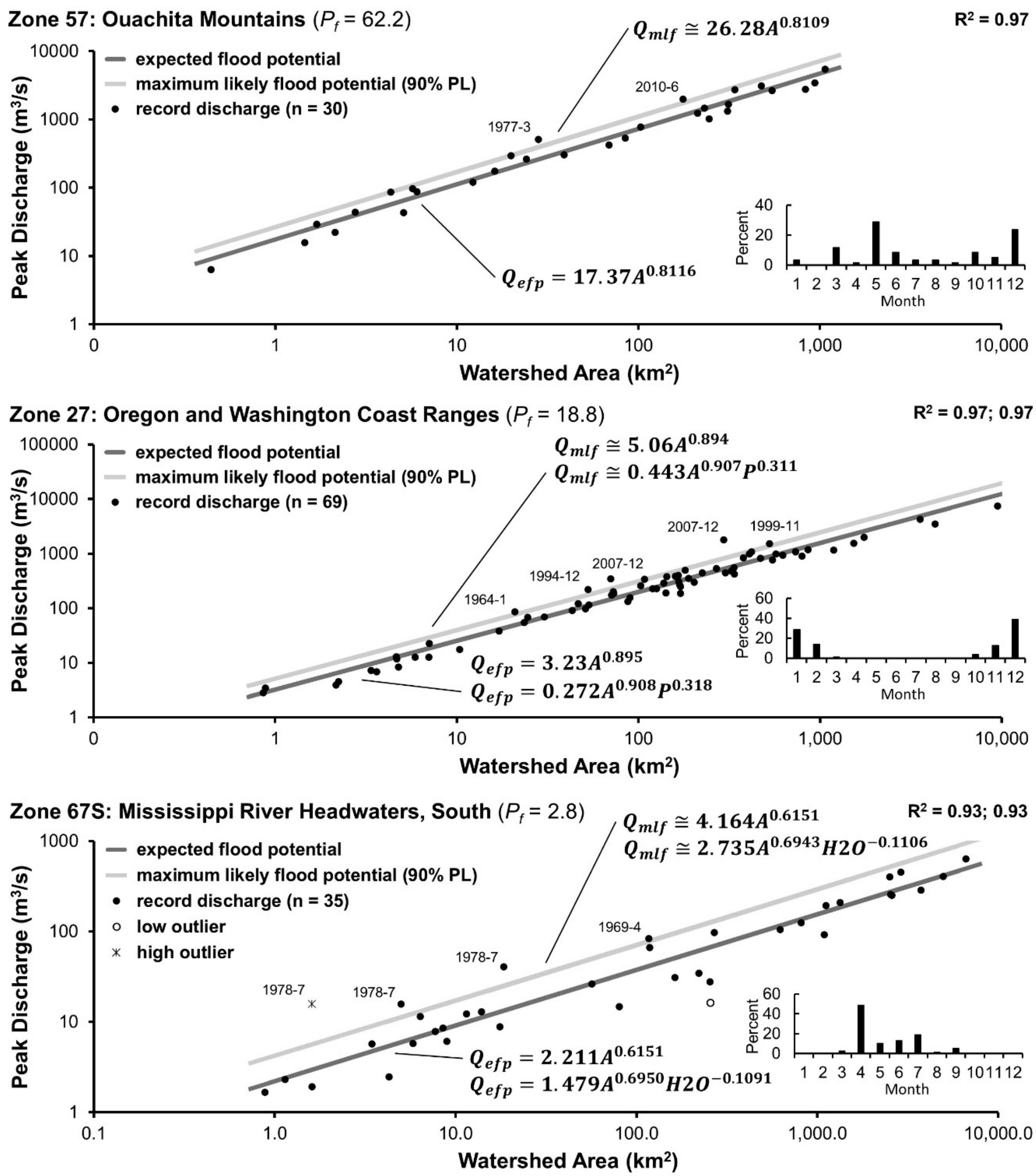


Figure 65: Example flood potential plots for zones 57, 27, and 67S, with prediction equations of the record peak discharges utilizing watershed area (A) and a second predictor (where significant; P: average annual precipitation in mm; H2O: percent of watershed as lake surface). These regression lines quantify the expected flood potential discharge (Q_{efp}), while the upper 90% prediction limit indicates the maximum likely flood potential discharge (Q_{mlf}). Floods greater than this were extreme. The flood potential index (P_f), number of records (n), high and low outliers, year and month of extreme events, and explained variance (R^2) are also provided. For R^2, the 2nd value is for the multiple-variable regression. Seasonality plots of the month of occurrence of the largest 5% floods are additionally shown within each plot.

Watershed Scale Ratio

As an additional metric on how floods vary in space, a plot of watershed scale ratios (R_f) for the analysis extent is provided (Figure 66; Appendix B). Lesser R_f values indicate that smaller watersheds experience relatively large flood magnitudes and greater values indicating that larger watersheds experience relatively large flood magnitudes. Note that the steeper sloped zone 27 flood potential plot (Figure 64) has R_f = 2.40, while the milder sloped zone 67S has R_f = 0.66.

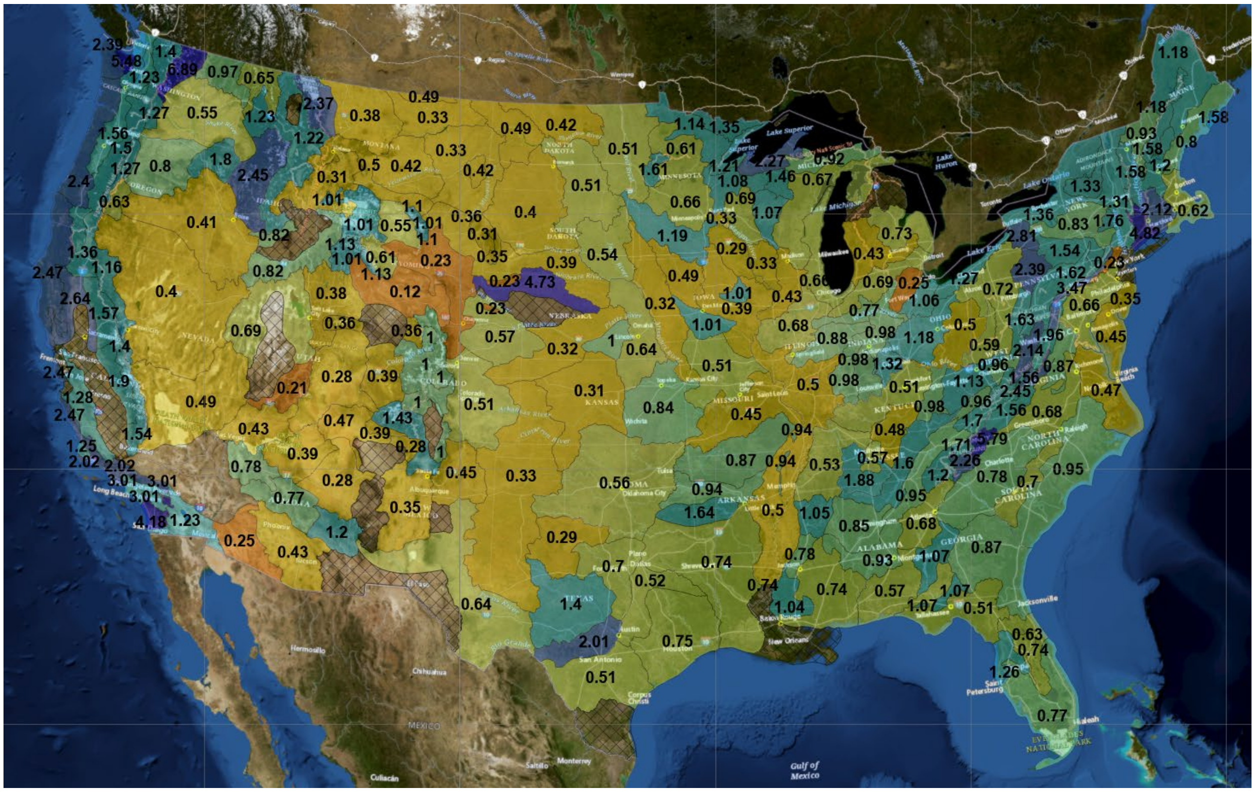
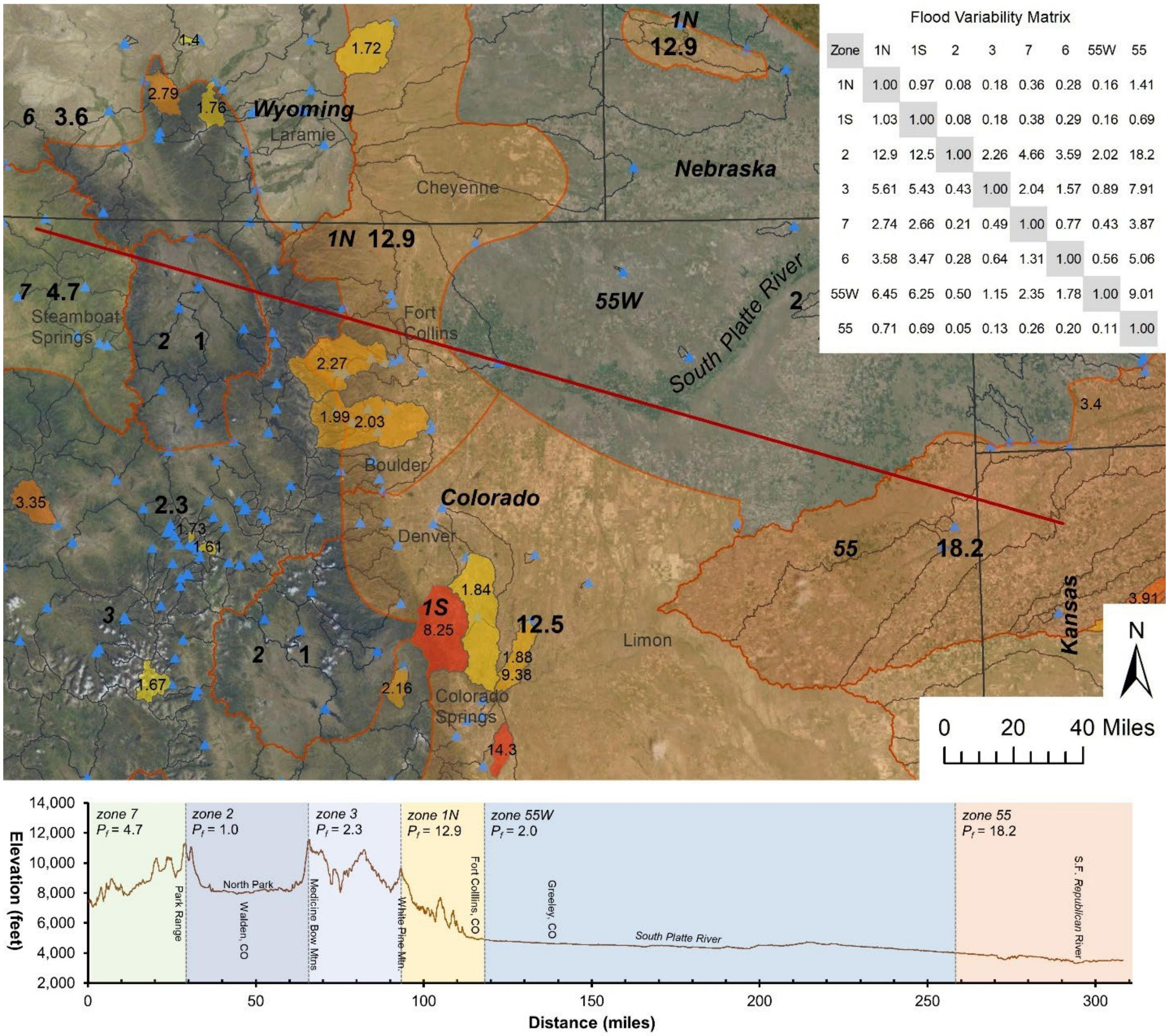


Figure 66: Watershed scale ratio (R_f) variability across the United States.

Example: Rocky Mountain Front

To illustrate the power of the flood potential method in understanding flood variability, a regional example is provided for the Rocky Mountain Front of Southern Wyoming and Colorado (the Colorado Front Range). Zones in this area (Figure 67) have variable flood potential, with floods being up to 12.9 times different in magnitudes (see flood variability matrix). Upslope-driven precipitation is likely the primary process that is inducing the flood potential variability (see cross-section in Figure 67).



Flood Variability Matrix

Zone	1N	1S	2	3	7	6	55W	55
1N	1.00	0.97	0.08	0.18	0.36	0.28	0.16	1.41
1S	1.03	1.00	0.08	0.18	0.38	0.29	0.16	0.69
2	12.9	12.5	1.00	2.26	4.66	3.59	2.02	18.2
3	5.61	5.43	0.43	1.00	2.04	1.57	0.89	7.91
7	2.74	2.66	0.21	0.49	1.00	0.77	0.43	3.87
6	3.58	3.47	0.28	0.64	1.31	1.00	0.56	5.06
55W	6.45	6.25	0.50	1.15	2.35	1.78	1.00	9.01
55	0.71	0.69	0.05	0.13	0.26	0.20	0.11	1.00

Figure 67: Rocky Mountain Front focus region, illustrating flood potential zones with the utilized streamgages (blue triangles) and associated watersheds. Zone IDs are provided (in italics), as well as flood potential index (P_f) values. The cross-section is along the red line, with warmer colors indicating higher flood potential along the Rocky Mountain Front and High Plains. Watersheds that have experienced extreme floods are illustrated, with flood extreme index (E_f) values. A flood variability matrix is also provided, which quantifies the variability in flood magnitudes for the zones of interest in this area.

Floods are generally larger within and east of the Rocky Mountain Front, in more arid areas than core portions of the Rocky Mountains. Lower flood potential exists in the Southern Rocky Mountains (zone 3; P_f = 2.3) as well as in northeast Colorado in the South Platte River valley (zone 55W; P_f = 2.0). Within the Southern Rockies the flood potential is higher in the northwest mountains in the Yampa River Basin (zone

7; P_f = 4.7), with floods twice as large in magnitude than in the Southern Rockies (zone 3), which in turn experiences floods 2.3 times larger than in the reference zone (zone 2; P_f = 1.0). Zone 2 consists of large, high-elevation mountain valleys (e.g. North Park and South Park) that are orographically sheltered from large storm events (see cross-section). Zone 1N is comprised of not only portions of the Rocky Mountain Front, but also includes the higher relief features of Scottsbluff and Pine Ridge, in Western Nebraska.

The flood potential method simplifies analyses for quantifying where existing methods are performing well in characterizing flood hazards, as well where existing methods may be overpredicting or underpredicting. Underprediction is the greatest concern, since such situations lead to less societal resilience to floods, the loss of public and private investment, and the possible loss of human life.

Utilizing the ratio of the expected flood potential discharge to the FEMA regulatory 100-year discharge (Q_{efp}/Q_{100}), the reliability of the FEMA regulatory discharges are plotted for an area along the Colorado Front Range (Figure 68). The green points indicate streams where there is good agreement between the approaches. Blue points indicate areas where the regulatory discharges may be overpredicted, likely due to how extreme events that occurred in 1965 and 1935 were integrated into the analyses. Yellow, orange, and red points indicate streams where the regulated discharges may be underpredicted. This last category is of the highest concern, since these areas will likely have undersized bridges and regulatory floodplains that are not extensive enough to address what may be the true flood risk. Streams that may have underpredicted regulatory discharges include the Cache la Poudre River in Fort Collins (true hazard perhaps 71% larger), and Fall River and Fish Creek in Estes Park (true hazard perhaps 10 times larger). The underprediction will be even more problematic if observed non-stationarity (increasing trends in flood magnitudes) are accounted for in this zone.

