FEMA Spillway Capacity & Extreme Flood Discharge Estimator Job Aid

Approximate Emergency Spillway Capacity and Extreme Flood Discharge

Fiscal Year 2024 Rehabilitation of High Hazard Dams Application Cycle

FEMA

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Table of Contents

Figures

Appendices

1. Introduction

1.1. Objective

The FEMA Spillway Capacity & Extreme Flood Discharge Estimator was designed to provide users with the ability to approximately estimate the discharge capacity of dam spillways and extreme flood inflow conditions when relevant design documents are not available. The computed extreme flood discharge and associated probabilities should be used for the HHPD screening-level risk assessment if a detailed probable maximum flood (PMF) study is unavailable and shall not be utilized for any design or any other purposes. Additional introduction of the FEMA Spillway Capacity & Extreme Flood Discharge Estimator is included in Section 2.2.

Questions relating to the use of this tool for the HHPD program may be directed to FEMA-NDSP@fema.dhs.gov.

1.2. Limitations

The tool is limited to developing spillway capacity for overflow spillways with a free water surface that can be estimated using weir equations. The tool cannot input riser-style or gate-controlled outlet works of a dam in the current version. No hydraulic routing or attenuation due to the upstream reservoir storage is accounted for in the spillway capacity estimation.

2. Compute Emergency Spillway Capacity

2.1. Overview

The emergency spillway capacity functionality was developed to estimate the capacity of up to two spillways of a dam structure. The calculation is based on weir discharge equations and requires the user to input spillway characteristics and geometry. The following section will help guide the user to understand each input required to calculate an estimated dam spillway capacity.

2.2. Sheet 1 – Instructions

The first sheet of the tool contains a welcome message along with basic instructions on how to use the tool (**Figure 1**). Below, there is a disclaimer stating that the tool is only to be used and shared by FEMA employees, state dam safety officials, and their approved consultants. User input is not required in this sheet.

Welcome to the FEMA Spillway Capacity & Extreme Flood Discharge Estimator Tool (Beta Version 5). Here are a few instruction about using this tool. Please refer to the Job Aid included with this tool.

Sheets 3-5 should be used to calculate the spillway capacity and extreem flood inflow for your structure. The following steps explain the methodology for data entry.

1. Go to the "2. Dam info" tab and enter dam information from the National Inventory of dams (NID) or other source and indicate if spillway capacity or probable maximum flood (PMF) flow is known. If spillway capacity is not known continue to steps 2 and 3, otherwise move to step 4.
2. Go to the "3. Spillway Type" tab and use the information to identify the weir type of the spillway and the length of the spillway.
3. Go to the "4. Emergency Spillway Capacity" and enter the spillway geometry and characteristics data to calculate the spillway capacity.
4. If PMF discharge is not known, go to the "5. Extreme Flood Discharge" Tab and enter the StreamStats and Drainage Area location data to estimate the extreme flood discharge and return period.
5. Go to the "6. Summary" Tab to see a summary of your inputs and the resulting spillway capacity and extreme flood discharge estimation.

The Spillway Capactiy & Extreme Flood Discharge Estimator tool is password protected. The tool may be copied and shared but is restricted to staff personnel and consultants approved by the state. It is not to be copied and provided to the public.
This is a screening level tool. It is only intended for use in applying for HHPD grant funding. It should not be used for design or other purposes.

Figure 1. Instructions Sheet

2.3. Sheet 2 – Dam Information

STEP 1: NATIONAL INVENTORY OF DAMS (NID) DATA

No data in this table is required by the tool to function. It is however, suggested to be completed for organization and tracking of the data for the subject dam. The data is reported in the final summary sheet for the tool calculations. **Figure 2** shows the dam information table.

National Inventory of Dams (NID) Data	
Dam Name:	Test
NID ID:	Test
State:	State
NID Hazard Potential:	High
Owner Type:	Local Gov
Latitude (in decimal degrees)	41.15333
Longitude (in decimal degress) (must be negative)	-80.77917

Figure 2. NID Data Inputs

Latitude and Longitude are suggested to be entered in decimal degrees as they are needed in the Project Prioritization Tool (PPT) in those units.

STEP 2: EVALUATOR INFORMATION

Again, the data in this table is not required but is meant to provide organization and tracking of the calculation. It is reported in the final summary sheet for the tool calculation. **Figure 3** shows the evaluator information table.

Evaluator Information	
Evaluator Name:	
Organization:	
Date of Evaluation:	

Figure 3. Evaluator Information Inputs

STEP 3: PREVIOUS DAM CAPACITY INFORMATION

This section allows the user to indicate if they have any previous information about the spillway capacity or PMF inflow for the subject dam. Figure 4 shows the tool default conditions of the user having no knowledge of previous information of the spillway capacity or PMF inflow.

Previous Dam Capacity Information	
Do you know the spillway capacity of the dam?	No
Do you know the PMF flow associated with the dam?	No

Figure 4. Previous Dam Capacity Information with Default Settings

If the user has information about either the spillway capacity or the PMF inflow, toggle the answers in the table to "Yes". A cell will then be displayed for the user to input the data. The user input data will be used in lieu of the calculated data. Figure 5 shows the Previous Dam Capacity Information table indicating the users has knowledge on both the spillway capacity and the PMF inflow.

Previous Dam Capacity Information	
Do you know the spillway capacity of the dam?	Yes
Known Spillway Capacity (cfs)	
Do you know the PMF flow associated with the dam?	Yes
Known PMF Flow (cfs)	

Figure 5. Previous Dam Capacity Information Table Indicating the User has Data for Spillway Capacity and PMF Inflow

2.4. Sheet 3 – Spillway Type

This sheet is provided to help the user define inputs for the spillway that will be used for the spillway capacity calculation.

Step 1: Spillway Type and Suggested Weir Condition

The tool can estimate spillway capacity for three different weir conditions: broad crested, sharp crested, and ogee crest weirs. Table 1 in this sheet illustrates each spillway type with a reference image and the suggested weir condition. To estimate the spillway capacity, in this step, users will have to select a weir condition that most applies to the spillway.

Step 2: Spillway Width Measurement

Spillway width is best acquired using previously published data for the structure. This data may be available in the National Inventory of Dams (NID), site observation, survey, inspection reports or as-built drawings. If spillway width data is not available, the width can be approximately estimated using aerial photography or high-resolution terrain data, both of which are accessible using the Google Earth and USACE Dam Screening Tool (DST). Table 2 on the "3. Spillway Type" sheet of the tool should be populated with spillway measurements. The tool provides the ability to estimate spillway capacity for up to two spillways indicated in the tool as "Primary" and "Secondary/Auxiliary". Both spillways must be overflow style spillways as the current version of the tool does not provide estimates for the capacity of riser-type spillways. **Figure 6** shows Table 2 using the Primary and Secondary/Auxiliary spillways option without additional measurement data.

Table 2: Spillway Width Data		
*Is there a secondary/auxilliary spillway?	Yes	
Structure Spillway:	Primary	Secondary/Auxilliary
*Total spillway width Including piers (ft), L_T:		
*Number of piers:		
Net Spillway Width, L_{NET}:	0	0

Figure 6. Table 2 Spillway Width Data Indicating Two Spillways without Additional Measurement Data

The following presents some methodologies for estimating the spillway width if other sources are unable to provide sufficient information.

Using Google Earth to Measure Primary Spillway with no Piers.

Figure 7 shows a spillway section of a dam as viewed from aerial photography in Google Earth. This dam has a walkway bridge over the spillway, but no piers. The spillway width can be estimated by measuring the distance between the left and right abutments.

Figure 7. Aerial Image from Google Earth of a Dam Emergency Spillway

Zooming into the image, the left and right abutment can be seen in the approach section of the spillway. Using the measuring tool in Google Earth the total spillway width can be estimated. See the image with the measured total spillway width in Google Earth below in Figure 8.

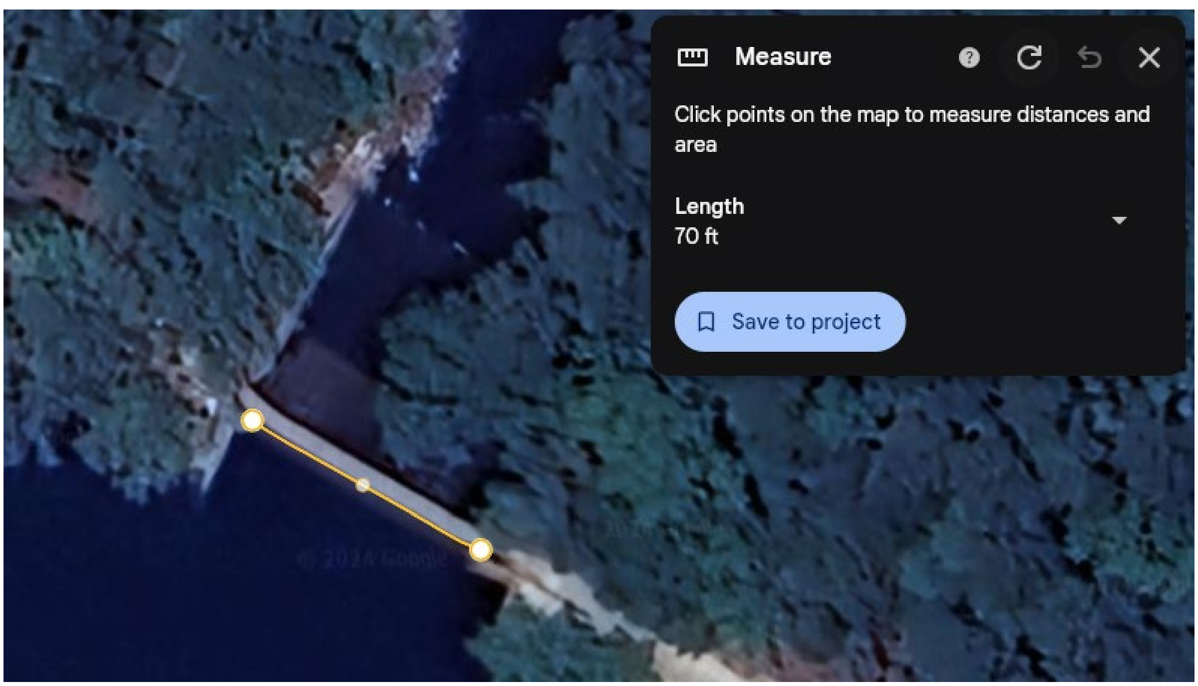

Figure 8. Google Earth Measurement of Total Spillway Width

Figure 9 shows Table 2 with the Google Earth estimated spillway width.

Table 2: Spillway Width Data	
*Is there a secondary/auxilliary spillway?	No
Structure Spillway:	Primary
*Total spillway width Including piers (ft), L_T:	70
*Number of piers:	0
Net Spillway Width, L_{NET}:	70

Figure 9. Table 2 Filled out For the Primary Spillway Only Condition Using Data Measure in Google Earth

<u>Using Google Earth to Measure Primary Spillway with Piers</u>

Using Google Earth aerial photography, we can see the following image shows a concrete spillway structure with piers. To input data for Table 2 the total spillway width including piers as well as the number of and width of the piers. **Figure 10** shows the total spillway width measurement from abutment to abutment.

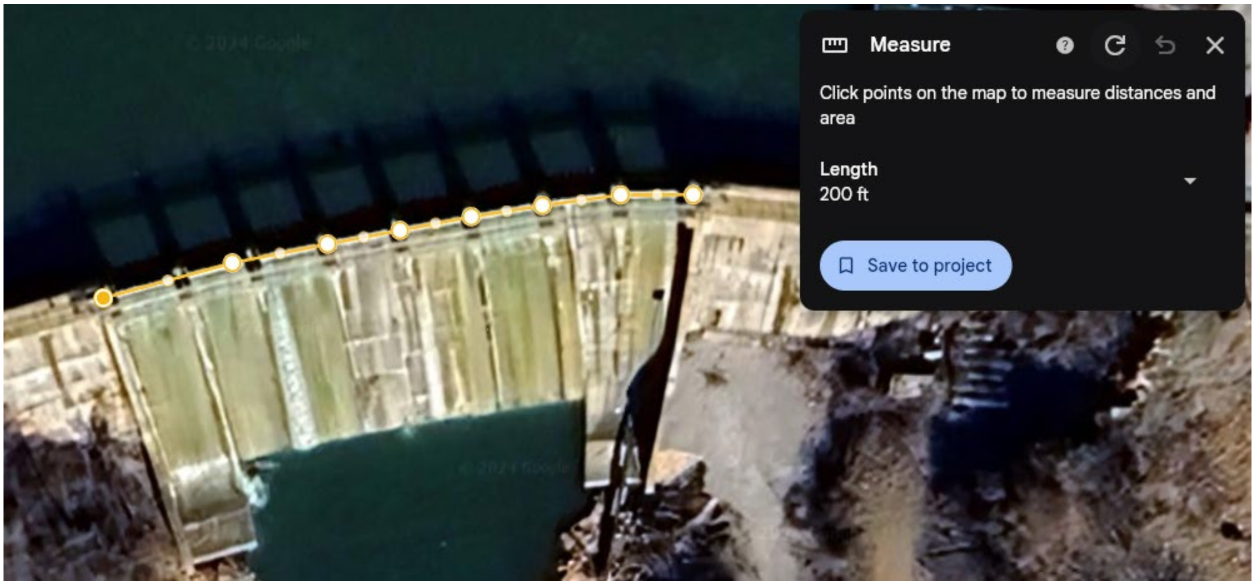

Figure 10. Total Spillway Width Including Piers Measurement

After counting the piers for the structure, the measure tool can again be used to estimate the width of the piers. See **Figure 11**.

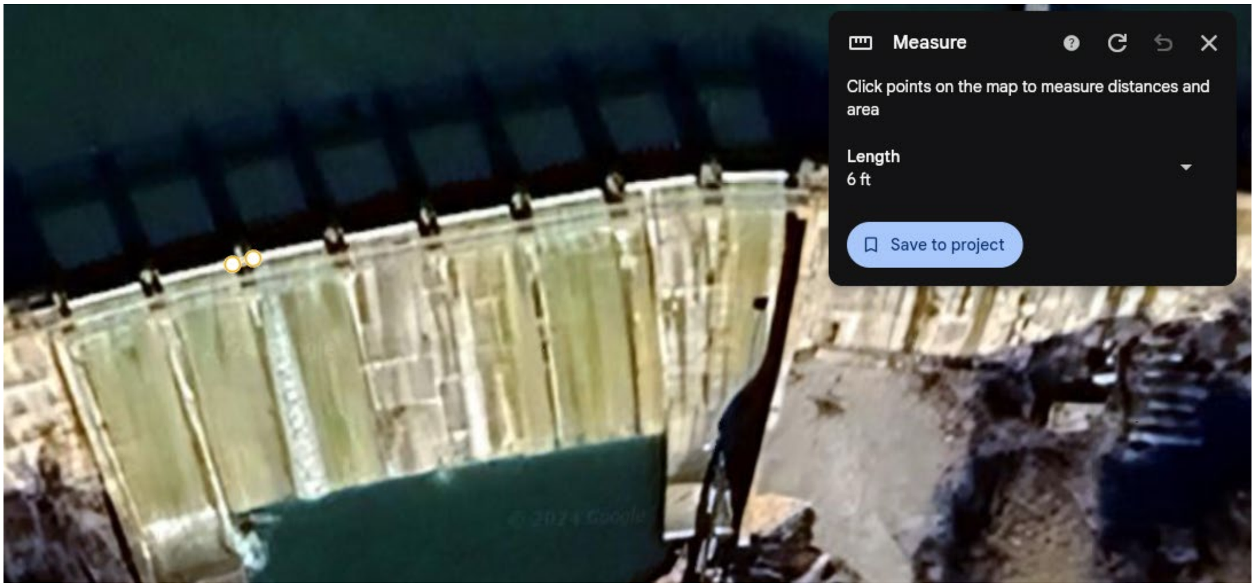

Figure 11. Estimating Pier Width in Google Earth

Figure 12 shows Table 2 with the spillway and pier data entered and the resulting net spillway width for the structure.

Table 2: Spillway Width Data	
*Is there a secondary/auxilliary spillway?	No
Structure Spillway:	Primary
*Total spillway width Including piers (ft), L_T:	200
*Number of piers:	7
*Pier Width (ft), L_p:	6
Net Spillway Width, L_{NET}:	158

Figure 12. Table 2 Data for Primary Spillway with Piers Measured in Google Earth

2.5. Sheet 4 – Emergency Spillway Capacity

On the Emergency Spillway Capacity sheet, spillway geometry and characteristics are the required inputs provided by the user for estimating the spillway capacity. Based on dam conditions, this sheet can perform the calculations for the Primary or Secondary/Auxiliary spillways based on the data selected on the Spillway Type sheet. **Figure 13** shows the Spillway Geometry and Characteristics table with no data entered. Description of each input follows.

Spillway Geometry & Characteristics		
Structure Spillway:	Primary	Secondary/Auxilliary
*Weir Type:	Broad Crested	N/A
*Do you wish to use a user-defined weir coefficient?	No	No
*Top of Dam Elevation:		
*Spillway Crest Elevation:		
*Side Slope (H:V):		
Net Spillway Width, L_{NET}:	0	0
Does the spillway have piers?	No	No
*Are abutments perpendicular to flow?	No	No

Figure 13. Spillway Geometry and Characteristics Input Data Table

Weir Type

In step one on the spillway type sheet (**Section 2.4**), the user should have investigated the structure and chose a suggested weir condition for the spillway. Indicate one of three possible weir conditions (Ogee, Broad Crested, or Sharp Crested) using the drop-down menu. If the weir type is broad crested or sharp crested, additional inputs provided by the user will be asked by the sheet.