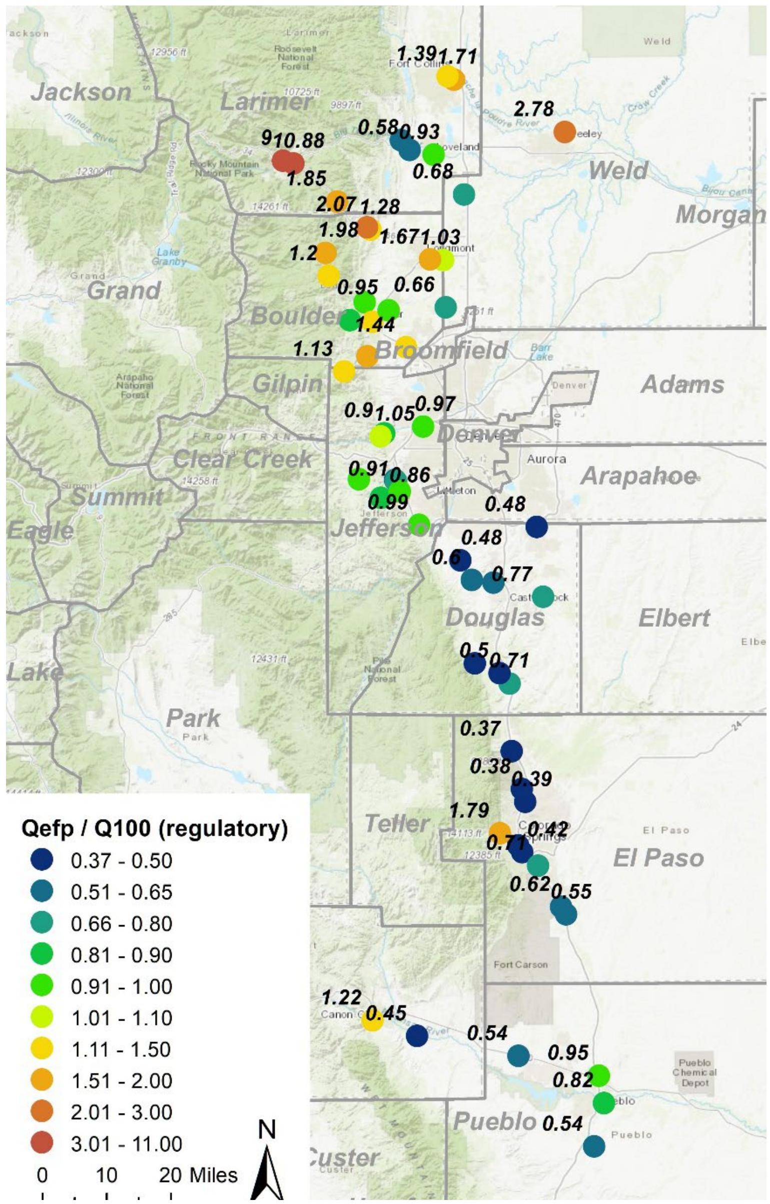


Figure 68: Ratio of expected flood potential discharge (Q_{efp}) to the FEMA regulatory 100-year discharge (Q_{100}) for streams along the Colorado Front Range. Q_{efp}/Q_{100} < 1 indicates possible overprediction, while Q_{efp}/Q_{100} > 1 indicate possible underprediction. The highest values (orange and red points) indicate streams where FEMA discharges may be most underpredicted.

Appendix B: Summary of Indices

The indices used in the flood potential method (and the Flood Potential Portal) are provided in this appendix, for ease of reference.

The flood potential index (P_f) ranks and compares experienced flood magnitudes between zones. Higher values indicate higher flood potential. This index is defined as:

Equation 4

$$P_f = \frac{\left(\frac{Q_a}{Q_{a,zone2}} + \frac{Q_b}{Q_{b,zone2}} + \frac{Q_c}{Q_{c,zone2}}\right)}{3}$$

where a = 20 km^2, b= 200 km^2, c = 2000 km^2 and $Q_{20,zone2}$ = 4.15 m^3/s, $Q_{200,zone2}$ = 21.0 m^3/s, and $Q_{2000,zone2}$ = 106 m^3/s. Where the largest watershed size within a zone is <1100 km^2, the Q_c term is assumed to be excessively extrapolated and dropped, with the utilized equation becoming:

Equation 5

$$P_f = \frac{\left(\frac{Q_a}{Q_{a,zone2}} + \frac{Q_b}{Q_{b,zone2}}\right)}{2}$$

As an example on how P_f is utilized for comparison, consider the Ouachita Mountains (zone 57; P_f = 54.3), and the Mississippi River Headwaters, South (zone 67S; P_f = 2.8). The Ouachitas experience some of the largest floods within the continental United States, as indicated by the high flood potential index. Floods in the Ouachitas are, on average, 54.3/2.8 = 19.4 times larger than in zone 67S.

The watershed scale ratio (R_f) quantifies the slope of the flood potential curve, with lesser values indicating that smaller watersheds experience relatively large flood magnitudes and greater values indicating that larger watersheds experience relatively large flood magnitudes. This index is defined as:

Equation 6

$$R_f = \frac{Q_c}{Q_{c,zone2}} \Big/ \frac{Q_a}{Q_{a,zone2}}$$

Zone 1N is in an area where R_f is low (0.23). In such a zone, it can be unexpected to discover that the Q_{efp} for a smaller watershed is not a great deal smaller than the Q_{efp} for a much larger watershed. For example, in the Buckhorn Creek watershed west of Fort Collins, Colorado, Q_{efp} = 3290 cfs for Sheep Creek, a 7.7 mi^2 headwater watershed, and Q_{efp} = 10,300 cfs for the 145 mi^2 Buchhorn Creek watershed just above the Big Thompson River confluence.

Flashiness is a measure of the frequency and rapidity of short-term changes in streamflow. A flashy stream responds to precipitation by rising and falling quickly. Two indices used in the Flood Potential Portal to quantify flashiness are Beard F index (Beard,1975) and the Richards-Baker index (Baker et al., 2004). Provided values in the Portal are the averages for each zone. Importantly, these indices are measures of the variability in the discharge data, rather than rates of hydrograph rise. The Beard F equation is:

Equation 7

$$F = \left[\frac{\sum (X_m - M)^2}{N - 1}\right]^{1/2}$$

where X_m is the natural logarithm of the annual maximum flood, M is the logarithm of the mean annual maximum flood, and N is the number of annual events. This index is the standard deviation of the natural logarithms of the annual peak flows at each streamgage; the Beard index quantifies flashiness using variability in annual peak discharges.

The Richards-Baker Flashiness Index (*R-B Index;* Baker et al., 2004) is:

Equation 8

$$R - B\ Index = \frac{\sum_{i=1}^{n} |q_i - q_{i-1}|}{\sum_{i=1}^{n} q_i}$$

where q is the mean daily discharge. The R-B Index quantifies flashiness using variability in daily average discharges. The R-B flashiness index is unitless and its value is independent of the units chosen to represent flow. Values can range from zero to two, with zero meaning the streamflow was constant. Streamgages must have at least 30 years of daily data.

The flood variability index (V_f) is computed as a ratio of the intercepts for the regressions for the maximum likely flood potential and the expected flood potential, specifically:

Equation 9

$$V_f = {a_{mlf}}/{a_{efp}}$$

where a is the intercept term in the single-predictor regression equation $Q = aA^b$, for each zone.

The flood hazard index (H_f) provides an index that subsumes both flood magnitude and flashiness, with higher values indicating greater hazard. This index is computed as:

Equation 10

$$H_f = P_f * F$$

The flood extreme index (E_f) ranks flood magnitudes and extremity, with higher values indicating larger or more extreme events, and values less than 1 indicating a flood is less than the expected flood potential discharge. This index is:

Equation 11

$$E_f = {Q}/{Q_{efp}}$$

The bimodality index (B_i) is the ratio of the largest measured annual peak discharge to the typical (median) annual peak discharge. Averages of each of these streamgage index values are made for each zone. Higher zone average B_i indicate that the largest floods are much larger that more typical flood magnitudes, due to different flood-producing meteorologic and hydrologic mechanisms. This index is similar to the upper tail ratio (Smith et al. 2018). The bimodality index is computed as:

Equation 12

$$B_i = {Q_{max}}/{Q_{median}}$$

where Q is the streamgage annual peak discharges. Streamgages with zero discharges included as the annual peak have these zero years excluded from the median computations.

Appendix C: Zone Delineations

Zones of relatively consistent flood hazards were identified, for defining the consistency (within zone) and variability (between zones) of expected flood magnitudes and other attributes. Zone boundaries are typically breaks in slope, including ridgelines (watershed boundaries), base of mountain slopes and hillslopes, and rivers. Zone boundaries may shift over time, as new floods occur (more data are available), and as climate change potentially modifies precipitation patterns and the hydrologic response. Hurricane Helene-induced flooding resulted in shifts in zone boundaries in Western North Carolina, for example, when these new data were incorporated into analyses in 2025, using water year 2024 data.

The ArcGIS shapefile (FloodPotential_Zones) is available for download from the flood potential project page. The attributes of this shapefile are defined in Appendix H.

Zones were heuristically delineated using the maximum measured (record) discharge at each streamgage, with the procedure consisting of:

1. Based on physiographic provinces and sections, watershed boundaries and topographic features, average annual precipitation, seasonality, and a flashiness index (Beard, 1975), the center of an assumed zone was identified.
2. From this geographic center, a plot of the maximum measured streamflow versus watershed area was created, using watersheds of a variety of scales and including all streamgages with ≥40 years of data, as well as gages with ≥10 years of data where large floods had been experienced.
3. Exploratory regressions were evaluated as individual streamgages were added, with a visual assessment of fit within the existing variability and changes in the explained variance (R^2) utilized to evaluate, as each was added, if this watershed was part of the same zone or, alternatively, part of an adjacent zone. Special attention was paid to where the largest watersheds consistently plotted below the regression line, to identify where to place a limit on contributing watershed sizes.
4. Assumed centers of adjacent zones were identified and steps 1 to 3 were applied for new zone.
5. In boundary areas, consistency with exploratory regressions was used to decide which zones a particular watershed should be included within. These assessments were done as groupings of streamgaged watersheds, to identify consistent plotting above or below the existing regressions, to place grouping of streamgaged watersheds between the adjacent zones and identify zone boundaries. Secondary and tertiary streamgage peak flow values were inspected to assess if the record peak discharge was atypically large (and a potential extreme flood). If a streamgaged watershed has a mixed flood response between two or more zones, either the dominant zone was used or the watershed was not utilized. These situations were used as opportunities, in combination with topographic information, to refine the zone boundaries.
6. Iterative checks on fit were performed (as additional streamgages were assigned to each zone) to reevaluate if the zone boundaries are most appropriate, with revisions that swapped streamgages between zones, identified new zones, and consolidated zones. Flood seasonality was also assessed to identify if a preliminary zone should be split or merged.

All streamgages with 40 or more years of data were required to be included in the analyses (to minimize bias), unless a specific streamgage was redundant with other nested streamgaged watersheds, measured flow for a watershed included more than one zone (with no single dominant zone), or a watershed was overly influenced by urbanization or reservoir storage. Exclusion also occurred in cases where a discharge had not been estimated for a high value record stage, or where a streamgage predominantly measured spring outflow.

Appendix D: Extreme Floods

A valuable attribute of the flood potential method is the ability to systematically define and rank extreme floods. This capability allows communication that makes distinctions between large floods, that may be record setting for a specific streamgage but not extreme, and extreme floods as systematically identified and ranked across zones of similar flood response. In regard to infrastructure, large floods are designed for while extreme floods are of a scale inappropriate for design in most situations.

Extreme floods experienced at streamgages throughout the contiguous United States with at least 10 years of record were identified and ranked (Figure 69). These extreme floods can also be plotted within the Portal, by viewing standard layers. Extreme events are relative to the zone that their watersheds fall within, and are identified by having experienced discharges greater than the upper 90% prediction limit of the expected flood potential regressions ($Q > Q_{mlf}$). Zonal watersheds experience floods that appear to be constrained by an upper bound in flood magnitudes (Enzel et al., 1993; Yochum et al., 2019), with extreme events defining this upper limit (the envelope curve) – not only is the central tendency of large flood magnitudes (the expected flood potential) an inherent and well defined characteristic of a zone, but the upper bound in flood magnitudes may also be an inherent characteristic determined by limits in the supply of precipitation and watershed response. This contrasts with a flood-frequency perspective, which essentially assumes an unbounded distribution with a non-zero probability of an ever larger flood occurring (Enzel et al., 1993), no matter what the magnitude. Paleoflood data have also supported the concept of bounded floods within flood potential zones (Yochum et al., 2019).

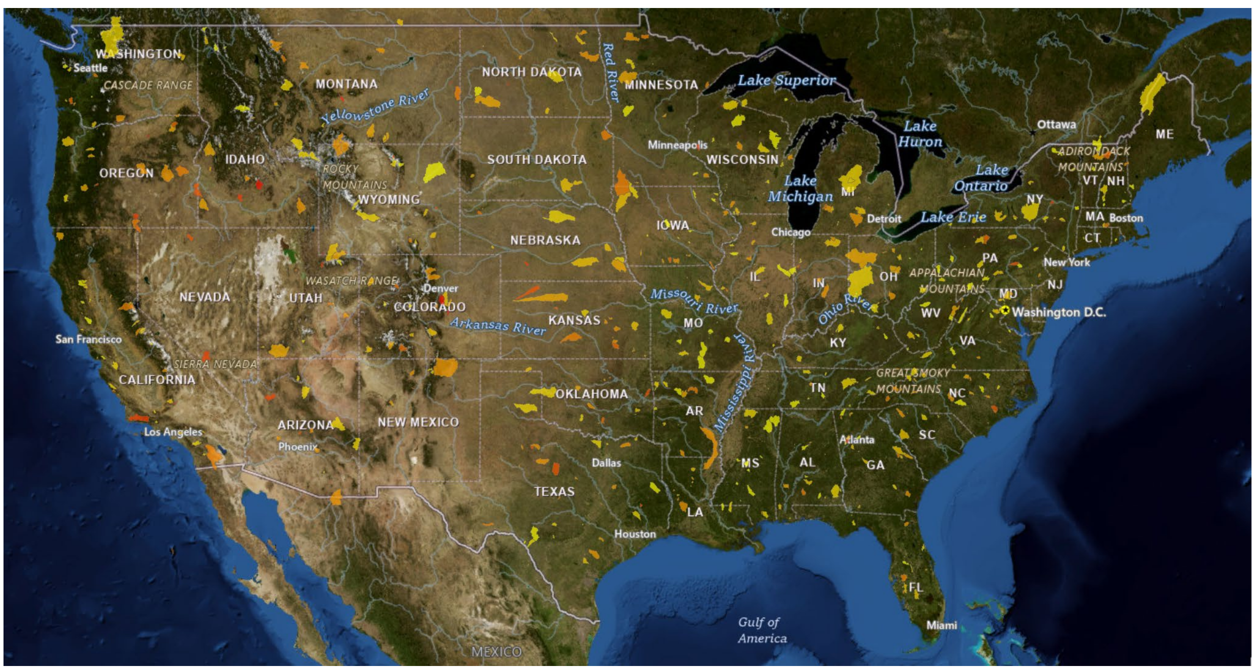


Figure 69: Watersheds that have experienced an extreme flood within the contiguous United States (using data collected through the 2024 water year), with warmer colors indicating greater extremity. The most extreme floods occur more commonly in more arid areas of the United States, though with exceptions including a cluster in Wisconsin and Minnesota.

Ranking of extreme floods is performed using the flood extreme index (E_f), with higher values indicating greater extremity. The E_f value is a multiplier of the Q_{efp}. For example, a watershed that has experienced an E_f = 5.0 has experienced a flood 5 times the magnitude of the expected flood potential discharge. These extreme floods are relative to the large flood magnitudes streamgage records indicate as being typical in each zone, and are not reliant on flood-frequency (Smith et al., 2018) or hydrologic modeling (Tarouilly et al., 2021) approaches for identifying and ranking unusually-large floods.

Western United States Summary

The most extreme floods have been documented in the western United States (Figure 70). Within this extent, extreme floods have had E_f values ranging from 1.23 to 35.4 (averaging 2.7). Areas that experience clusters of higher flood extremes include southern Nebraska, along the Rocky Mountain Front (see next section), in the vicinity of the Uinta Mountains, the Columbia Plateau, west of Carson City near Lake Tahoe, and in Southern California. Areas with less average annual precipitation have experienced floods that are most extreme (Figure 71), with generally lesser E_f values in watersheds that experience higher average annual precipitation.