Figure 14 shows the inputs for a broad crested weir type. Crest material can be selected as Gravel/Unpaved or Paved/Smooth Surface using the drop-down menu.

Broad Crested Weir User Inputs	
*Crest Material	Gravel/Unpaved
*Longitudinal Length (ft), L_r:	
*Downstream Water Surface Height Above Sill (ft), h_t:	

Figure 14. Broad Crested Weir Type Additional Inputs

For the two other inputs, reference **Figure 15** below. Longitudinal Length refers to the crest length in the longitudinal direction (i.e., in the direction of flow). Downstream Water surface height above sill (h_t) is to be used when the tailwater elevation is above the crest of the weir also referred to as a submerged flow condition. For most conditions and spillways this should be zero feet to represent a free outflow condition.

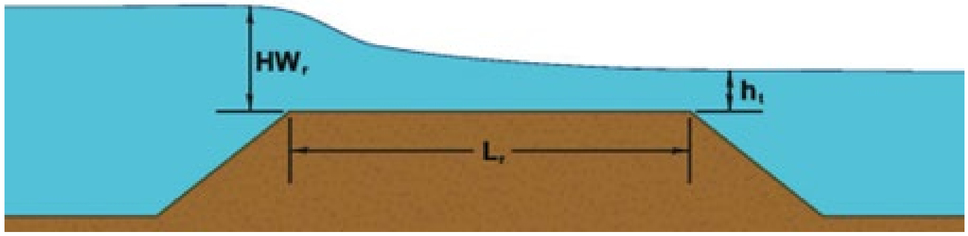

Figure 15. Broad Crested Weir Reference Image

The sharp crested weir type additional inputs are shown in **Figure 16** and **Figure 17**. Two additional inputs are required for sharp crested weir type. The first is the downstream water surface height above sill. As stated above, this represents a condition where the tailwater elevation is above the weir crest elevation. For most conditions and spillways this should be zero feet to represent a free outflow condition. The second input is the height of the weir crest above the invert of the approach channel. This is shown as "P" in **Figure 17** If this is not known, the user can leave the cell blank, and the tool will assume a sharp crested weir discharge coefficient of 3.3.

Sharp Crested Weir User Inputs	
*Downstream Water Surface Height Above Sill (ft), H_2:	
*Height of weir crest above approach channel invert (ft), P:	

Figure 16. Sharp Crested Weir Type Additional Inputs

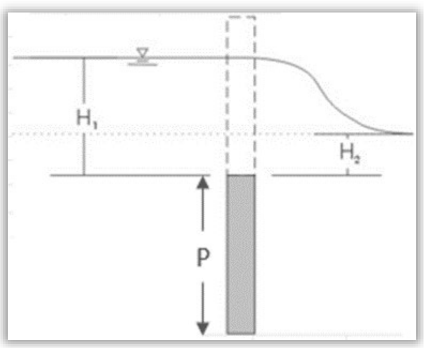

Figure 17. Sharp Crested Weir Reference Image

Do you wish to use a user-defined weir coefficient?

Based on the weir type inputs, the tool will automatically calculate a weir discharge coefficient. However, if the user has a preferred weir coefficient or is unsatisfied with the calculated coefficient, they can input a user-defined weir coefficient. To do so, select "Yes" using the drop-down menu. A cell to input the user-defined coefficient will be displayed (**Figure 18**).

*Do you wish to use a user-defined weir coefficient?	Yes
*User entered weir coeffeicnt, Cd:	

Figure 18. User-Defined Weir Coefficient Option

Broad crested spillways such as a runaround or chute spillways may have a significant longitudinal length that is difficult to define. In this case, it is suggested to use a user-defined weir coefficient of 2.6.

Top of Dam Elevation, Spillway Crest Elevation and Side Slope

Top of dam elevation and spillway crest elevation should be entered using the best available data. If these data are unavailable to the user, they can be estimated using the terrain layer of the DST. Reference the DST Job Aid (FEMA 2024) for instructions to display the DST terrain layer. Once the terrain layer is displayed in the DST program, hover the cursor along the top of dam and the spillway sill to estimate an elevation for each. Figure 19 shows an example of using the DST terrain layer to estimate the spillway sill elevation.

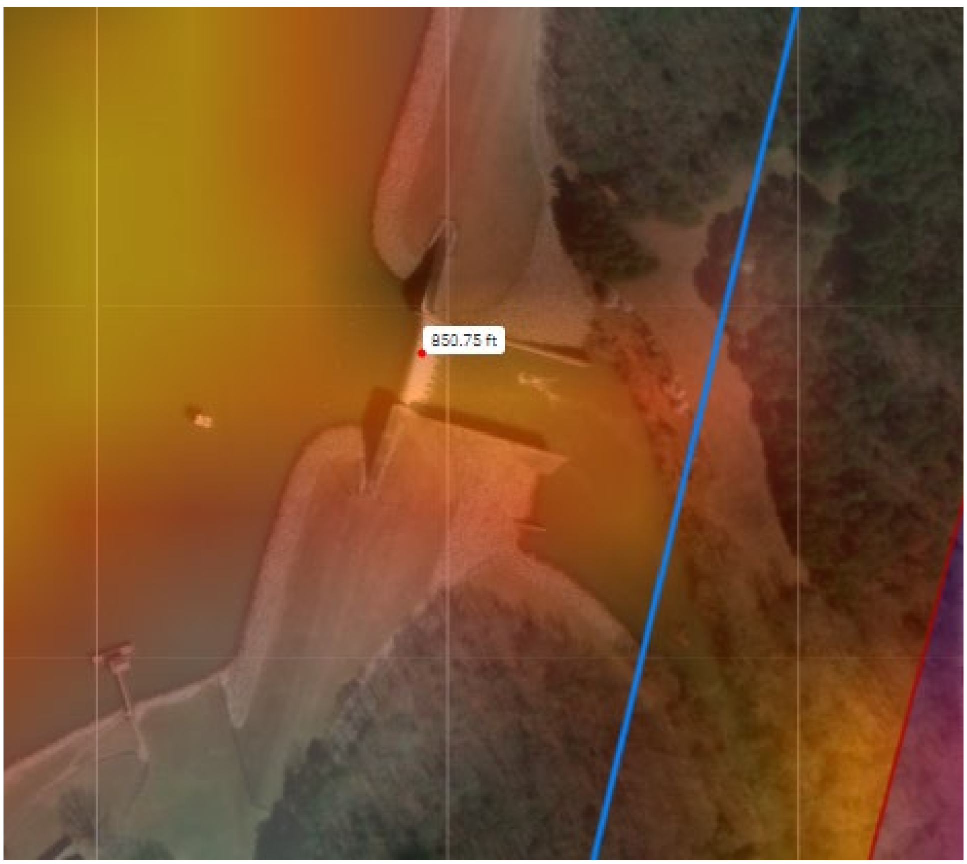

Figure 19. Approximate Spillway Sill Elevation from DST Terrain Layer

If side slope data is unavailable, enter zero for vertical walls and 2.5 if the spillway has a trapezoidal geometry.

Pier Nose Type

If the user indicated that the structure has piers on the Spillway Type sheet, then the tool will prompt the user to choose a pier nose type. Three options are available as shown in Figure 20. Select the type that best represents the structure using the drop-down menu.

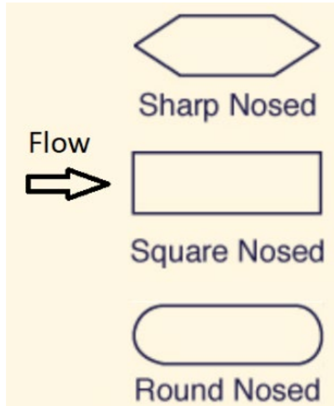

Figure 20. Pier Nose Type Reference

Are abutments perpendicular to flow?

If the spillway abutments are perpendicular to the flow indicate "Yes" using the drop-down menu. Use Figure 21 to indicate if the abutment is "Square" or "Rounded".

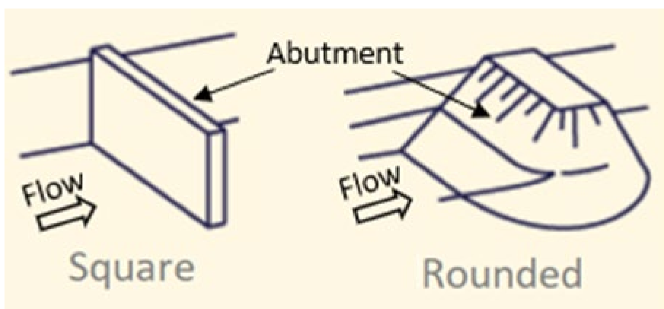

Figure 21. Abutment Type Reference

Figure 22 shows an example of spillway abutments perpendicular to the flow.