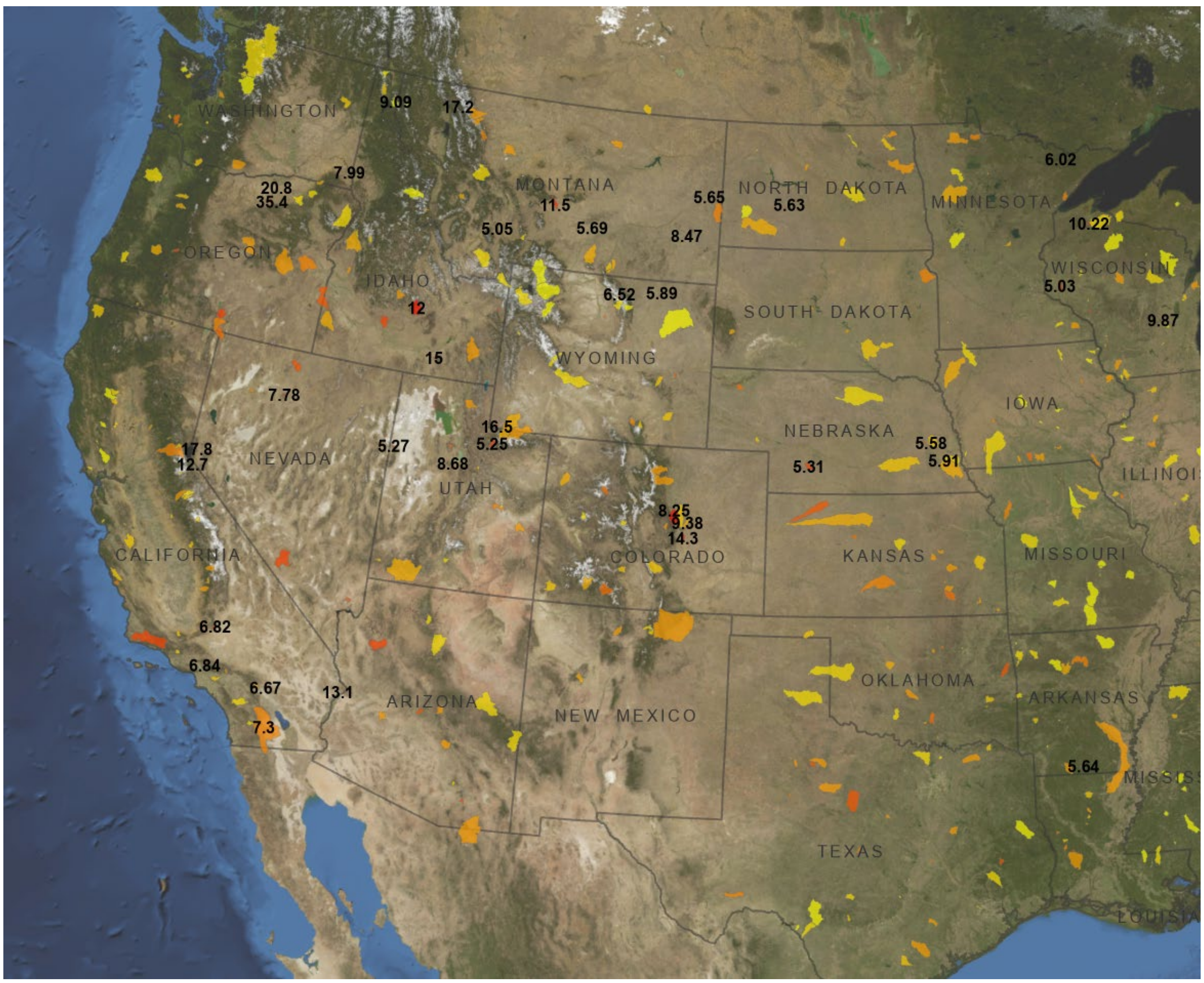


Figure 70: Watersheds that have experienced identified extreme floods in the western United States (using data collected prior to 2022). These watersheds have warmer colors where the flood extreme index (E_f) is higher (where floods are more extreme), with E_f labeled where >5.0.

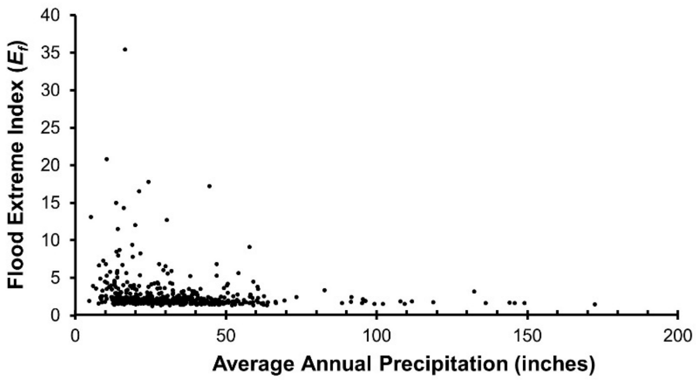


Figure 71: Flood extremity (E_f) versus average annual precipitation, for 502 detected extreme floods in the western United States.

The Columbia Plateau has experienced the most extreme floods. Floods on the Columbia Plateau are variable, and with lesser flood potential that increases to the north across the three zones (30S, P_f = 2.3; 30, P_f = 2.8; 36, P_f = 5.5; Figure 62, Figure 63). In the southern portion of these zones, extreme flood have predominantly occurred in larger watersheds (400 to 850 mi^2), with E_f ranging from 1.89 to 3.55. In the northern portion of these zones, extreme floods have predominantly occurred in smaller watersheds (1.4 to 59 km^2) on sloped transitional terrain rising from the Columbia and Snake Rivers into the Blue Mountains of Oregon. This area hosts the two most extreme floods (E_f = 35.4, June 1903, Balm Fork near Heppner, OR; E_f = 20.8, June 1948, Butter Creek tributary near Pine City, OR), in zone 30. Two other higher extreme floods have also been recorded in this area (E_f = 7.99, August 1976; E_f = 5.78, June 1978), with additional events in summers of 1956, 1965, and 1971 (Smith et al., 2018). These extreme events occurred during a secondary flood season for zone 30, with the primary season of this zone occurring during the winter from atmospheric river activity. The Heppner flood of 1903, which claimed 250 lives, was a flashy event generated from a hail-storm that occurred during a ~30-minute duration, 3 to 7 km wide, super-cell thunderstorm that moved south to north down the arid to semi-arid watershed, accentuating the flood response (Smith et al., 2018). In contrast with this transition area, within the Blue Mountains zone (35; P_f = 3.2) large floods are consistent and have low extremes (E_f ranging from 1.62 to 1.66), with primary and secondary seasonality of late spring and winter, respectively.

Example: Rocky Mountain Front

Areas where there are clusters of more extreme floods include along portions of the Rocky Mountain Front (Figure 70). The northern Rocky Mountain Front and Northern Rockies, in vicinity of Glacier National Park, Montana (zone 48N) have recorded both a cluster of moderately-extreme floods (E_f ranging from 2.09 to 3.00) and a highly extreme flood (E_f = 17.2), in an area that has the highest flood potential in the Rocky Mountains (P_f = 19.2). These extreme floods all occurred during one meteorological event in June 1964, which was due to an influx of moist air from the Gulf of Mexico driven easterly (upslope) by several mechanisms, including a low-pressure system over Wyoming (Boner and Stermitz, 1967). The flood potential index of 19.2 indicates that floods are high in this zone compared to neighboring zones, but flood extremes well beyond the high central tendency of this zone are also possible. Additionally, considering a similar flood event that occurred in June 1975 that also induced record flooding, the June 1964 event and resulting extreme floods should not be considered unique.

Extreme floods are also prone to more southern portions of the Rocky Mountain Front, though the degree of extremity varies (Figure 9). Floods occurring in zone 1S, along the southern portion of the Colorado Front Range, have been more extreme than in the north, in zone 1N. Specifically, the floods of May 1935 and June 1965 in the vicinity of Colorado Springs, Colorado were some of most extreme recorded in the contiguous United States. Specifically, floods with E_f = 8.3 occurred on Plum Creek (6/16/1965; 154,000 cfs), E_f = 14.3 on Jimmy Camp Creek (6/17/1965; 124,000 cfs), and E_f = 9.4 on Kiowa Creek (5/30/1935; 43,500 cfs). The Jimmy Camp Creek flood is one of the most extreme flood on record, with a magnitude more than 14 times what is expected. Interestingly, two extreme events of similar magnitude (E_f = 9.4 and 8.9) occurred on Kiowa Creek at the same location (ID: 06758000), in 1935 and 1965. Considering these streamgage records, as well as other earlier large floods that have occurred in the area (in 1864, 1896, 1904, 1912, and 1921; Dollman, 2017), this area (the Palmer Divide and surrounding areas along the Colorado Front Range) appears to be especially vulnerable to some of the most extreme floods in the United States, which is a matter of special concern for the management of stream corridors and such structures as high hazard dams in this heavily-populated area. However, the decreasing magnitude and frequency of large floods in this area and the lack of extreme events since 1965 suggests that floods may be decreasing in severity.

Compared to zone 1S to the south, the floods of September 2013 and July 1976 in zone 1N in the foothills and along the Front Range between Boulder and Fort Collins were less extreme (E_f ranging from 1.99 to 2.27; Figure 9), though still catastrophic (Jarrett and Vandas, 2006; Yochum et al., 2017). The 1976 Big Thompson Flood claimed 144 lives, and the 2013 Front Range Flood had large impacts on roads and communities in the foothills (Figure 72) and adjacent High Plains. The Spring Creek Flood in Fort Collins in July of 1997 (which claimed 5 lives) was extreme (E_f = 2.73), with Q = 8300 cfs > Q_{mlf} = 4800 cfs (Grigg et al., 1998), but still less so than floods experienced in zone 1S.

Figure 72: Impacts of the Front Range Flood on West Creek in Glen Haven, Colorado (September, 2013). At this location, the flood was not extreme (E_f = 1.40; Q = 7300 cfs < Q_{mlf} = 8200 cfs), but the impacts on the community were catastrophic.

Spring and summer floods along the Colorado Front Range and adjacent portions of the Rocky Mountain Front are driven by synoptic events, with the 1965 event associated with an intense cutoff western low that steered warm, moist, unstable air into Eastern Colorado and a blocking pattern forcing a cold front to be stationary for three days, inducing extreme rains (Hirschboeck, 1987). A similar synoptic pattern induced the 2013 Colorado Front Range flood (Gochis et al., 2015), and the 1935 event may have been similar in development.

Example: Probable Maximum Flood Verification

Extreme floods are of a magnitude exceeding what is typically reasonable for floodplain management and infrastructure design. There are, however, important exceptions to this, such as high hazard dams and nuclear power plants. In these cases, it is standard practice to utilize probable maximum precipitation estimates and rainfall-runoff modeling to estimate probable maximum flood (PMF) magnitudes for these most hazardous structures. The occurrence of extreme events (and the highest E_f values) that have been experienced within a flood potential zone can be valuable for independently verifying these PMF estimates. This can be performed using a simple analysis, as the example below illustrates. Alternatively, a more complex procedure such as stochastic storm transposition (Wright et al., 2020) could be applied within a flood potential zone, based on observed extreme floods.

Consider Spirit Lake at Mount St. Helens, Washington, which was dammed during the 1980 eruption by landslide blockage across the headwaters of the North Fork Toutle River (Figure 73). The lake level is currently maintained by a tunnel, to prevent a catastrophic failure of this natural dam and a resulting lahar (volcanic mudflow) that would threaten thousands of lives. Seven extreme floods have occurred in this zone 28 (P_f = 18.7), with E_f ranging from 1.65 to 3.19.

Figure 73: Spirit Lake at Mount St. Helens.

Possibly increasing trends in the largest quarter of annual peak discharge magnitudes have been observed (Q4, >4 year return interval: +1.8%), as well as events with 2 to 4-year return interval (Q3: +0.4%), with more frequent events experiencing decreasing trends. However, these trends in magnitude are minimal, and there are no trends in frequency or flashiness in this zone; stationarity may be a reasonable assumption, though increasing magnitudes by 1.8% could be justifiable.

The most extreme flood (E_f = 3.19) occurred on January 20, 1972 for a 8.1 mi^2 watershed (ID 14138900). With an assumption that this event is on the envelope curve, and considering that Q_{efp} = 5800 cfs for the 18.6 mi^2 Spirit Lake watershed, the maximum flood size that the streamgage record indicates as being possible for Spirit Lake is 5800*3.19 = 18,500 cfs (18,800 cfs with application of the Q4 percent increase). These values are very similar with the computed probable maximum flood size (Q = 20,100 cfs; USACE, 2017) as lake input – streamgaging data indicate that the probable maximum flood estimate is reasonable.

Appendix E: Flood Trends

The flood potential method provides a framework for monitoring flooding to identify areas where there are changes over time. This approach accounts for flood variability by zone while maximizing statistical power for identifying trends due to climate change and other non-stationary mechanisms (Milly et al., 2008; Lins and Cohn, 2011; Galloway, 2011), for understanding which zones are experiencing shifts in flooding as observed through the nation's streamgage network. These results provide the opportunity to monitor and adjust for non-stationarity.

Trends in five ranges of flood magnitudes, annual flood-frequency, event flood-frequency, and flashiness are presented as zone attributes within the mapping tool of the Flood Potential Portal. These analyses are for large floods of the scale appropriate for the infrastructure design and floodplain management, as well as for more frequent events, from a 4 year (25% chance of annual occurrence) to a <1.33 year (75% chance of occurrence) annual peak discharges.

Monotonic trends in magnitudes and frequency were tested using both parametric and non-parametric procedures, using ordinary least squares regression (linear) and Mann-Kendall tests (non-parametric; Kendall, 1975; Mann, 1945). Tests for trends in flood magnitudes were evaluated using Mann-Kendall (for analysis periods ending in 2023 or later) or ordinary least squares regression (for analysis periods ending in 2022 or earlier). Event-scale zonal frequency trends were computed using Mann-Kendall, while annual frequency trends were tested using either Mann-Kendall (for analysis periods ending in 2023 or later), or linear models (for analysis periods ending in 2022 or earlier) using natural log-transformed data. Trends are reported as significant if p-value ≤ 0.05 = α, and possible where 0.05 < p-value ≤ 0.15.

Trends in flood magnitudes were assessed on a zonal basis using flood extreme index values (E_f; Appendix B). The E_f index normalizes discharges within and between flood potential zones through use of the expected flood potential discharge (Q_{efp}) for each location. Streamgages can be then grouped to perform analyses across each flood potential zone to increase statistical power and trend detection capability, while also permitting separate analyses of floods of differing severities. Five trends in flood magnitude have been computed and are presented within the Portal, specifically:

- Q5: Least frequent (largest) 5% of all zone annual peak discharges; all E_f values with probability ≤ 0.05; appropriate for the selection of design flood discharge for infrastructure design
- Q4: Least frequent (largest) quarter of all zone annual peak discharges; all E_f values with probability ≤ 0.25 (3rd quartile of E_f values); floods with return interval ≥ 4 years; appropriate for the selection of design flood discharge for infrastructure design
- Q3: Larger quarter of moderately frequent annual peak discharges; all E_f values with probability ≤ 0.50 (2rd quartile of E_f values, median) and > 0.25 (3rd quartile of E_f values); floods return interval ≥ 2 year and <4 year
- Q2: Smaller quarter of moderately frequent annual peak discharges; all E_f values with probability ≤ 0.75 (1rd quartile of E_f values) and > 0.50 (2rd quartile of E_f values, median); floods return interval ≥ 1.33 year and <2 year (bankfull-scale flood)
- Q1: Most frequent (smallest) quarter of all zone annual peak discharges; all E_f values with probability > 0.75 (1rd quartile of E_f values); floods with return interval <1.33 year (less than bankfull-scale flood, lowest annual peak discharges, dry-years annual peak discharges)

The three quartile divisions were computed from the Weibull plotting position for each annual peak discharge value, for each flood potential utilized streamgage.

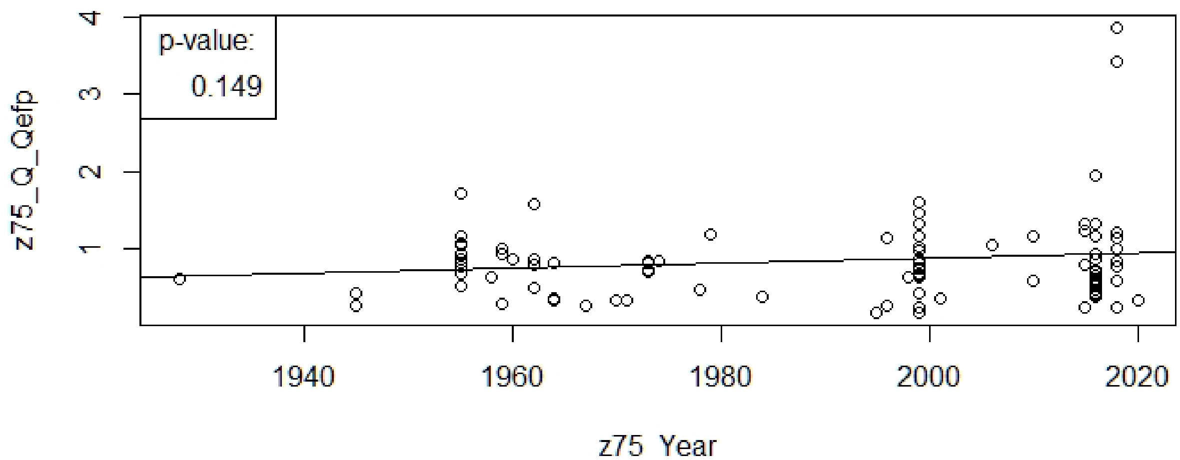
Trends in magnitude were performed using ordinary least squares regression (linear) for analyses completed through WY2022, or Mann-Kendall (nonparametric) test for zones with analysis periods ending in WY2023 and later. (Flood potential analyses were completed for the contiguous United States using streamgage data collected through WY2022, after which updates of a portion of the zones was completed each year.) See the analysis end years in the zone summary tab of the mapping module.

Plot illustrating trends are provided for each analysis (available on-hover within the Mapping module), with provided p-values for the plotted linear line. These figures are plotted with the x-axis being the year (showing the analysis period) and the y-axis being E_f (Q/Q_{efp}).

Where trends are significant or possible (as determined using p-values from linear analyses for zones with analysis periods ending in WY2022 or earlier, or Mann-Kendall analyses for periods ending in WY2023 or later), percent change is computed by comparing E_f values between the most recent 30-years of record and the entire record. Example analysis results are provided in Figure 74 and Figure 75, for zone 75 (Southern Atlantic Coastal Plain) and zone 27 (Oregon and Washington Coast Ranges). These plots can be copied to the clipboard or saved from the on-hover display within the mapping module. Trends are reported as significant if $p\text{-value} \leq 0.05 = \alpha$, and possible where $0.05 < p\text{-value} \leq 0.15$.

Increasing trends in large flood magnitudes (Q5, Q4) can be accounted for in the selection of design flood and base flood discharges, through application of the observed percent change to the base values. These adjustments have been performed automatically within the watershed analysis module for the flood potential results, but are not automatically applied for the flood-frequency results; the user should consider manual application. Importantly, a professional should be wary of adjusting for decreasing trends – while non-stationary mechanisms such as flood control reservoir storage and attenuation may be appropriate to account for, other mechanisms are less clear. An assumption that decreasing trends are the result of climate change can be problematic (and not conservative), since such trends may be due to climate variability (a long drought) rather than climate change.

Trends in the frequency of floods were evaluated using both annual and daily data, with separate analyses that counted zonal floods in each year that exceeded a threshold based on a fraction of the expected flood potential discharge at each streamgage. Trend in annual frequency are provided in trend plots for each analysis (which are available on-hover within the Mapping module). The period of the frequency analyses was from 1945 to the end of the analysis period (varies from 2016 to the most recent water year); the utilized period for the annual analyses can be observed from the on-hover plots, and is presented under the zone summary information of the Mapping module. The daily analyses included only one peak within a 15-day period (event), to avoid multiple counts during individual flood events. Additionally, there are substantial variabilities in streamgaging periods and record lengths within each zone, with a trend of reduced data collection over the last 50 years (Yochum et al., 2019); the frequency trend analyses corrected for this by dividing the annual counts by the number of streamgages operating in each year. Example analysis results for the annual trend analyses are provided in Figure 76 and Figure 77, for zone 59N (Ozarks, North) and zone 15 (Rio Grande Basin).



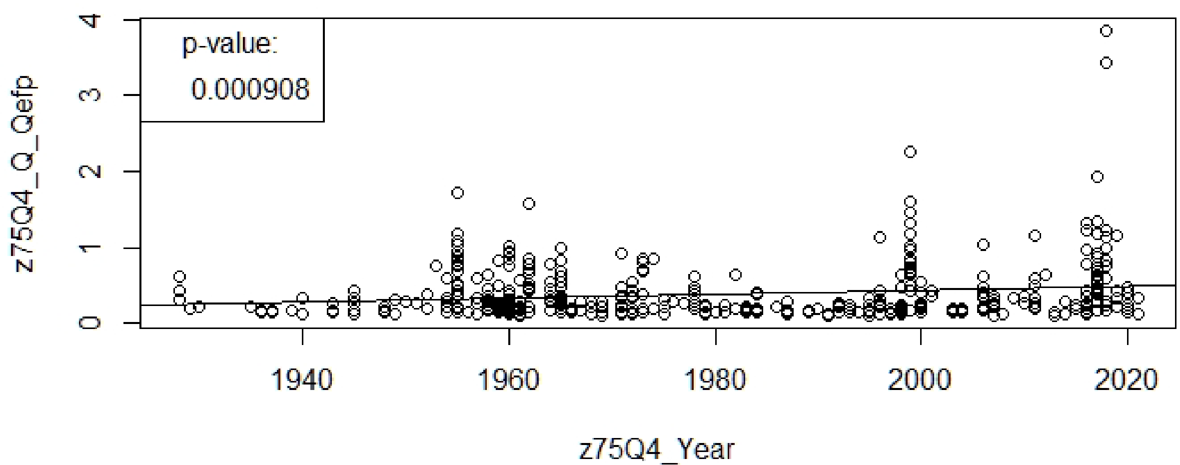
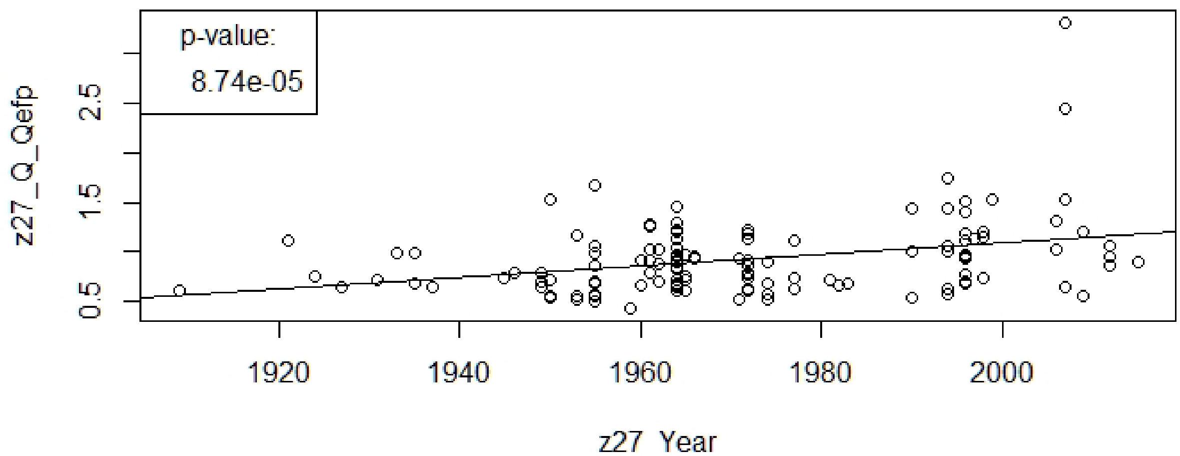


Figure 74: Trend results for large flood magnitudes within zone 75 (Southern Atlantic Coastal Plain), for both the largest 5% (upper) and largest quarter (lower) of annual peak discharges, using flood extreme index values for all flood-potential utilized streamgages. The Q5 data (largest 5%), a possible trend (p-value = 0.149 < 0.15), indicate a 8.4 percent increase in the magnitude of large floods. The Q4 data (largest quarter), a significant trend (p-value = 0.00091 < 0.05) indicate a 17.5 percent increase. These percent change values are computed using the most recent 30 years of data compared to the entire record. Extreme floods experienced during hurricane Florence (9/2018) are evident in these plots, as are the large floods experienced in 1999 (Hurricane Floyd), and in 1954 (Hurricane Hazel). These trend results support a hypothesis that large riverine floods in this portion of the Atlantic coastal plain are becoming more severe due to intensifying hurricanes from climate change.



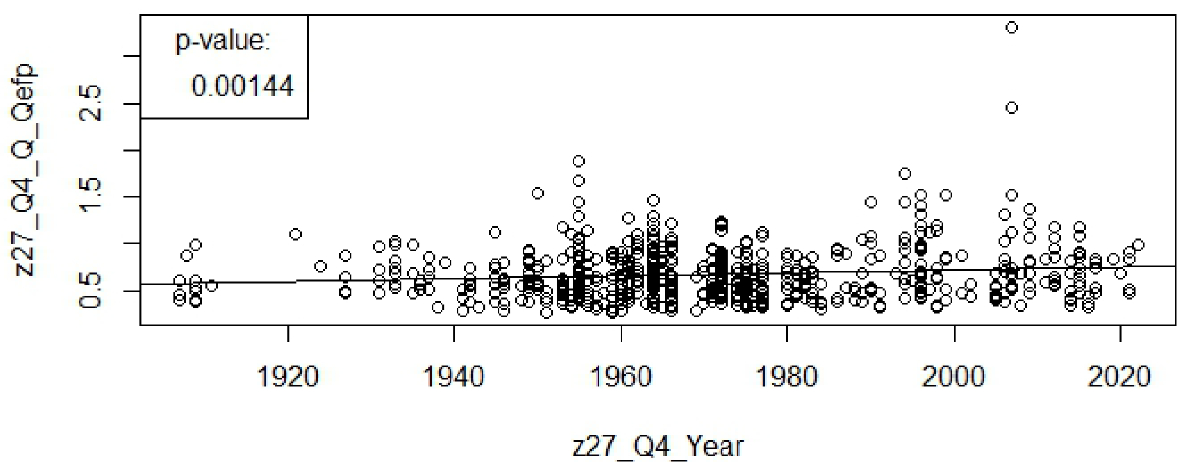


Figure 75: Trend results for large flood magnitudes within zone 27 (Oregon and Washington Coast Ranges), for both the largest 5% (upper) and largest quarter (lower) of annual peak discharges, using flood extreme index values for all flood-potential utilized streamgages. The Q5 data (largest 5%), a significant trend (p-value = 0.000087 < 0.05), indicate a 23.4 percent increase in the magnitude of large floods. The Q4 data (largest quarter), a significant trend (p-value = 0.0014 < 0.05) indicate a 14.1 percent increase. These percent change values are computed using the most recent 30 years of data compared to the entire record.

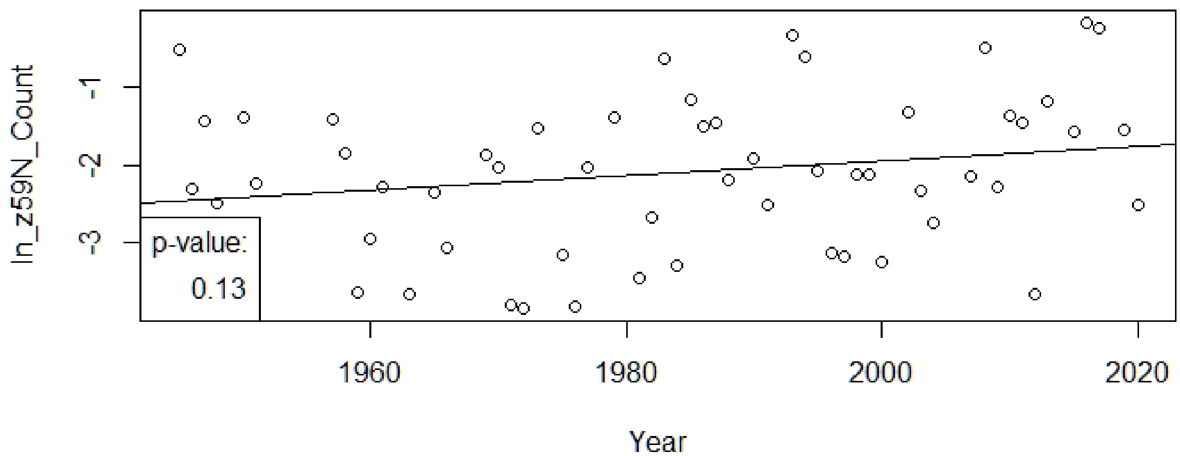


Figure 76: Frequency trend results for events with Q > 0.5*Q_{efp} for a period from 1945 through 2020 in zone 59N (Ozarks, North). Possibly increasing trend (0.05 < p-value = 0.1301 < 0.15), with a slope = +0.0093.

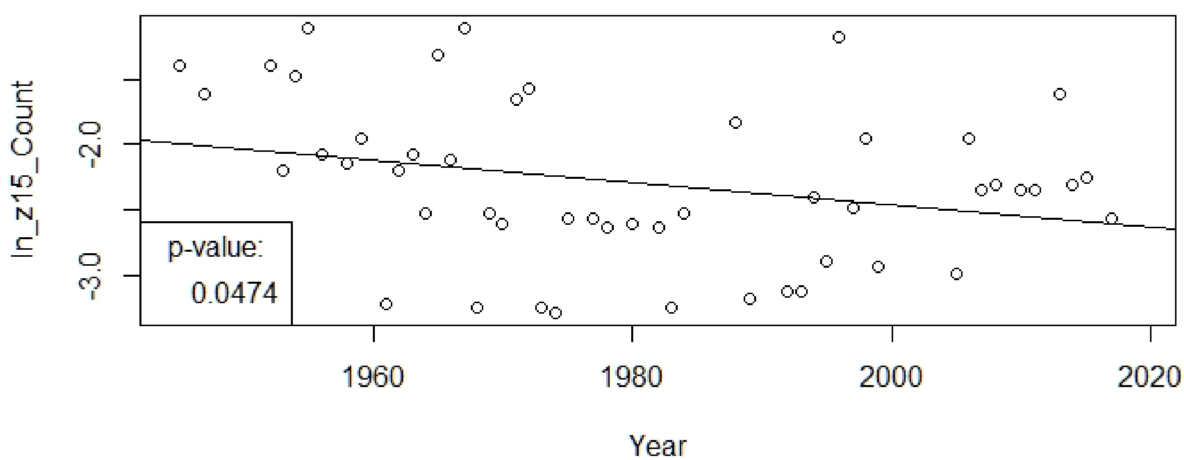


Figure 77: Frequency trend results for events with Q > 0.5*Q_{efp} for a period from 1945 through 2019 in zone 15 (Rio Grande Basin). Significantly decreasing trend (p-value = 0.047 < 0.05), with a slope = -0.0085.

Trends in flashiness were computed using the Richards-Baker (R-B) flashiness index (Baker et al., 2004; Appendix B). For this trend analysis, only streamgages in operation for 30 water years within the most recent 40 years (generally, 1982-2021) were included in this analysis, though analyses were performed for the entire available record of average daily discharge for each utilized streamgage within each zone (see analysis periods in the Zone Summary information). For each streamgage, the significance of the flashiness trend was tested using the Mann–Kendall test, with the slope estimated using the Sen's method (Sen, 1968). Trends are reported as significant if $p\text{-value} \leq 0.05 = \alpha$, and possible where $0.05 < p\text{-value} \leq 0.15$. The weighted average method (Baker et al., 2004) estimates the trend in the R-B flashiness index for each zone.

A weighted average (W) of trend direction and significance was calculated for each zone using weighting factors (Table 1). The weighting of 1, 2, 3, 4, 5, and 6 for six categories are used from decreasing trend with p-value ≤ 0.05 to increasing trend with p-value ≤ 0.05. With these weighting factors, zones with a weighted average ≤ 3 would, on average, have significantly/possibly decreasing flashiness trend, while zone with a weighted average ≥ 4 would, on average, have significantly/possibly increasing flashiness trend (Table 2).

Table 1: Weighting values used for zonal flashiness trend analysis

Trend Direction	Significance Level	Weight
Increasing	P ≤ 0.05	6
Increasing	0.05 < p ≤ 0.15	5
Increasing*	P > 0.15	4
Decreasing*	P > 0.15	3
Decreasing	0.05 < p ≤ 0.15	2
Decreasing	P ≤ 0.05	1

* trend is not significant

Table 2: Weighted average categories used for zonal flashiness trend analysis

Zone Trend	Weighted Average (W)
Significantly Increasing	W ≥ 4.5
Possibly Increasing	4 ≤ W < 4.5
No trend	3 < W < 4
Possibly Decreasing	2.5 < W ≤ 3
Significantly Decreasing	W ≤ 2.5

Appendix F: Example Index Equations Development

The zone summary tab provides index flood-frequency equations for each flood potential zone. The Watershed Analysis tool provides flood discharge estimates at user-selected points of interest using the index method as one of the flood-frequency approaches. As supporting information, a detailed example is provided illustrating how these index equations are developed and discharges are computed.