Figure 22. Weir Abutment Perpendicular to flow

Once all input data is complete, the tool will report the calculated weir coefficient and the spillway capacity for each spillway. A combined capacity is also calculated if the user indicates a primary spillway and a secondary/auxiliary spillway. **Figure 23** shows an example of the calculated weir coefficients and the spillway capacities.

Spillway Capacity Output		
Weir Coefficent, Cd	3.60	3.00
Spillway Capacity, Q (cfs):	17759	33960
Total Capacity, Q (cfs)	51720	

Figure 23. Calculated Weir Coefficient and Spillway Capacities Example

3. Approximate Probable Maximum Flood Discharge Calculation

3.1. Overview

This section outlines the steps required to estimate Extreme Flood Discharge for a given drainage area. The computed extreme flood discharge could be considered as an approximation of the Probable Maximum Flood (PMF) discharge when detailed PMF studies are unavailable. The term "Approximate PMF" is used throughout this guidance to represent the Extreme Flood Discharge calculated by the tool. The methodology underlying the estimation of Extreme Flood Discharge (i.e., Approximate PMF) is detailed in Appendix A.

3.2. Sheet 5 – Extreme Flood Discharge

STEP 1: INPUT FLOOD FREQUENCY DISCHARGES

If site-specific flood frequency discharge data is available, complete Table 1 with the corresponding values. The first column represents the Percent Annual Chance (PAC) of a flood event occurring, while the second column shows the associated return interval, calculated as 100/PAC. The third column requires the user to input the discharge or inflow corresponding to each return interval (**Figure 24**).

Alternative Data Source: In the absence of site-specific flood frequency discharge data, StreamStats (https://streamstats.usgs.gov/ss/) is a web based program that can be utilized as a reliable source to obtain the necessary information.

Table 1. Flood Frequency Discharge		
Percent annual chance of flood[1]	Return Interval (Yrs)	Discharge or Inflow (cfs)[2]
50	2	604
20	5	1030
4	25	1820
1	100	2620
0.2	500	3560

Figure 24. Table 1 showing Frequency Flood Discharges

STEP 2: LOCATE DRAINAGE AREA OF A STRUCTURE

Use the Google Earth .kmz file (FloodRegBoundaries.kmz) or the GIS shapefile (FloodRegBoundaries.shp) of flood region boundaries provided by this tool package to identify the flood region corresponding to the drainage area of the structure. The drainage area of a structure, such as a dam, refers to the geographic region from which all surface runoff flow toward the streams that ultimately lead to the structure. This area is typically bounded by natural topographical features, such as ridges or divides, that direct water towards the structure. If the drainage area is not available, it can be delineated using StreamStats. A delineated drainage area can be exported in either shapefile or KMZ format from StreamStats.

- **Google Earth Pro Users (KMZ file):**

The KMZ file of flood region boundaries (FloodRegBoundaries.kmz) can be opened in “Google Earth Pro” by simply double-clicking it. To import the drainage area, go to the File menu, select Open, and navigate to the folder where the drainage area file is stored, then select it. The drainage area will be added to the map, and by clicking on the region, the name of the region can be located. For example, the **Figure 25** shows a drainage area located in Region 6.

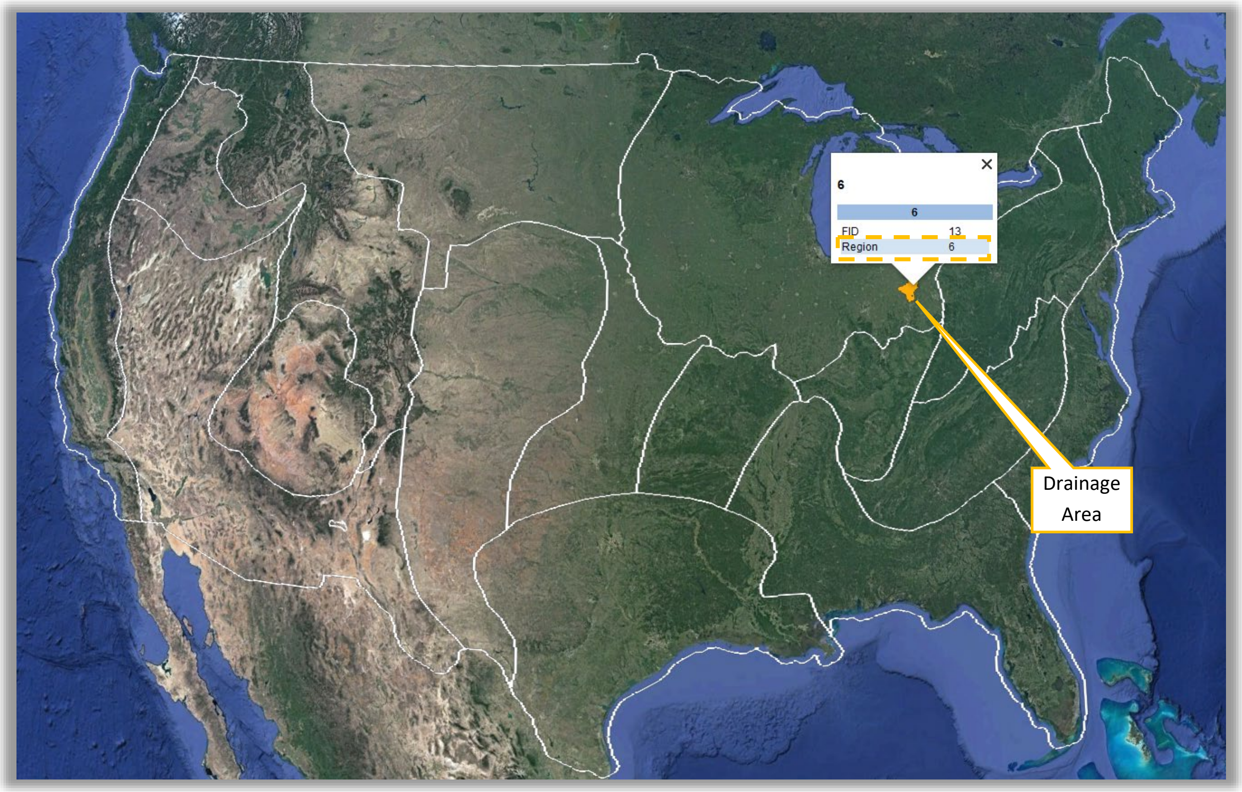

Figure 25. Imported Drainage Area Displayed in Google Earth Pro

- ArcGIS Pro Users (Shapefile):

The flood region boundaries shapefile (FloodRegBoundaries.shp) can be opened in ArcGIS Pro (or ArcMap). Add and display both the flood region boundaries shapefile and the drainage area shapefile to the map to locate the region. **Figure 26** below shows an example where the drainage area is located in Region 6.

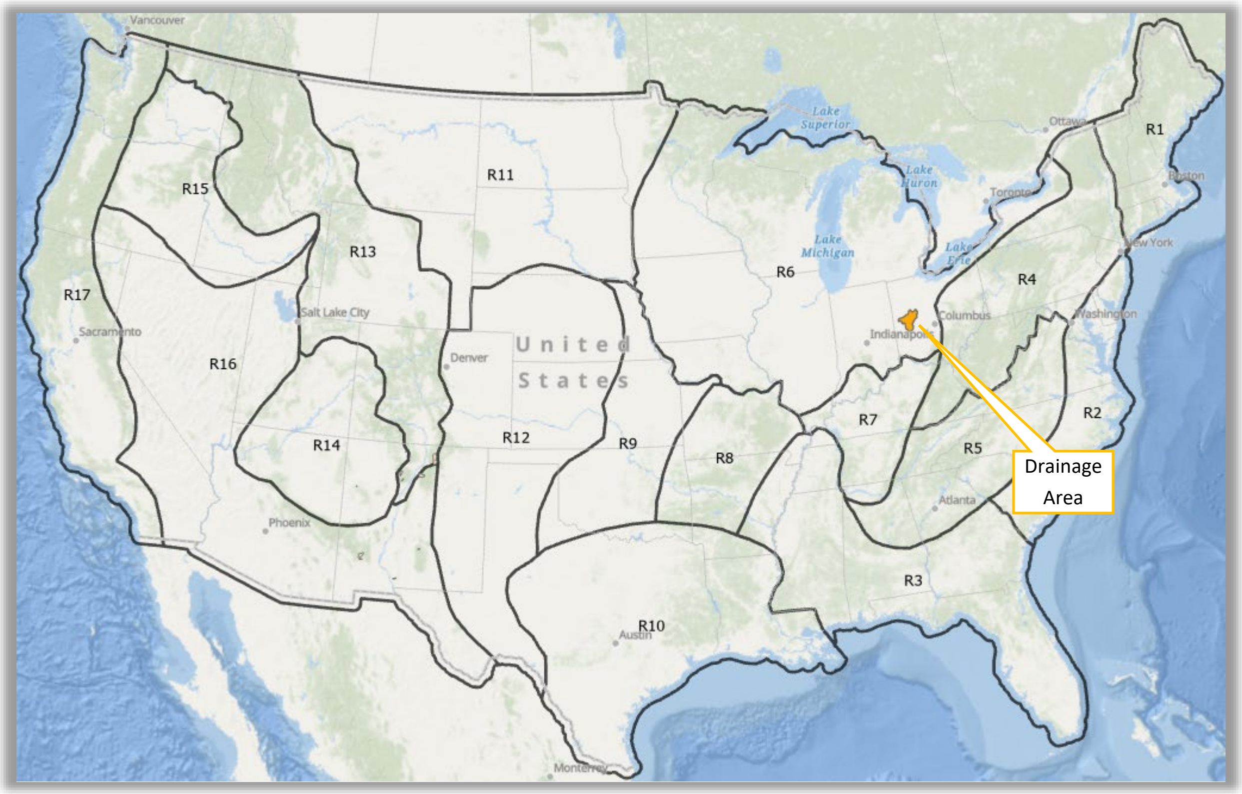

Figure 26. Imported Drainage Area Displayed in ArcGIS Pro

STEP 3: ESTIMATE APPROXIMATE PROBABLE MAXIMUM FLOOD (PMF)

Table 2 is used to estimate the Approximate PMF. The first input required is the number of flood regions intersecting the drainage area, which can be 1, 2, or 3. If the drainage area does not intersect multiple flood regions, select 1, which is the default value. Next, enter the value of the drainage area and choose the region where the structure drainage area is located. If the drainage area intersects multiple flood regions, refer to the "Additional Applications" section provided at the end of this section.

Once the drainage area and the flood region it intersects are entered, the other cells will automatically populate with the corresponding values. For example, as shown in **Figure 27**, for a 10 mi^2 drainage area located in Region 6, the Approximate PMF is 43,000 cfs, with the coefficients used in the envelope curve displayed in the last four columns (Refer to Appendix A for more details about the coefficients). This computed PMF value will be used in Sheet 6 – Summary for the remaining analysis.

Table 2. Regional PMF Calculation

What number of flood-regions intersect with the structure's drainage area? (max of 3)			1						
ID	Drainage Area (mi^2)	% of Total Drainage Area	Flood Region	Un Rounded Computed Approx. PMF (cfs)	Computed Approx. PMF (cfs)	K1	K2	K3	K4
1	10	100%	6	43350	43000	45000	0.85	-0.95	5
Total	10	100%		43350	43000				

Figure 27. Table 2 Displaying the Regional PMF Calculation for a Drainage Area that intersects with one Flood Region

3.3. Additional Applications

1. For some structures, their drainage areas might intersect with more than one flood region. In such cases, based on the structure drainage area boundary, the intersected area within each flood region boundary should be computed. For example, if a 10 mi² drainage area intersects both Region 6 and Region 4, the intersected areas within Region 6 and Region 4 should be separately determined. To compute the intersected areas within different flood region boundaries, for example, using the "Intersect" tool of ArcGIS Pro program to overlay the structure drainage area with the flood region boundaries and calculate the area of each intersected segment. In Table 2 of the sheet of "5. Extreme Flood Discharge", select either "2" or "3" based on the number of flood regions intersecting with the drainage area. Depending on the selection, one or two new rows will be added to the table. Enter the intersected drainage area corresponding to each region. For example, as shown in **Figure 28**, an 8 mi² area of a 10 mi² drainage area is located in Region 6 and the remaining 2 mi² is located in Region 4. The computed Approximate PMF is 32,000 cfs.

Table 2. Regional PMF Calculation

What number of flood-regions intersect with the structure's drainage area? (max of 3)			2						
ID	Drainage Area (mi^2)	% of Total Drainage Area	Flood Region	Un Rounded Computed Approx. PMF (cfs)	Computed Approx. PMF (cfs)	K1	K2	K3	K4
1	8	80%	6	37312	37000	45000	0.85	-0.95	5
2	2	20%	4	8593	8600	60000	0.95	-1.4	5
Total	10	100%		31568	32000				

Figure 28. Table 2 Displaying the Regional PMF Calculation for a Drainage Area that intersect with two Flood Regions

2. The Approximate PMF estimation is specifically developed for the contiguous United States (CONUS) and does not cover Puerto Rico, Hawaii, and Alaska. Based on comparisons of previous PMF studies in these regions with the developed CONUS curve (Figure 19, Appendix B), it is recommended that the CONUS envelope curve be selected as the flood region for analyses in Puerto Rico and Hawaii. In the case of Alaska, the comparison indicates that the Region 17 curve (Figure 18, Appendix B) also provides a reliable estimate. Therefore, it is suggested to use either CONUS or Region 17 for the analysis in Alaska. It is important to note that choosing CONUS as the flood region will provide the most conservative estimate.

3. The comparisons between the Approximate PMF discharges and the previous PMF studies for Regions 1-3 indicate that the developed envelop curve discharges may be less than the PMF discharges from the previous detailed studies (Refer to Appendix A for more details). To address this, an additional regression curve was created based on the average PMF from earlier studies. In fact, the previous PMF studies were prepared by performing a watershed hydrological modeling from the critical PMP storm event in accordance with the NOAA HMR guidance. These studies present the results, which are subjective to engineer's selections of the hydrologic model inputs and were not calibrated. In accordance with the recent modern PMP research (examples provided in Appendix B of this job aid) in Regions 1, 2 and 3, the PMP depths calculated using the HMR methods, such as HMR 51, are often overestimated and could lead to overestimate the PMF discharge to a structure. While users can still apply the additional curve for Regions 1-3 (R 1,2,3 PMF), they should be aware that, according to the latest studies, this approach may result in an overestimation of the PMF.

4. Computation Summary and Export the Outputs

4.1. Overview

Once users have selected and input all applicable data for the spillway capacity computation and the extreme flood discharge estimation, they may proceed to Sheet 6 – Summary.

4.2. Sheet 6 – Summary

The Summary sheet serves as a compilation of information gathered from the preceding sheets, providing users with convenient access to critical input data and computation results. The sheet presents the computed discharges of a dam spillway capacity and the extreme flood discharge and the corresponding annual exceeding probabilities (AEP). To estimate the AEP, a standard power function as shown in **Figure 29** is fit to the flood frequency discharge data. The resulting function is used to calculate the AEP for both the spillway capacity and the extreme flood discharge.

Export Results to HHDP Project Prioritization Tool

On the summary sheet, Section 4 RESULTS shows the output results from the tool. These outputs can be used in the PPT for a risk assessment. **Figure 29** shows the results data to be used in the PPT. Reference the PPT Job Aid for instruction on entering data.

Printing to PDF

The Summary page is designed to be easily printable to PDF format, facilitating the exportation of information for documentation or further analysis purposes.

4. RESULTS

The following data are to be used in the FEMA Project Prioritization Tool

	Flow (cfs)	Return Period (Yrs)
PMF	32000	249927
Spillway Capacity	16176	31001
Spillway Capacity % of PMF	51%	

Data to be used in PPT

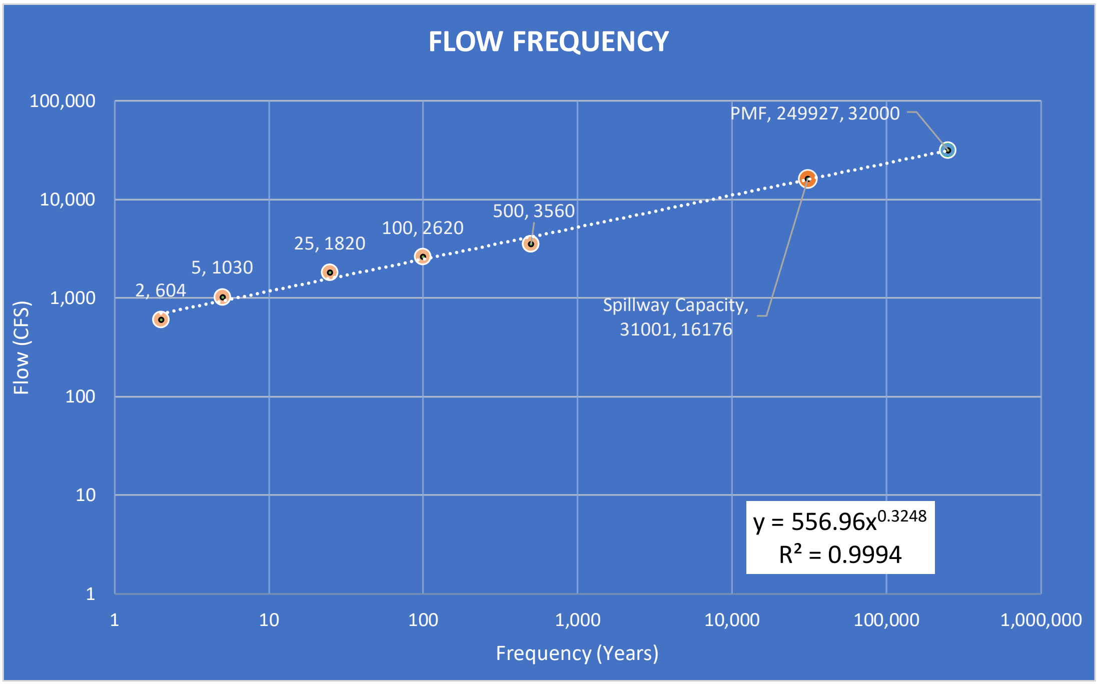

Figure 29. Summary Sheet Output Data to be Used in the HHDP Project Prioritization Tool