This application of the index flood method is provided for zone 42W (Northern Rockies, West), in Idaho and a small portion of western Montana. The analysis was performed according to the following steps:

1. The annual peak discharges for the identical stations used in flood potential analysis were collected for each station. Zone 42W includes 55 stations within the flood potential analysis, with these same stations used in the index flood-frequency analysis. For each station, the mean annual peak discharge was obtained by aggregating the annual peak discharges and dividing by the number of record years. Table 3 shows the stations within zone 42W and the estimated mean annual peak discharge (the index flood).

Table 3: Streamgaging stations and mean annual peak discharges (Q) used in the zone 42W index equation development.

Station ID	Mean Annual Peak Q (cfs)	Station ID	Mean Annual Peak Q (cfs)	Station ID	Mean Annual Peak Q (cfs)
13340600	19878.5	13257000	905.6	13308500	1726.2
13310700	3806.5	13258500	5478.4	13235000	4506.1
13313000	3139.5	13316500	5270.4	13235100	173.8
13311000	212.5	13316800	163.3	13236500	1342.2
13312000	1008.3	13337200	100.3	13234300	194.6
13314000	12504.6	13338000	5510.0	13186000	4592.0
13336500	26695.7	13336850	297.1	13187000	557.9
13337000	19461.9	13336900	1694.0	13185000	7376.7
13337500	1978.8	13336600	80.5	13184200	346.5
13335690	11873.6	13336650	82.3	13237500	6229.0
13335700	8022.7	12342950	526.1	13238000	8578.7
13310500	1060.7	12347500	655.3	13247500	12839.7
13261000	831.5	12350000	722.8	13237000	2005.8
13239000	3004.2	12350500	837.5	13248900	97.6
13254500	290.4	13339700	130.9	13200000	1920.8
13289960	1099.6	13340500	16974.8	13141500	2809.5
13252500	56.2	13339500	2894.9	13240000	1672.1
13251300	42.7	13309220	9936.8		
13251500	539.3	13309000	2197.2		

2. For each station, the annual peak discharge records were made dimensionless using the associated index flood (normalized). Then at-a-site and regional Generalized Extreme Value (GEV) distribution parameters were estimated using “nsRFA” package in R (Viglione et al, 2020). The estimated regional GEV parameters for Zone 42W are as follows:

   Location(ξ) = 0.805; Scale(α) = 0.316; Shape (k) = 0.014

Estimates of dimensionless quantiles were then obtained by the GEV quantile functions (Coles 2001):

$$q_T = \begin{cases} \xi + \frac{\alpha}{k}\left[1 - \left\{-\log\left(\frac{1}{T}\right)\right\}^k\right] & k \neq 0 \\ \xi - \alpha \log\left\{-log\left(\frac{1}{T}\right)\right\} & k = 0 \end{cases}$$

where q_T is the dimensionless regional frequency distribution; and ξ, α, and k denote the regional location, scale, and shape parameters of GEV distribution.

For example, in zone 42W, q_{100}(100-year return period) is equal to 2.2111. In other words, the ratio of 100-year flood to the index flood (mean annual peak discharge) is 2.2111.

Afterwards, a dimensionless frequency curve, also known as the regional growth curve, was developed that represents the ratio between flooding of any frequency and an index flood. The below figure shows the curve for zone 42W.

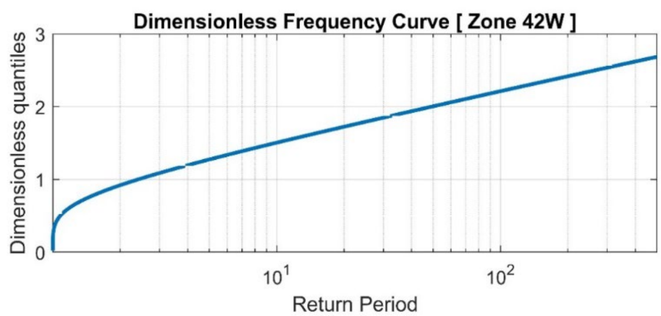


Figure 78: Dimensionless frequency curve for zone 42W.

3. A multiple linear regression analysis was carried out to link the natural logarithm of the index flood to the watershed area, and sometimes with another watershed characteristic (slope, elevation, aspect, annual or monthly precipitation). In zone 42W, the index flood at site i was defined as:

$$u_i = 0.1829\ A_i^{0.8572}\ P_i^{1.339}$$

where u_i denotes the index flood at site i, A_i denotes site i watershed area (mi^2) and P_i represents the mean average watershed annual precipitation (inches). Explained variance (R^2) was computed to be 0.97 for zone 42W.

4. Flood discharges are estimated by first estimating the value of the index flood (u_i) and then multiplying that by the ratios from the dimensionless frequency curve for each return period (q_T):

$$Q_T^i = q_T u_i$$

where Q_T^i is a flood with a return period T at site i, u_i denotes the index flood at site i, and q_T is the dimensionless quantiles for a return period T.

Specifically, in zone 42W, the flood quantile equations for return periods of 1.5, 2, 5, 10, 25, 50, 100, 200, and 500 are as follows:

$$Q_{1.5}^{i} = 0.7752 \times 0.1829\, A_i^{0.8572}\, P_i^{1.339} = 0.1418\, A_i^{0.8572}\, P_i^{1.339}$$

$$Q_{2}^{i} = 0.9207 \times 0.1829\, A_i^{0.8572}\, P_i^{1.339} = 0.1684\, A_i^{0.8572}\, P_i^{1.339}$$

$$Q_{5}^{i} = 1.2739 \times 0.1829\, A_i^{0.8572}\, P_i^{1.339} = 0.2330\, A_i^{0.8572}\, P_i^{1.339}$$

$$Q_{10}^{i} = 1.5046 \times 0.1829\, A_i^{0.8572}\, P_i^{1.339} = 0.2752\, A_i^{0.8572}\, P_i^{1.339}$$

$$Q_{25}^{i} = 1.7926 \times 0.1829\, A_i^{0.8572}\, P_i^{1.339} = 0.3278\, A_i^{0.8572}\, P_i^{1.339}$$

$$Q_{50}^{i} = 2.0037 \times 0.1829\, A_i^{0.8572}\, P_i^{1.339} = 0.3664\, A_i^{0.8572}\, P_i^{1.339}$$

$$Q_{100}^{i} = 2.2111 \times 0.1829\, A_i^{0.8572}\, P_i^{1.339} = 0.4044\, A_i^{0.8572}\, P_i^{1.339}$$

$$Q_{200}^{i} = 2.4158 \times 0.1829\, A_i^{0.8572}\, P_i^{1.339} = 0.4418\, A_i^{0.8572}\, P_i^{1.339}$$

$$Q_{500}^{i} = 2.6827 \times 0.1829\, A_i^{0.8572}\, P_i^{1.339} = 0.4906\, A_i^{0.8572}\, P_i^{1.339}$$

For example, at an ungauged location in zone 42W with latitude = 44.913366 and longitude =-115.722620 (upper South Fork Salmon River; Figure 79), the watershed area is 266 mi^2, and the mean average watershed annual precipitation is 39.9 inches. The flood quantiles for return periods of 1.5, 2, 5, 10, 25, 50, 100, 200, and 500 are as follows:

Table 4: Peak discharge estimates for the 1.5 to 500-year return interval floods, for the upper South Fork Salmon River, Idaho.

Return Period (year)	**1.5**	**2**	**5**	**10**	**25**	**50**	**100**	**200**	**500**
Peak Discharge (cfs)	2360	2810	3890	4590	5470	6110	6740	7370	8180

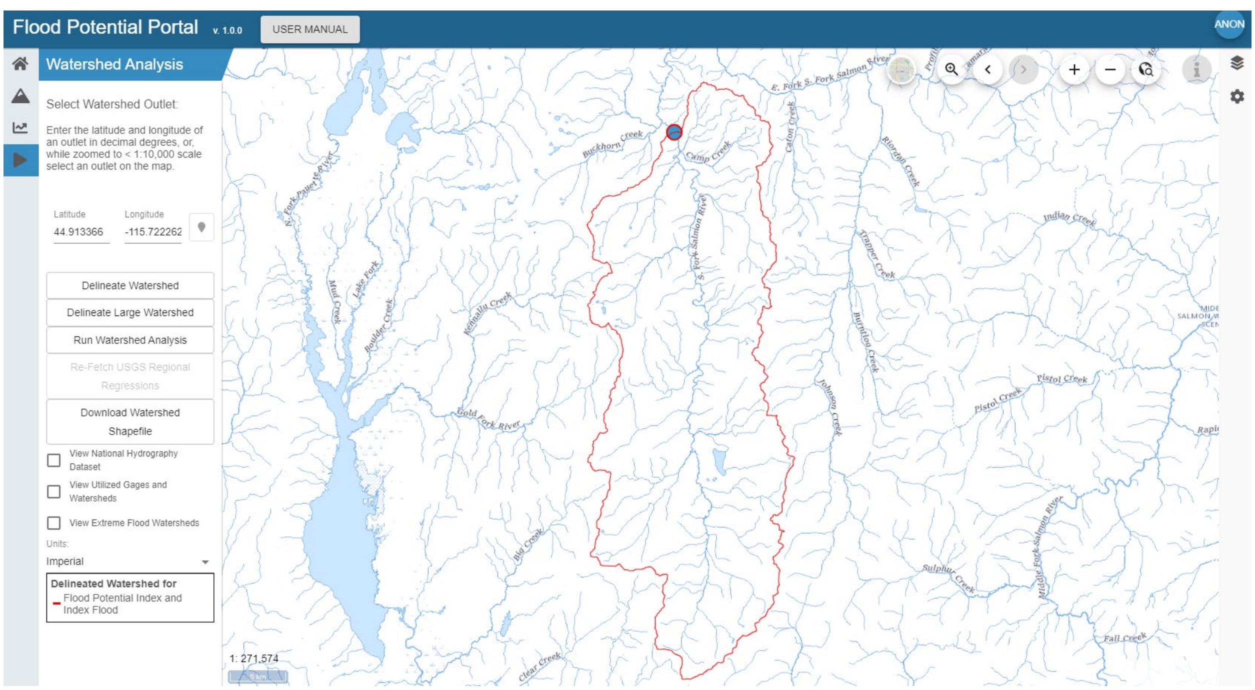


Figure 79: Watershed boundary for the upper South Fork Salmon River peak discharge estimates.

Appendix G: Mixed Populations and Flood-Frequency Analyses

The nature of records at streamgaged locations can have fundamental implications when paired with the standard statistical distribution used for streamgage analysis the United States, for flood-frequency estimates: the log-Pearson Type 3 distribution (IACWD, 1982; England et al., 2018). Generally, the relevant characteristics are data independence, data sufficiency, climate cycles and trends, watershed changes, mixed populations (bimodal floods, heavy tail floods), and reliability of flow estimates. Below, a summary of each of these characteristics is provided, followed by a focus on mixed populations and bimodal floods.

Data Independence: In order to perform a valid discharge-frequency analysis the data points used in the analysis must be independent, i.e. not related to each other. Flow events oftentimes occur over several days, weeks, or even months, as can be the case with snowmelt. Using subsequent days of high flow from the same event in a frequency analysis is not appropriate since these data are dependent upon each other. This would exaggerate the frequency of this magnitude of event. It is common practice to minimize this problem by extracting annual peak flows from the streamflow record to use in the frequency analysis. The annual maximum flow for each water year (October 1 to September 30) is used in flood-frequency analyses.

Data Sufficiency: Streamgage records should contain at least 10 years of consecutive peak flow data and, to minimize bias, should span both wet and dry years.

Climate Cycles and Trends: Climatic cycles, or periodicity, have been identified in meteorological and hydrological records. Climate trends are also a concern, as an indicator of non-stationarity and the relevance of historic data for future conditions. Cycles in streamflow have been found in the world's major rivers. For example, Pekarova et. al. (2003) identified 20 to 22 and 28 to 29 year cycles of large floods in river discharge records throughout the world. Some cycles have been associated with oceanic cycles, such as the El Niño - Southern Oscillation, in the Pacific (Dettinger et al, 2000) and the North Atlantic Oscillation (Pekarova et. al, 2003). The timing of streamgaging records in relation to climate cycles impacts the results of flood-frequency analyses, with differing periods and record lengths interacting with cycles in complex ways that can add noise or bias to subsequent analyses (such as regional regression studies).

Watershed Changes: Changes in watersheds can change the frequency of floods in streams, with different scales of floods responding differently to such changes. Changes that induce the greatest changes in flow include urbanization, reservoir storage, stream diversions, as well as moderate and high severity wildfires.

Mixed Populations (Bimodal Floods): At many locations, high flows are created by different types of events, which can result in a bimodal flood regime (and heavy-tailed frequency distributions) with floods of dramatically different scales present within an individual record. For example, in watersheds along the Rocky Mountain Front high flow may result from snowmelt events, rain events, or rain-on-snow events. Also, tropical cyclones, large synoptic systems, and frontal systems may all produce floods of varying scales, with a preponderance of saturation-excess overland flow and variable source area hydrology (Betson 1964; Dunne et al. 1975) possibly inducing higher mode floods.

Reliability of Flow Estimates: Errors exist in streamflow records, as with all measured values. These streamgage inaccuracies are often random, possibly minimizing the resultant error in frequency analyses. Overestimates may be greatest for larger, infrequent events, especially "historic" events.

General Method

A series of reports that have provided guidelines for performing flood-frequency analyses have been published since 1967 (England et al., 2018), including Bulletins 15, 17, 17A, 17B, and 17C. These guidance documents have had the objective of providing a uniform and consistent analysis approach for application across the United States, which is a reasonable objective, though also creates a risk of systematic bias in results where there is a common violation of required data characteristics, as may be the case with mixed populations and bimodal floods being recorded, resulting in heavy tails (see examples below). Of current relevance are the two most recent publications (IACWD, 1982: 17B; England et al., 2018: 17C), which describe the methods typically used in streamgage flood-frequency analyses within then United States. Bulletin 17C provided a number of changes, including the expected moments algorithm, which accommodates interval and censored data (through such concepts as perception thresholds), and improvements in the identification of low outliers and computation of confidence intervals.

Both IACWD (1982) and England et al. (2018) utilize the Pearson Type 3 distribution, with log transformation of the flood data (log-Pearson). Other countries commonly use other distributions (Singh and Strupczewski, 2002), but log-Pearson is standard in the United States. Historical and paleoflood data are utilized in the England et al. (2018) analyses, where they are available, with the Expected Moments Algorithm providing techniques for incorporating such data into the analyses. For both IACWD (1982) and England et al. (2018), adjustments are made for possibly influential low values, and regional skews are utilized to adjust analyses for local characteristics.

Flood-frequency relationships are expressed in terms of both return intervals (T) and the annual exceedance probability (AEP), with the latter being preferred by many hydrologists and the former more commonly used (e.g., 100-year flood). These terms are directly comparable, with the AEP = 1/T. For example, a 100-year storm has an annual probability of occurrence of AEP = 0.01 = 1%.

The log-Pearson Type 3 distribution is, generally, as follows:

$$Q_{LP,T} = \overline{Q_l} + K_{LP,T} S_l$$

where: $Q_{LP,T}$ = logarithm of predicted discharge, at return period T, $\overline{Q_l}$ = average of annual peak discharge logarithms, $K_{LP,T}$= a parameter that is a function of return period and skew coefficient, and S_l= standard deviation of logarithms of annual peak discharge.

To illustrate the influence of bimodal annual peak discharge on streamgage analyses using the log-Pearson distribution and procedures outlines in Bulletins 17B and 17C, three examples are provided from Northern Colorado. These examples use flood potential results and other information to illuminate how these flood-frequency analyses perform considering bimodal annual peak discharges, and varying record lengths and periods. These examples show situations where flood-frequency results agree with flood potential predictions, as well as situations were flood-frequency analyses may be overpredicting and underpredicting results used for selecting base flood and design flood discharges (typically assumed to be the 1% AEP or the 100-year discharge, Q_{100}). These examples have had streamgage data collected by both the U.S. Geological Survey and the Colorado Division of Water Resources.

Both streamgage flood-frequency analyses and regional regression analyses, which are both computed using the log-Pearson distribution, are influenced by bimodal data.

The bimodality index (B_i) quantifies areas where this issue may be more prevalent in the contiguous United States (Figure 80). This index is computed as the maximum recorded discharge divided by the median annual peak discharge, for each streamgage. An average is then computed for each zone. The B_i is similar to the upper tail ratio utilized by Smith et al. (2018), which uses the 10-year discharge instead of the median.

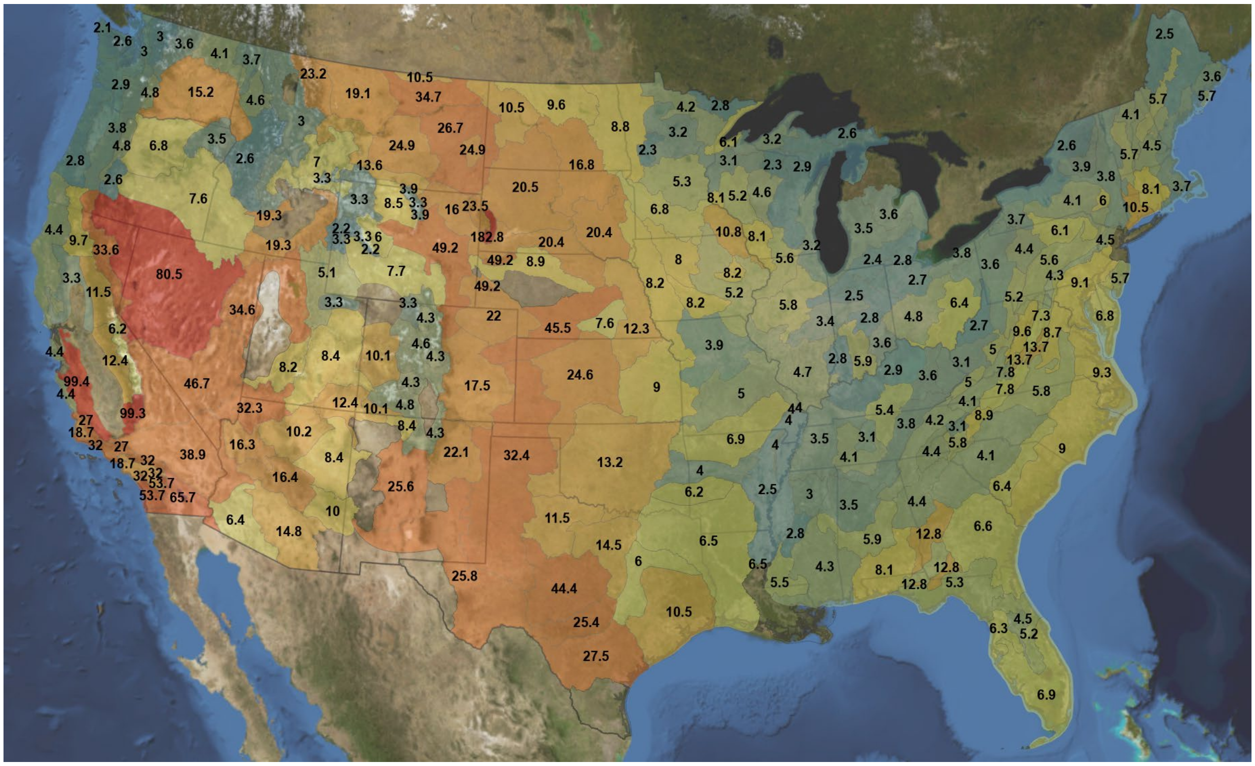


Figure 80: Zone averaged bimodality index (B_i) values for the contiguous United States, with warmer colors indicating higher B_i values. A higher B_i can be associated with flood-frequency analyses being biased low. Use of an ensemble approach for the selection of design flood discharges is especially important in areas with higher B_i values.

Example: Big Thompson River

The Big Thompson River at the canyon mouth west of Loveland, Colorado is a 306 mi^2 watershed in flood potential zones 3 and 1N (Figure 81). There are possibly increasing trends in the largest 5% flood magnitude in zone 3 (+12.8%), and significantly increasing trends in observed flood magnitude (+13.1%) and annual frequency in zone 1N (trend adjusted Q_{efp} = 16,100 cfs, Q_{mlf} = 25,500 cfs). This is a long record streamgage (98 years of record in 2022; Figure 82) that has experienced two high-mode floods, including the Big Thompson Flood of 1976, which claimed 144 lives.

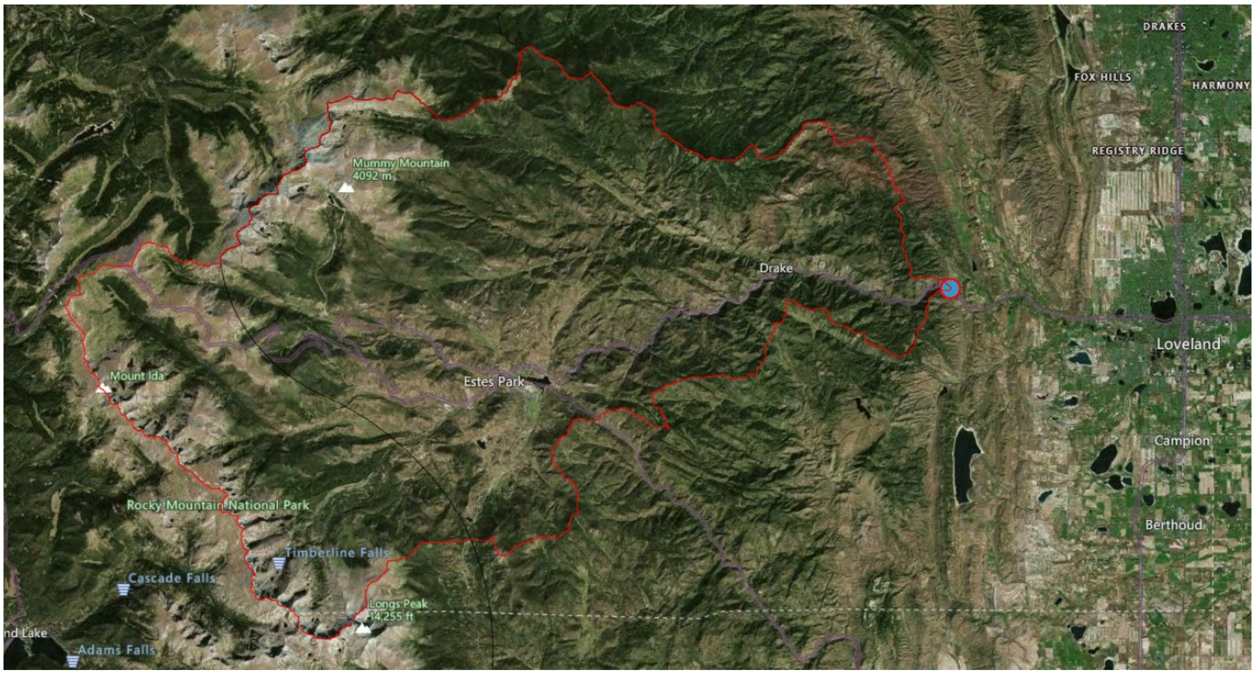


Figure 81: Watershed boundary for the Big Thompson River, with the watershed extending from the Continental Divide though the foothills to the edge of the High Plains.

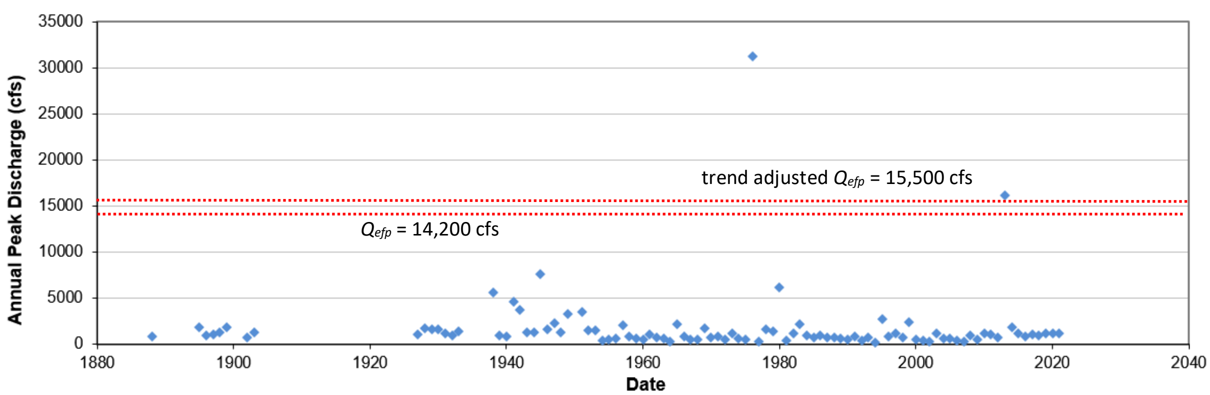


Figure 82: Annual peak streamgage data for the Big Thompson River at Canyon Mouth site (USGS ID: 06378000, CO ID: BTABCMCO), for 1888 to 2021. Expected flood potential discharge (Q_{efp}) is also provided.

It is important to graph data, to illuminate data characteristics. These Big Thompson River data are bimodal, due to mixed populations of flood producing mechanisms (snowmelt versus rainfall-induced floods). Most flood events are produced by spring snowmelt, with peak flows less than 5000 cfs. Three intermediate-scale floods (5000 to 10,000 cfs) have also occurred, with two high mode floods experienced in 2013 (16,200 cfs) and 1976 (31,200 cfs). The 1976 event was extreme (E_f = 2.27), but at a lower level of extremity than what has been experienced further south along the Colorado Front Range (Appendix D).

Several flood-frequency analyses were performed, to illustrate the influence of the bimodal flood magnitudes and varying record lengths and periods on analysis results. Specifically, three analyses were performed for data collected from 1888 to 1975 (52 years), 1888 to 2012 (89 years), and 1888 to 2021 (98 years). All of these analyses are for what would commonly be considered longer (and sufficient) record lengths (≥ 40 years). The results of these analyses are provided in Table 5. Index flood results and USGS regional regression results are also provided, for comparison.

Table 5: Flood-frequency analysis results (using the Bulletin 17B methodology) for the Big Thompson River at the canyon mouth streamgage. At this location, the Q_{efp} = 14,300 cfs and Q_{mlf} = 22,500 cfs , and the trend adjusted Q_{efp} = 16,100 cfs and Q_{mlf} = 25,500 cfs.

Return Interval (year)	Annual Percent Chance of Exceedance	1888 to 1975 (cfs)	1888 to 2012 (cfs)	1888 to 2021 (cfs)	Index	Regional Regression
200	0.5	9840	18,700	21,900	11,400	5410
100	1	7660	12,500	14,300	8520	4630
50	2	5880	8330	9290	6400	3890
25	4	4440	5470	5950	4800	3110
10	10	2940	3050	3220	3240	2490
5	20	2060	1890	1960	2330	1960
2	50	1110	900	920	1320	1310

It is clear that the length and period of record has a large impact on flood magnitude predictions, with the Q_{100} increasing from 7660 cfs, to 12,500 cfs, and then to 14,300 cfs (an 87% increase from the initial value) after the high mode floods were experienced. Hydrologists performing flood-frequency analyses for this site in 1975, 2012, and 2021 would have specified substantially different flood discharge values over time, with such inconsistency problematic for design and regulatory purposes. Also, note that Q_{efp} = 14,300 cfs (the central tendency of record flood magnitudes across each zone) is identical to the 1888 to 2021 Q_{100} value; the flood potential method, and the expected flood potential discharge, can help confirm or illuminate problems with streamgage-based estimates of flood magnitudes, as well as flood-frequency results produced by USGS regional regressions (StreamStats) and Index methods. In this case, a hydrologist can be confident in the use of Q = 14,300 cfs (from the streamgage analysis) or Q = 16,100 cfs (from the trend-adjusted flood potential analysis).

Example: Buckhorn Creek

Buckhorn Creek, west of Fort Collins, Colorado, is a 136 mi^2 watershed exclusively in flood potential zone 1N (Figure 83). This zone is experiencing significantly increasing trends in the observed largest 5% flood magnitude (+13.1%) and annual frequency (Q_{efp} = 10,100 cfs, Q_{mlf} = 15,900 cfs; trend adjusted Q_{efp} = 11,400 cfs, Q_{mlf} = 17,900 cfs). This watershed has 32 years of record collected between 1923 and 2013 (Figure 84). It has experienced 3 floods between 10,200 and 11,200 cfs, plus an additional flood of 14,200 cfs in 1951 that is noted to have been influenced by a dam breach. With an average annual peak discharge of 780 cfs during the other years, this bimodal flood regime, on average, occurs across more than an order of magnitude.

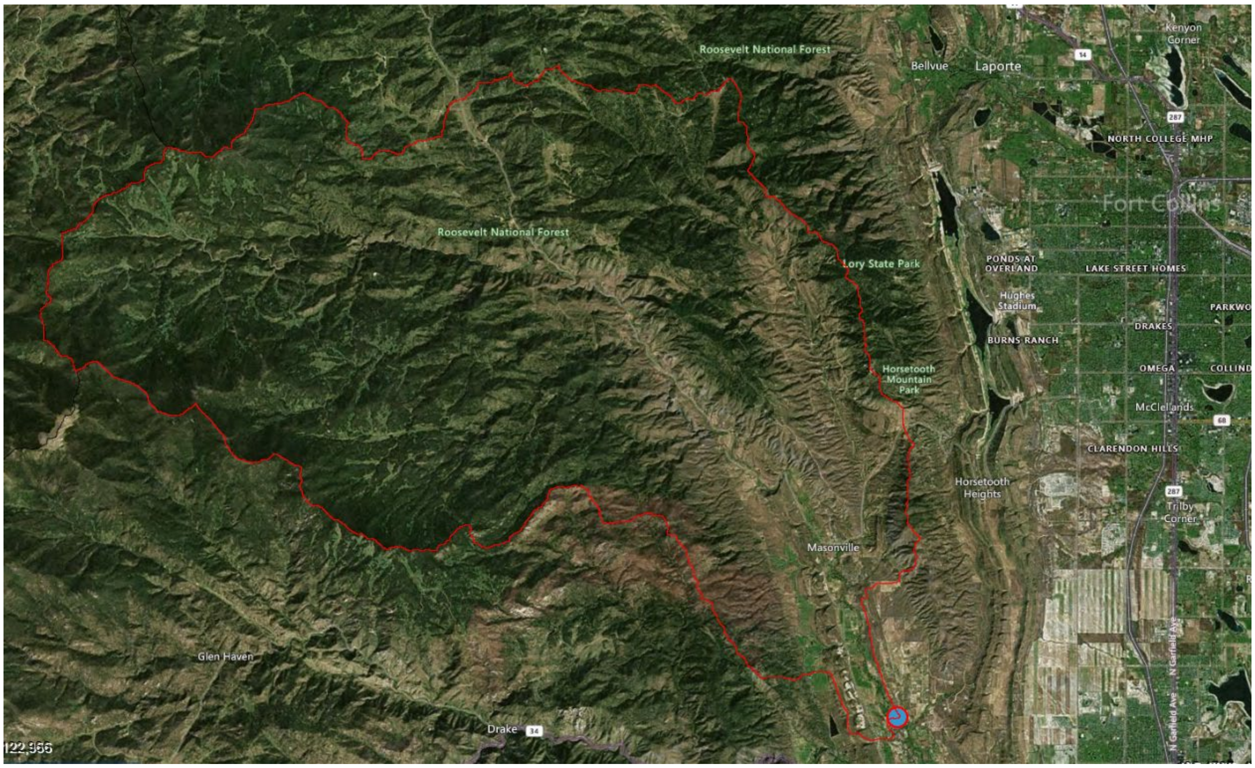


Figure 83: Watershed boundary for Buckhorn Creek.

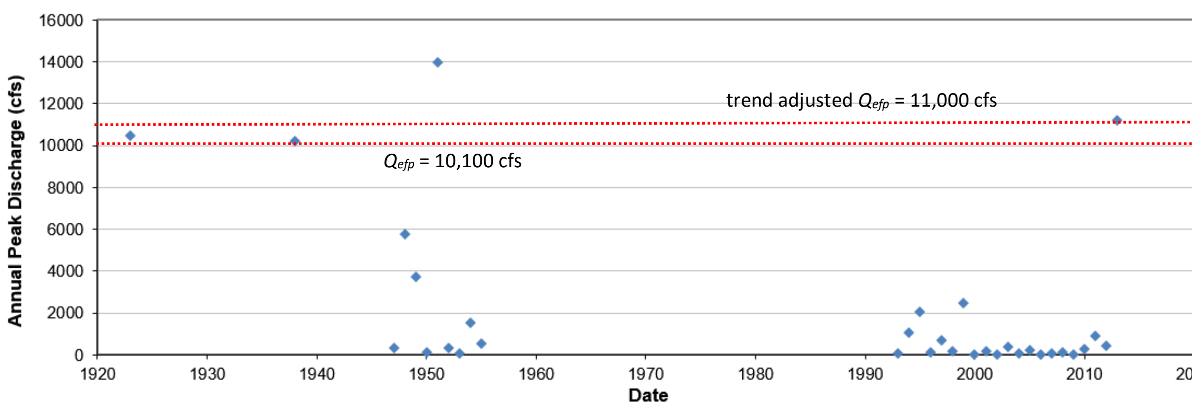


Figure 84: Annual peak streamgage data for Buckhorn Creek (USGS ID: 06739500, CO ID: BUCRMVCO), illustrating typical flood magnitudes and four high-mode events. Expected flood potential discharges (Q_{efp}) are also provided.