5. References

Crippen, J.R., Bue, C.D., 1977. Maximum flood flows in the conterminous United States. US Geological Survey Water Supply Paper.

Federal Emergency Management Agency, 2024. Create a Risk Assessment Using the FEMA Project Prioritization Tool. FEMA Project Prioritization Tool Guidance.

Appendix A. *Spillway Discharge Capacity Estimation Methodology*

This appendix outlines the methodology used to estimate the spillway discharge capacity for a given dam spillway.

Using weir discharge calculations is an appropriate engineering methodology to calculate the discharge of dam spillways. This methodology has been leveraged to approximate the discharge capacity of a dam spillway given spillway geometry estimations and weir type.

Weir Type and Discharge Coefficient Calculation

Three weir types were considered based on most dam spillway.

- Broad-crested
- Sharp-crested
- Ogee

For each weir type, the tool calculates a weir discharge coefficient. Methodologies differ for each weir type as described as follows.

Broad Crested Discharge Coefficient Methodology

Broad crested discharge coefficient was estimated using a methodology from the Federal Highway Administration (FWHA) Hydraulic Desing of Highway Culverts, Third Edition (2012). Assuming a broad crested spillway section is similar to that of a roadway embankment, the discharge coefficient can be approximated given the headwater and tailwater conditions and the longitudinal width of the crest. **Figure 1** shows a broad crested weir profile and plots which allow for estimation of the discharge coefficient based on the flow characteristics and geometry of the weir.

Based on the ratio of the headwater height (HW_r) above the weir crest and the longitudinal width (L_r), a no-submergence discharge coefficient (C_r) can be calculated using plots A or B. Plot C all is used to calculate a submergence factor (k_t) based on the ratio of HW_r to the tail water height (h_t) above the weir crest. A final weir discharge coefficient (C_d) is calculated using the following equation:

$$C_d = K_t * C_r$$

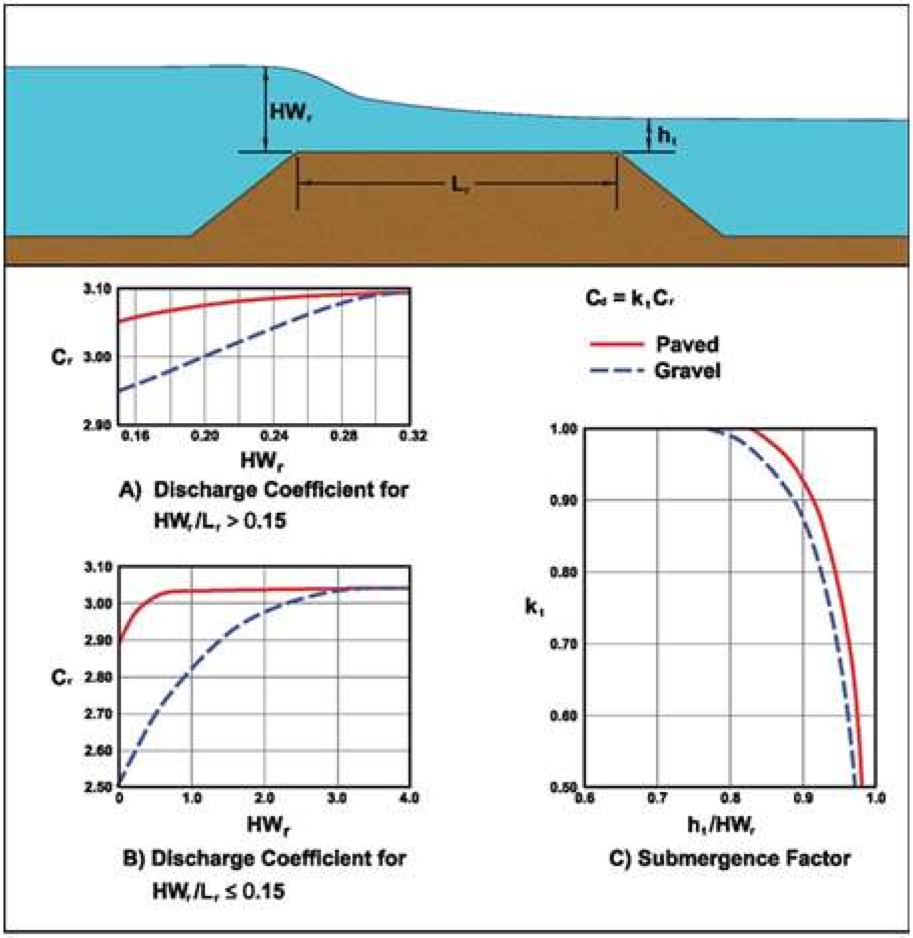

Figure 1. Broad Crested Discharge Coefficient Relationship (FWHA, 2012)

Sharp Crested Weir Discharge Coefficient Calculation

Sharp crested weir discharge coefficient was calculated using Rehbock's 1929 methodology. The method uses the relationship between water head over the weir crest (h) the weir height (P). **Figure 2** shows a graphical representation of h and P.

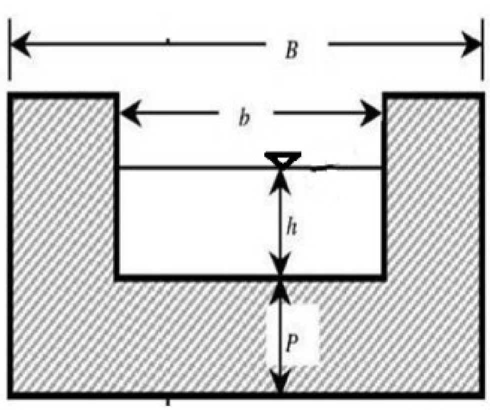

Figure 2. Sharp Crested Weir Variables

The sharp crested weir coefficient was calculated using the following equation:

$$C_d = 2/3*(2g)^{0.5}(0.611 + 0.08(h/P)+h/1000)$$

Where:

g = 32.2 ft/$s^2$and acceleration due to gravity

In the case where P is not known by the user, the sharp crested weir discharge coefficient is assumed to be 3.3.

Ogee Weir Discharge Coefficient Calculation

Ogee weir discharge coefficient is calculated based on the height of the upstream face (P) and the head water elevation above the crest (H_o). **Figure 3** (US Bureau of Reclamation) below shows the relationship between P and H_o and the discharge coefficient (C_o). Due to the lack of easily accessible data for the height of the upstream face, the discharge coefficient was conservatively assumed to be 3.6 for all ogee crested spillways.