Table 6: Flood-frequency analysis results for the Buckhorn Creek streamgage, including both Bulletin 17B and 17C results. At this location, the trend adjusted Q_{efp} = 11,400 cfs and Q_{mlf} = 17,900 cfs.

Return Interval (year)	Annual Percent Chance of Exceedance	Bulletin 17B (cfs)	Bulletin 17C (cfs)	Index (cfs)	Regional Regression (cfs)
200	0.5	37,700	32,600	8800	14700
100	1	23,500	21,400	6200	10800
50	2	14,100	13,400	4340	7500
25	4	7920	----	3000	5080
10	10	3260	3410	1780	2820
5	20	1410	1530	1150	1630
2	50	284	310	530	610

Results of the flood-frequency analyses are provided (Table 6), along with index and regional regression predictions. Results for Q_{100} are similar for both the Bulletin 17B and 17C analyses, with the use of expected moments algorithm reducing the Q_{100} by 9% for this highly intermittent record (32 years of record over 91 years). The relatively short record and the presence of multiple high mode floods is resulting in a Q_{100} that is high (21,400 cfs) in comparison with the experienced flood magnitudes of 11,200 cfs (2013), 10,500 cfs (1923) and 10,200 cfs (1938). However, the regional regression Q_{100} (10,700 cfs) and the trend adjusted Q_{efp} (11,400 cfs) are similar to each other and the three high-mode events. Use of the streamgage analysis Q_{100}, may likely result in overregulation of the floodplain and excessive sizing of infrastructure. In this case, the log-Pearson distribution results may likely be overpredicting the true flood hazard of this watershed.

As an alternative, the trend-adjusted Q_{efp} = 11,400 cfs is appealing for use as a base flood and design flood discharge value since it is very similar to the regional regression Q_{100} result while also accounting for increasing flood magnitudes observed within this zone. This Q_{efp} may be appropriately conservative, and not overly conservative as the streamgage flood-frequency results appears to be, balancing the needs for both infrastructure resilience and cost effectiveness.

Example: Cache la Poudre River

The Cache la Poudre River at the canyon mouth streamgage illustrates a situation where a long record within a streamgage analysis may result in the underestimation of the true flood hazard. This watershed is large (1060 mi^2), and is composed of areas within flood potential zones 3 and 1N (Figure 85). Zone 3 is experiencing increasing trends in magnitude (+12.8%), and zone 1N is experiencing significantly increasing trends in observed flood magnitude (+13.1%) and annual frequency. The Q_{efp} = 23,900 cfs and Q_{mlf} = 37,800 cfs, with trend adjusted values Q_{efp} = 27,000 cfs and Q_{mlf} = 42,700 cfs.

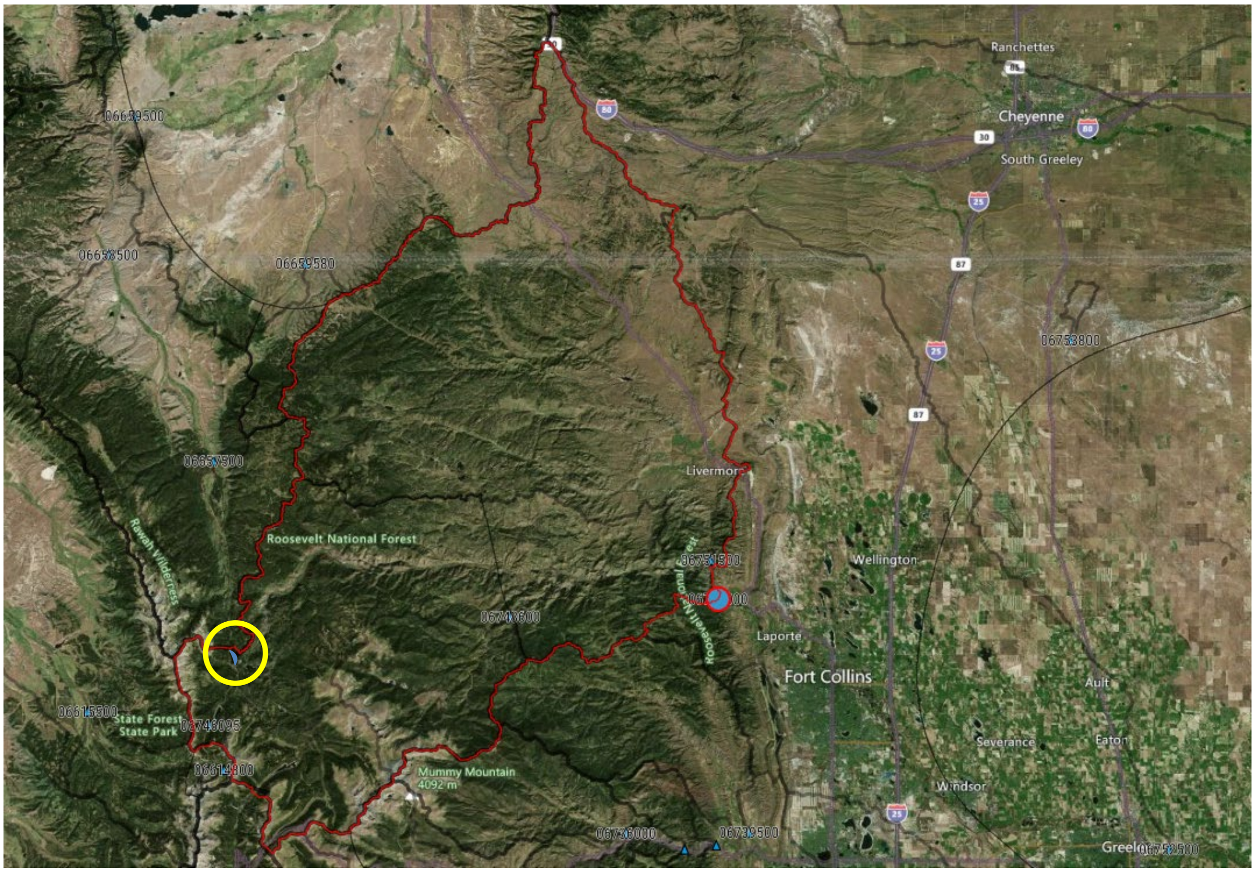


Figure 85: Watershed boundary for the Cache la Poudre River watershed. The current extent of Chambers Lake is shown in blue (within the yellow circle).

This streamgage has 139 years of annual peak discharge data collected (Figure 86), with one quantified event that appears to be a high mode (21,000 cfs in 1891) and a second known high mode stage (18.5 ft in 1904, 11 ft higher than the 12,000 cfs peak in 1901). However, both the 1891 and 1904 peaks were influenced by Chambers Lake dam failures in the headwaters of the watershed (see small blue polygon in the yellow circle), which confounds interpretations. Though, importantly, the N.F. of the Cache la Poudre River, which was not influenced by a dam failure, experienced a 20,000 cfs peak during the 1904 event – a large rain (and, possibly, rain-on-snow) event occurred across the Cache la Poudre watershed, with unknown contributions from the precipitation and the dam failure to the 18.5 ft peak stage. Additional streams that contribute to the Cache la Poudre watershed, that drain the Cheyenne Ridge between Cheyenne and Fort Collins (from the Boxelder watershed), are also known to have experienced high mode floods, suggesting a bimodal flood regime dominates the area. Furthermore, zone 1N (64% of the watershed area) is known to have a high flood potential, with highly bimodal floods (B_i = 49.2).

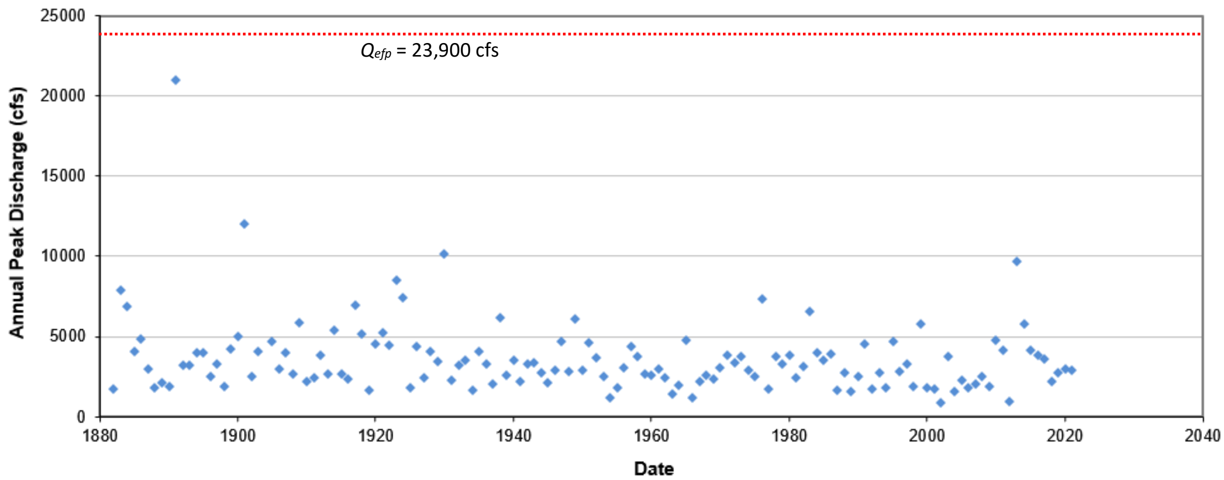


Figure 86: Annual peak streamgage data collected for the Cache la Poudre River at the canyon mouth (USGS ID: 06752000, CO ID: CLAFTCCO), with 139 years of data, a high mode flood recorded in 1891, and an additional (larger) high mode flood known to have occurred in 1904 (from stage information; not plotted). Expected flood potential discharge (Q_{efp}) is also provided.

A standard frequency analysis was performed using the available 139 years of peak discharge data, using both 17B and 17C procedures. Additionally, to test the sensitivity of high mode floods on long record lengths within log-Pearson analyses, the 1904 flood was hypothetically assumed to have experienced a discharge equivalent to the Q_{efp}, for an analysis using 140 years of data. Results from these analyses are provided (Table 7), along with the results of Index and regional regression analyses.

Table 7: Flood-frequency analysis results for the Cache la Poudre at canyon mouth streamgage, using Bulletin 17B and 17C procedures and a 1882 to 2021 record length. At this location, the trend adjusted Q_{efp} = 27,000 cfs and Q_{mlf} = 42,700 cfs. For the Streamgage Analysis w/ 1904 Placeholder column, the year 1904 discharge is assumed to be the Q_{efp}. For the 17C analysis (without the assumed 1904 value), the missing 1904 flood was provided perception thresholds of 20,000 and 50,000 cfs, since the N.F. Cacha la Poudre streamgage recorded a 20,000 cfs flood peak.

Return Interval (year)	Annual Percent Chance of Exceedance	Streamgage Analysis, 17B (cfs)	Streamgage Analysis, 17C (cfs)	Streamgage Analysis w/ 1904 Placeholder, 17B (cfs)	Streamgage Analysis w/ 1904 Placeholder, 17C (cfs)	Index (cfs)	Regional Regression (cfs)
200	0.5	14,200	18,200	18,200	18,200	21,700	11,200
100	1	11,900	14,600	14,600	14,600	16,400	9370
50	2	9910	11,600	11,600	11,600	12,400	7600
25	4	8140	----	9140	----	9370	5900
10	10	6100	6490	6490	6490	6390	4470
5	20	4740	4850	4850	4850	4640	3300
2	50	3050	3010	3010	3010	2650	1990

Interpretation for the selection of the most appropriate base flood and design flood discharges at this site is difficult. The available streamgage data indicate Q_{100} = 11,900 cfs using the Bulletin 17B procedure and Q_{100} = 14,600 cfs using the 17C procedure. Inclusion of an assumed 1904 high mode discharge increased the 17B results, but does not change the 17C results. Hence, the log-Pearson distribution produce results are relatively insensitive to high mode discharge inclusion, with 140 years of record. This long record length (and perhaps the nature of the more common flood magnitudes) appears to be minimizing the influence of the high mode flood events in the log-Pearson analysis, which is problematic since these larger floods are most important in understanding flood magnitudes to utilize in planning and design. The index flood estimate produces a Q_{100} that is larger but similar in magnitude to the streamgage analyses. All of these Q_{100} estimates are low in comparison to the Q_{efp}, as informed by floods experienced in streamgages across zones 1N and 3.

Considering the convoluted circumstances involved in this example, specifically in regard to the influence of the Chambers Lake dam failure, it is unclear at this time (2022) if the higher (Q_{efp}) or lower (Q_{100}) value should be used as the base flood and design flood discharge. An appropriate value is expected to be within the range of 14,600 cfs to 26,100 cfs, though this spread is wide and assumes that the Chambers Lake failure in 1891 is not a significant contributor to the flood peak. A flood-frequency distribution that better accounts for bimodal flood regimes, rather than the log-Pearson distribution, could be valuable for application at this site.

The flood potential results are valuable for illuminating a range of appropriate discharge values, though introduces a conundrum regarding what specific discharge to select. If this watershed is not unique as other situations (such as the Eleven Point River) have eventually shown to be the case (which time will tell), the upper end of this range is most appropriate (especially considering the trend results), but if this watershed is unique (which is likely unknowable), the lower end of this range is most appropriate. A conservative value would be the trend-adjusted Q_{efp} = 26,100 cfs, with the assumption that the Cache la Poudre River will eventually experience one or more floods similar in scale to what its neighbors (such as the Big Thompson River) have experienced.

Summary

Where there are substantial bimodal flooding characteristics recorded by the streamgaging network, resulting flood-frequency analyses can be heavily influenced by the presence (or absence) of these events in the record, potentially leading to misconceptions on appropriate base flood and design flood discharges. Additionally, these situations can lead to misconceptions on how floods may be changing, as the example for analyses performed for the Big Thompson River indicate. With the setting of being within a bimodal flood regime, due to multiple mechanisms inducing annual peak flows, estimates for the Big Thompson River were initially underestimated, despite the presence of 52 years of data prior to the 1976 flood. In contrast, the relatively short record for nearby Buckhorn Creek, with the presence of at least three high mode floods, is biasing Q_{100} estimates high, with none of the experienced floods being close to the projected Q_{100} value.

The impacts of bimodal flood regimes is complex, with variable record lengths that exclude or include the higher mode of flooding being highly influential on results. These examples illustrate the impact of variable record lengths and periods across the streamgage network, which can result in an artificial perspective on flood variability that in actually is noise due to the variable records and the statistical analyses. Analyses of such datasets over time can encourage a misconception of floods becoming much larger due to climate change. For the Big Thompson River, the 87% increase in Q_{100} could be interpretated by some as an indicator of climate change, while in actually the high mode floods prevalent along the Rocky Mountain Front had simply not yet been experienced in the earlier analyses. Recognizing the value of what watersheds across the flood potential zone have experienced, through use of Q_{efp} and Q_{mlf}, can illuminate these situations. While this area is experiencing increasing trends in both the magnitude and frequency of large floods, as detected using the flood potential method, the increase in flood magnitudes is much more moderate (+12.8 to +13.1%).

The Cache la Poudre River example shows the resistance of log-Pearson distributions for accommodating the occurrence of high mode floods when the record length is long, using both Bulletin 17B and 17C procedures. This results in possible underprediction of discharges, due to the dominance of the smaller mode floods in a long record. As streamgage records continue to build for key gages across the United States, this issue may become more problematic over time, especially in areas where bimodal floods are documented to exist (Figure 80).

Beyond the impacts to individual streamgage analyses (and infrastructure and floodplain management based on such analyses), the bimodal (mixed population) flood problem also impacts analyses that imbed such flood-frequency analyses within their development, such as regional regression analyses for application at ungaged locations (StreamStats). In areas where bimodal flood magnitudes are experienced, this issue of varying record lengths and periods combined with the seemingly chaotic nature of precipitation events that induce high mode floods, as well as the inherent insufficiency of log-Pearson analyses for addressing bimodal floods, can induce noise and bias in regional regression analyses. The use of flood potential results (Q_{efp} and Q_{mlf}) can illuminate these situations, for decision making.