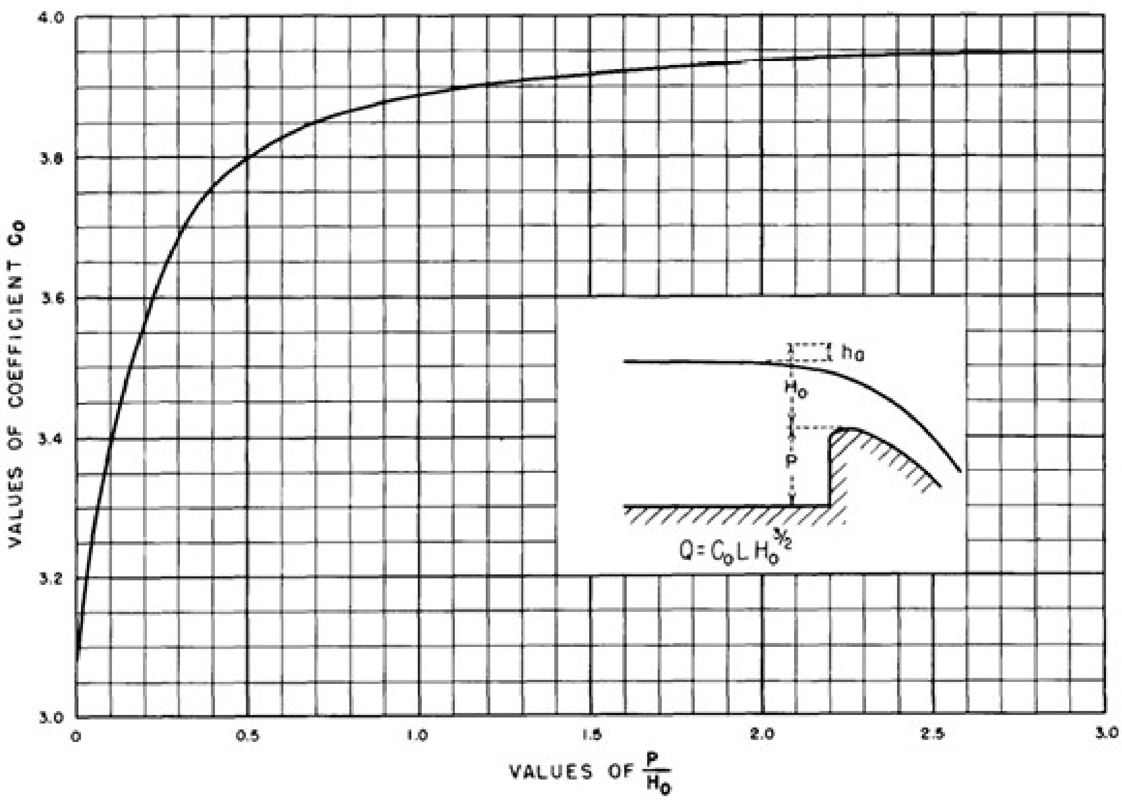

Figure 3. Ogee Crested Weir Discharge Coefficient relationship (USBR)

Effective Length Calculation

Contractions due to abutments and piers is accounted for by modification of the crest length. The modification was applied using the effective length calculation as presented in the USACE's Hydraulic Design of Spillways Engineer Manual. See the effective length equation below.

$$L_e = L - 2(nK_p + K_a)H_e$$

Where:

L = net length of crest
n = number of piers
K_p = pier contraction coefficient
K_a = abutment contraction coefficient
H_e = total head above crest (ft)

To avoid complexity, the pier and abutment contraction coefficients were simplified as explained in Chapter 17: Hydraulic Design of Spillways of the Hydraulic Design Handbook. See **Figure 4** below.

	K_p
For square-nosed piers with corners rounded on a radius equal to approximately 0.1 of the pier thickness	0.02
for round-nosed piers	0.01
for pointed-nose piers	0.00

The following are values of the abutment contraction coefficient

	K_a
for square abutments with headwall at 90° to the direction of flown	0.20
for rounded abutments with headwall at 90° to the direction of flow when $0.5H_e > r > 0.15H_e$	0.10
for rounded abutments, where $r > 0.5H_e$, and the headwall is placed no more than 45° to the direction of flow, where r = radius of the abutment rounding.	0.00

Figure 4. Pier and Abutment Contraction Coefficient from Chapter 17 of the Hydraulic Design of Spillways

Weir Calculation

The spillway weir calculation estimates a trapezoidal weir section using an aggregate of a rectangular weir and a v-notch weir section. This is comparable to other weir calculations in software such as EPA SWMM. Below are the equations used to estimate the weir flow for the rectangular and v-notch sections.

Rectangular:

$$Q = CLh^{3/2}$$

Where:

C = weir discharge coefficient
L = net crest length (ft)
h = total head above crest (ft)

V-notch:

$$Q = CSh^{5/2}$$

Where:

C = weir discharge coefficient
S = side slope (horizontal : vertical)
h = total head above crest (ft)

The weir discharge coefficient is assumed to be the same between the rectangular and v-notch sections. The total head above crest is estimated as the dam embankment elevation minus the spillway crest elevation, and the side slope is a user input. If the spillway is not trapezoidal, only the rectangular weir section is used to produce spillway capacity estimation.

Submergence

Submergence is assumed to only affect broad crested and sharp crested weirs for this application. As previously noted, the submergence effects on broad crested weirs are calculated when determining the weir coefficient. Therefore, additional calculations for the effect of submergence are only required for the sharp crested weir. Sharp crested weir submergence is calculated in accordance with the equation by Villemonte in 1947.

$$Q_{submerged} = Q_{free} \left[1-(h_1/h_2)^n\right]^{0.385}$$

Where:

h_1 = the upstream water level above the crest of the weir
h_2 = the downstream water level above the crest of the weir
n = the exponent in free flow relationships (rectangular=1.5, triangular=2.5)

Like the weir discharge calculation, the sharp crested submerged flow calculation is an aggregate of the rectangular and v-notch sections.

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FHWA, Hydraulic Design of Highway Culverts, 3rd Edition, (April 2012)

Mays, Larry W., ed. 1999. Hydraulic Design Handbook. 1st ed. New York: McGraw-Hill Education. Chapter 17, Hydraulic Desing of Spillway

Rehbock, T. (1929), Discussion of E. W. Schoder and K. B. Turner's ”Precise weir measurements”, Trans. ASCE 93(Paper No. 1711), 1143–1162.

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Villemonte, J.R., 1947. Submerged weir discharge studies. Engineering news record 866, 54–57.

Appendix B. *Approximate Probable Maximum Flood Discharge Estimation Methodology*

This appendix outlines the methodology used to estimate the Extreme Flood Discharge for a given drainage area as an approximation of the Probable Maximum Flood (PMF). The term "Approximate PMF" is used throughout this appendix to denote the Extreme Flood Discharge calculated by the methodology.

Flood-envelope curves have often served as guides in engineering practice, providing a representation of the maximum recorded flood flow in relation to drainage area for a given region. Various studies have developed flood-envelope curves for different regions, with one of the most comprehensive being the US Geological Survey Water Supply Report by Crippen and Bue (1977) that covers the contiguous United States (CONUS) and includes curves specifically developed for 17 distinct flood regions (Figure 1).

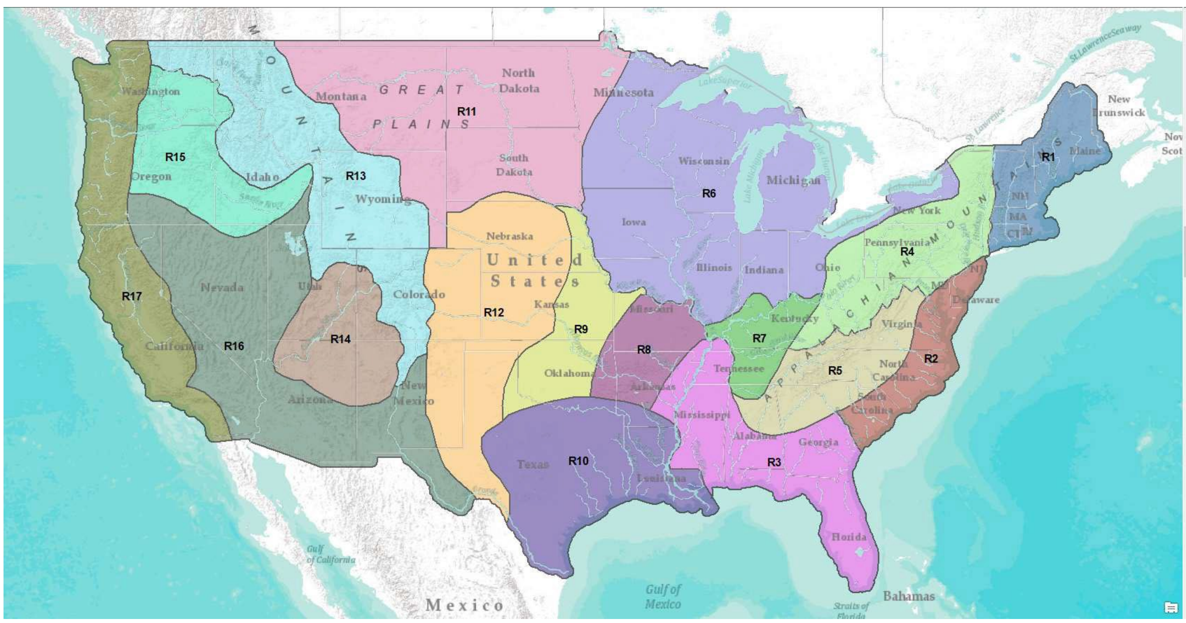

Figure 1. Map of the conterminous United States showing flood-region boundaries. (Crippen and Bue, 1977)