Appendix H: Zone Shapefile Attribute Definitions

The ArcGIS shapefile (FloodPotential_Zones) with the flood potential zones used in the analyses contain a substantial number of attributes. This shapefile is available for download from the flood potential project page. The attributes are defined below:

- Zone: zone identification
- ZoneName: zone name
- FldPotIndx: Flood Potential Index (P_f)
- BeardF: Beard flashiness index (F)
- FldHazIndx: Flood Hazard Index (H_f) = Flood Potential Index * Beard F
- VarIndx: Flood Variability Index (V_f, variability across the zone, in both space and time)
- FloodYears: years when major (widespread) floods have occurred within the zone
- FldMonths: most frequent months of occurrence of largest 5% floods (in order of decreasing frequency)
- DmntMonth: Dominant flood month
- DmntMonth2: Second peak dominant flood (or 2nd most dominant month, if a second peak does not exist)
- EFP_IntA: Expected flood potential computation parameter (watershed area-only regression), intercept (Q_{efp}=EFP_IntA*Area^EFP_ExpA). Area = watershed area
- EFP_ExpA: Expected flood potential computation parameter (watershed area-only regression), watershed area exponent
- MLF_IntA: Maximum likely flood potential computation parameter (watershed area-only regression), intercept (Q_{mlf}=MLF_IntA*Area^MLF_ExpA)
- MLF_ExpA: Maximum likely flood potential computation parameter (watershed area-only regression), watershed area exponent
- EFP2_Pred: Second predictor used in expected flood potential and maximum likely flood potential calculations, along with watershed area (E: mean average watershed elevation, m; S: mean average watershed slope, degrees; P: mean average watershed annual precipitation, mm; P#: mean average watershed monthly precipitation, for month #, mm)
- EFP2_IntAB: Expected flood potential computation parameter (multiple variable regression), intercept (Q_{efp}=EFP2_IntAB*Area^EFP2_ExpA*EFP2_Pred^EFP2_ExpB)
- EFP2_ExpA: Expected flood potential computation parameter (multiple variable regression), watershed area exponent
- EFP2_ExpB: Expected flood potential computation parameter (multiple variable regression), second predictor exponent
- MLF2_IntAB: Maximum likely flood potential computation parameter (multiple variable regression), intercept(Q_{mlf}=MLF2_IntAB*Area^MLF2_ExpA*MLF2_Pred^MLF2_ExpB)
- MLF2_ExpA: Maximum likely flood potential computation parameter (multiple variable regression), watershed area exponent
- MLF2_ExpB: Maximum likely flood potential computation parameter (multiple variable regression), watershed area exponent
- AMin_km2: minimum watershed contributing area within zone (km^2)
- AMax_km2: maximum watershed contributing area within zone (km^2)
- AveE_m: zonal mean average watershed elevation (m)
- AveS_deg: zonal mean average watershed slope (degrees)
- AveP_mm: zonal mean average watershed annual precipitation (mm)

- Area_km2: zonal area (km^2)
- FldPtl20: Flood Potential Index, 20 km^2 component of computation
- FldPtl200: Flood Potential Index, 200 km^2 component of computation
- FldPtl2000: Flood Potential Index, 2000 km^2 component of computation
- FPI2000_20: ratio of FldPtl2000/FldPtl20: Watershed Scale Ratio (R_f)
- Paleo: Paleofloods used in flood potential computations (Yes/No)
- SingleQ: Indirect measured floods at non-streamgaged locations used in flood potential computations (Yes/No)
- NumGages: number of streamgages in zonal analysis
- Freq1P: p-value for trends in annual flood-frequency where Q is greater than 0.5*Q_{efp}, with (+) indicating increasing trends and (-) indicating decreasing trends. Value between 0 and +/-0.05: significant trend. Value between +/-0.05 and +/-0.15: possible trend. Value = 1: attribute not reported due to insufficient streamgage data.. All other values: no trend.
- Freq1S: Annual flood-frequency trend slope. Value = 1: attribute not reported.
- Freq2P: p-value for trends in event flood-frequency where Q is greater than (Freq2Thrsh/100)*Q_{efp}, with (+) indicating increasing trends and (-) indicating decreasing trends. Value between 0 and +/-0.05: significant trend. Value between +/-0.05 and +/-0.15: possible trend. Value = 1: attribute not reported due to insufficient streamgage data. All other values: no trend.
- Freq2S: Event flood-frequency trend slope. Value = 1: attribute not reported.
- Freq2Thrsh: Percentage threshold used for Freq2P
- RBFlash: average zonal Richards-Baker flashiness index (R-B)
- RB_TrndVal: Richards-Baker flashiness index trend value
- RB_Trend: Richards-Baker flashiness index trend description
- PRISM: End year of PRISM period used in flood potential regressions (2010 = period of 1981 to 2010; 2020 = period of 1991 to 2020)
- R2_1: R^2 (explained variance) of flood potential regression using area as the only predictor
- R2_2: R^2 (explained variance) of flood potential regression using area plus an additional watershed descriptor as predictors
- R2_Overall: R^2 (explained variance) of flood potential regression
- Mag5_P: p-value for trends in the largest 5% of annual peak discharges (>20 year return interval), with (+) indicating increasing trends, (-) indicating decreasing trends. Value between 0 and +/-0.05: significant trend. Value between +/-0.05 and +/-0.15: possible trend. Value = 1: attribute not reported. All other values: no trend.
- Mag5_S: trend slope for the largest 5% of annual peak discharges. Value = 1: attribute not reported due to insufficient significance (p-value > 0.15).
- Mag5_Perc: percent change in largest 5% of annual peak discharges, computed by comparing most recent 30 years of record to the entire zonal record. Value = 0: attribute not reported, due to insufficient significance (p-value > 0.15). For adjustment application: Q_{adj} = Q + Q*(Mag5_Perc)/100.

- MagQ4_P: p-value for trends in the largest quarter (Q4) of annual peak discharges (>4 year return interval), with (+) indicating increasing trends, (-) indicating decreasing trends. Value between 0 and +/-0.05: significant trend. Value between +/-0.05 and +/-0.15: possible trend. Value = 1: attribute not reported. All other values: no trend.
- MagQ4_S: trend slope for the largest quarter (Q4) of annual peak discharges. Value = 1: attribute not reported due to insufficient significance (p-value > 0.15).
- MagQ4_Perc: percent change for the largest quarter (Q4) of annual peak discharges, computed by comparing most recent 30 years of record to the entire zonal record. Value = 0: attribute not reported, due to insufficient significance (p-value > 0.15). For adjustment application: Q_{adj} = Q + Q*(MagQ4_Perc)/100.
- MagQ3_P: p-value for trends in the upper-middle quarter (Q3) of annual peak discharges (2 to 4 year return interval), with (+) indicating increasing trends, (-) indicating decreasing trends. Value between 0 and +/-0.05: significant trend. Value between +/-0.05 and +/-0.15: possible trend. Value = 1: attribute not reported. All other values: no trend.
- MagQ3_S: trend slope for the upper-middle quarter (Q3) of annual peak discharges. Value = 1: attribute not reported due to insufficient significance (p-value > 0.15).
- MagQ3_Perc: percent change in the upper-middle quarter (Q3) of annual peak discharges, computed by comparing most recent 30 years of record to the entire zonal record. Value = 0: attribute not reported, due to insufficient significance (p-value > 0.15).
- MagQ2_P: p-value for trends in the lower-middle quarter (Q2) of annual peak discharges (1.33 to 2 year return interval), with (+) indicating increasing trends, (-) indicating decreasing trends. Value between 0 and +/-0.05: significant trend. Value between +/-0.05 and +/-0.15: possible trend. Value = 1: attribute not reported. All other values: no trend.
- MagQ2_S: trend slope for the lower-middle quarter (Q2) of annual peak discharges. Value = 1: attribute not reported due to insufficient significance (p-value > 0.15).
- MagQ2_Perc: percent change in the lower-middle quarter (Q2) of annual peak discharges, computed by comparing most recent 30 years of record to the entire zonal record. Value = 0: attribute not reported, due to insufficient significance (p-value > 0.15).
- MagQ1_P: p-value for trends in the smallest quarter (Q1) of annual peak discharges (< 1.33 year return interval), with (+) indicating increasing trends, (-) indicating decreasing trends. Value between 0 and +/-0.05: significant trend. Value between +/-0.05 and +/-0.15: possible trend. Value = 1: attribute not reported. All other values: no trend.
- MagQ1_S: trend slope for the smallest quarter (Q1) of annual peak discharges. Value = 1: attribute not reported due to insufficient significance (p-value > 0.15).
- MagQ1_Perc: percent change in the smallest quarter (Q1) of annual peak discharges, computed by comparing most recent 30 years of record to the entire zonal record. Value = 0: attribute not reported, due to insufficient significance (p-value > 0.15).
- Bimodal_Bi: zone average bimodality index (B_i), computed for each streamgage as the ratio of the largest measured annual peak discharge to the typical (median) annual peak discharge.
- StYrFP: start year, flood potential analysis
- StYrIF: start year, index flood-frequency analysis
- StYrQ5: start year, trend analysis of largest 5% annual peak discharges
- StYrQ4: start year, trend in Q4 quarter of annual peak discharges
- StYrQ3: start year, trend in Q3 quarter of annual peak discharges
- StYrQ2: start year, trend in Q2 quarter of annual peak discharges
- StYrQ1: start year, trend in Q1 quarter of annual peak discharges
- StYrFr1: start year, trend in annual frequency

- StYrFr2: start year, trend in event frequency
- StYrFl: start year, trend in flashiness
- EndYrFP: end year, flood potential analysis
- EndYrIF: end year, index flood-frequency analysis
- EndYrQ5: end year, trend analysis of largest 5% annual peak discharges
- EndYrQ41: end year, trend in Q1 through Q4 quarter of annual peak discharges
- EndYrFr1: end year, trend in annual frequency
- EndYrFr2: end year, trend in event frequency
- EndYrFl: end year, trend in flashiness

Appendix I: Research Needs

Considering the ever present threats large riverine floods have on lives, property, and infrastructure, and the need for societal resilience from such hazards, the field of flood hydrology has been insufficiently active over the last several decades (specifically for the purpose of prediction by practitioners, for design and management). Changes in flood hazards in some areas due to climate change make new research even more essential. The flood potential method has been developed in an attempt to increase understanding of flood hazards as well as provide communication tools that, together, can contribute to invigorated research within the field. The following suggestions are provided for researchers to consider.

The flood potential method quantifies the inherent scale and variability of large floods across zones of similar flood response, as recorded within the streamgaging record. Hypotheses on relevant processes that are inducing this variability include precipitation variability through orographic forcing and other mechanisms that drive, for instance, the sizes of storms that induce the largest floods, as well as infiltration (considering cover, soils, and underlying geology), watershed orientations in comparison to storm tracks, watershed shape and storage, and floodplain attenuation. The preponderance of saturation-excess versus infiltration-excess runoff during large floods is also relevant. Research is needed to better understand the inherent variability of large flood magnitudes in the United States. Understanding of this status of flooding is required to make dependable predictions of future conditions.

1. **Precipitation variability** is likely a major contributor to varying flood potential. How does precipitation vary in regard to depths, rates, spatial scale, and antecedent soil moisture development between zones with substantially different flood potential? Adjacent zones that have substantially different flood potential index (P_f) values may offer especially enlightening research opportunities.
2. **Hydrologic conditions:** A variety of hydrologic mechanisms are at play while precipitation on a watershed is transferred to floods at a watershed outlet to drive the flood potential, including infiltration, floodplain attenuation, and other mechanisms. Research is needed to understand dominant mechanisms that produce floods across flood potential zones.
3. **Flood variability:** Rather than being random or chaotic, large floods appear to occur on periodic bases (Tipton, 1937; McMahon & Kiem, 2018; Yochum et al., 2019). Investigations into the periodicity of large flood events across flood potential zones is needed, including an assessment of climate teleconnections.
4. **Saturation-excess overland flow:** Higher flood modes present within the streamgage record (see below) may be due to the prevalence of saturation-excess overland flow during large floods. Greater understanding of the prevalence and extent of this mechanism may likely be needed to better understand the processes that induce large floods.
5. **Machine learning:** Investigations into the value of flood potential zones for constraining machine learning-based research on flooding is needed.

Extreme floods are, by definition, of an atypically large size compared to the expected flood potential (central tendency) of large floods and the observed intrazonal variability in flood magnitudes (scatter). The most extreme events represent the envelope curve for large floods within each zone. Understanding of such extreme floods, from a zonal perspective, is important for the management of high hazard infrastructure, such as dams and nuclear power plants. With the flood potential method systematically identifying and ranking extreme floods, opportunities are provided for research to better understand extreme events. A shapefile database of extreme floods is provided on the project webpage, which can form the basis for research into the fundamental nature of extreme events.

6. Greater understanding of the atmospheric and hydrologic conditions that have resulted in extreme flooding is needed. There are excellent opportunities for investigation of these extreme floods, especially more recent events where satellite and other remotely sensed data are available. Previous work in the field includes:
    a. Boner and Stermitz (1967): Floods of June 1964 in Northwestern Montana
    b. Wolman and Costa (1984): Envelope curves for extreme flood events: Discussion
    c. Costa (1987): A comparison of the largest rainfall-runoff floods in the United States with those of the People's Republic of China and the world
    d. Hirschboeck (1987): Catastrophic flooding and atmospheric circulation anomalies
    e. Smith et al. (2000): Catastrophic rainfall and flooding in Texas
    f. Osterkamp and Friedman (2000): The disparity between extreme rainfall events and rare floods – with emphasis on the semi-arid American West
    g. Jarrett and Vandas (2006): 1976 Big Thompson Flood
    h. O'Connor and Costa (2004): Spatial distribution of the largest rainfall-runoff floods from basins between 2.6 and 26,000 km^2 in the United States and Puerto Rico
    i. Gochis et al. (2015): The great Colorado flood of September 2013
    j. Saharia et al. (2017): Characterization of floods in the United States
    k. Smith et al. (2018): Strange floods: The upper tail of flood peaks in the United States
    l. Smith et al. (2019): The paroxysmal precipitation of the desert: Flash floods in the Southwest United States
    m. Tarouilly et al. (2021): Western U.S. Superfloods in the Recent Instrumental Record.
7. Spatial clustering: Floods that are more extreme appear to be clustered in some areas. What are the underlying mechanisms that make more extreme floods prevalent in such areas?

Analyses in support of the flood potential method have indicated the relevance and possible preponderance of **bimodal annual peak discharge streamgage data, due to mixed populations**. It is common for streamgage records to include both a plurality of lower magnitude flood events as well as a higher mode that is 2, 3 or even 10 times larger. With common occurrence of such larger scale floods across zonal streamgages, such larger events are not necessarily extreme but can instead represent the large flood magnitudes that need to managed and designed for. The log-Pearson distribution, the standard statistical distribution imbedded within the Bulletin 17B and 17C methods for analyzing annual peak streamgage data, poorly addresses such bimodal data (Appendix G); this is an acknowledged issue in flood-frequency analyses (England et al., 2018).

8. Development of a distribution to be used for streamgage flood-frequency analyses that properly accounts for bimodal and multimodal events, allowing practitioners to perform analyses using a more appropriate distribution than the Pearson distribution in the Bulletin 17B and 17C procedures (IACWD, 1982; England et al., 2018).
9. Understanding of the hydrologic mechanisms that induce high-mode flood events in zones that experience the mixed populations events that create bimodal annual peak datasets. Such mechanisms are expected to include rain-on-snow floods, synoptic-scale rain events, and saturation-excess overland flow.

Rainfall-runoff simulations are important for predicting flood hazards and are essential for understanding the impacts of wildfires on flooding and prognosticating future climate impacts on flood hazards. However, current rainfall-runoff modeling typically does not simulate the actual mechanisms that may be inducing large floods, with climate prediction modeling performing hydrologic simulations at too large a scale for relevance in the smaller watersheds that make up a preponderance of infrastructure projects. Research is need on such topics as:

10. Intensity-duration-frequency curves
11. Area-reduction factors (the watershed scale ratio, R_f, may be helpful)
12. Data collection, though perhaps new remote sensing tools, to better quantify mechanisms that induce riverine flooding
13. Development of modeling tools that simulate large flood-inducing mechanisms (such as saturation-excess overland flow), at sufficiently fine spatial and temporal scales to yield dependable results for infrastructure design and floodplain management.