With the accumulation of new hydrological data over time, more recent datasets are now available. These new data sources provide additional records regarding extreme flood discharges, which can be utilized to refine the previous extreme flood envelope curves or to re-develop new envelope curves that better reflect current flood region conditions. Therefore, this analysis leverages more recent flow data alongside the data used in the Crippen and Bue report (Crippen and Bue 1977) to develop flood-envelope curves by plotting the maximum recorded flood discharges against drainage areas for 17 flood regions across CONUS. These curves estimate the highest probable flood-peak discharge observed regionally for various watershed sizes. The recent dataset comprises flood records from approximately 8,000 USGS stream gages within the CONUS, focusing on drainage areas smaller than 50,000 square miles, with data extending through the water year 2021. The historical flood data in the Crippen and Bue report (1977) were integrated with the updated dataset to ensure that flood records not captured by USGS gages, referred to as miscellaneous sites in the report, are considered in the analysis. Combined data were categorized according to the flood region boundaries. For each region, the floods were plotted logarithmically against their respective drainage areas, and an envelope curve was calculated using the following equation (Meyer 1994):

$$Qp = K_1 \times A^{(K2)}(A^{0.5} + K_4)^{K3}$$

where Qp is peak discharge computed using an envelope curve and considered as an approximate PMF in this study. The coefficients $K_1$to K_4 were estimated through iteration to ensure that the envelope curve provides reasonable limits for maximum flood estimates.

Figures 2 to 19 present the developed Flood Envelope Curves for the 17 flood regions and a national curve for the Conterminous United States (CONUS), along with their corresponding equations. Each plot includes the following elements:

- The developed flood envelope curve, depicted as a red line.
- Blue circles representing the maximum recorded flood discharges for the USGS gages in the region.
- Red diamonds indicating historical floods from the US Geological Survey Water Supply Report by Crippen and Bue (1977).
- Black triangles representing the Probable Maximum Flood (PMF) values from previous studies, where available for the region.

The estimated coefficients for all regions are presented in **Table 1**. It should be highlighted that the flood-envelope curve was developed specifically for the CONUS, excluding Puerto Rico, Hawaii, and Alaska. However, based on comparisons of previous PMF studies in these regions with the developed CONUS curve (Figure 19), it is recommended that the CONUS envelope curve be selected as the flood region for analyses in Puerto Rico and Hawaii. In the case of Alaska, the comparison indicates that the Region 17 curve (Figure 18) provides a reliable estimate. Therefore, it is suggested to use either CONUS or Region 17 for the analysis in Alaska. It is important to note that choosing CONUS as the flood region will provide the most conservative estimate.

Another important point to note is that a comparison of the developed flood curves for Regions 1-3 with previous PMF studies indicates that the developed envelop curve discharges may be less than the PMF discharges from the previous detail studies. To address this, an additional regression curve was created based on the average PMF from earlier studies (**Figure 20**). In fact, the previous PMF studies were prepared by performing a watershed hydrological modeling from the critical PMP storm event in accordance with the NOAA HMR guidance. These studies present the results, which are subjective to engineer's selections of the hydrologic model inputs and were not calibrated. In accordance with the recent modern PMP researches (examples provided in Appendix B of this job aid) in Regions 1, 2 and 3, the PMP depths calculated using the HMR methods, such as HMR 51, are often overestimated and could lead to overestimate the PMF discharge to a structure. While users can still utilize the additional curve for Regions 1-3, they should be aware that, according to the latest studies, this approach may overestimate the PMF.

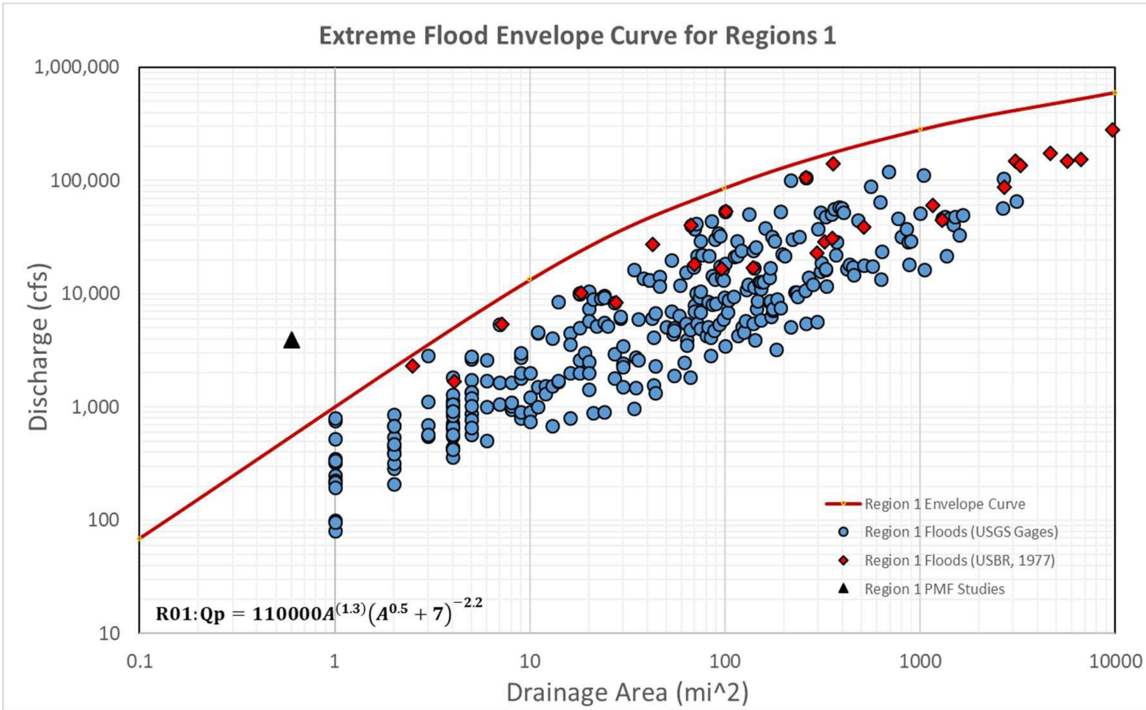

Figure 2. Flood envelope curve for Flood Region 1

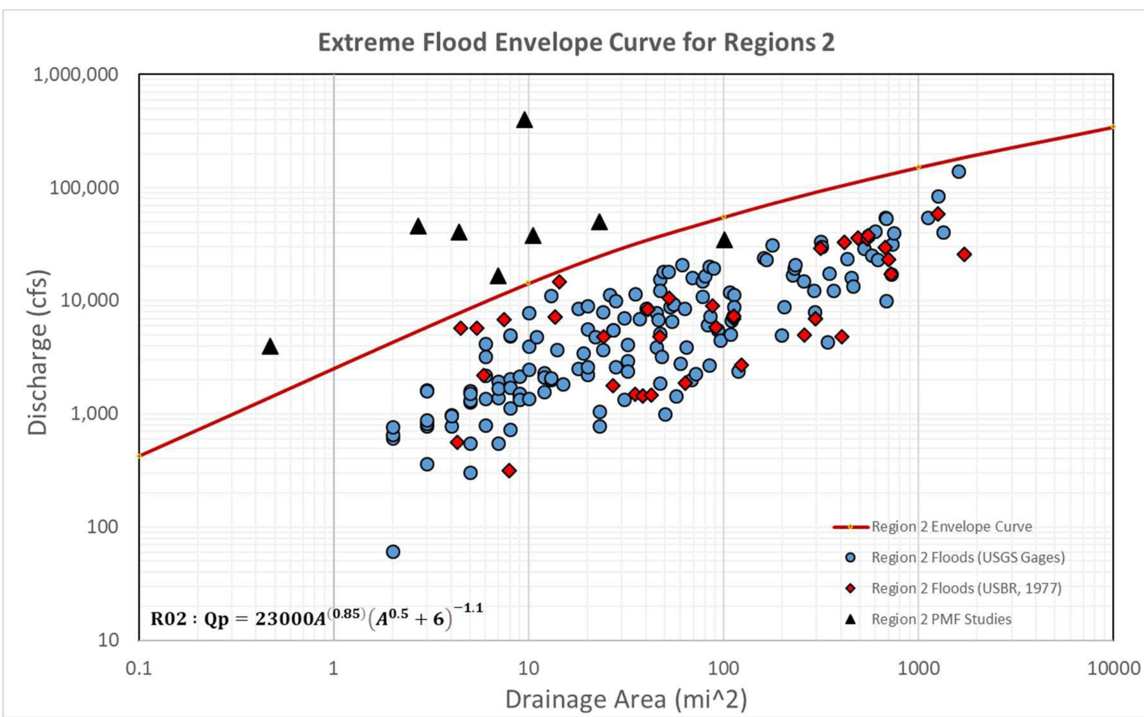

Figure 3. Flood envelope curve for Flood Region 2

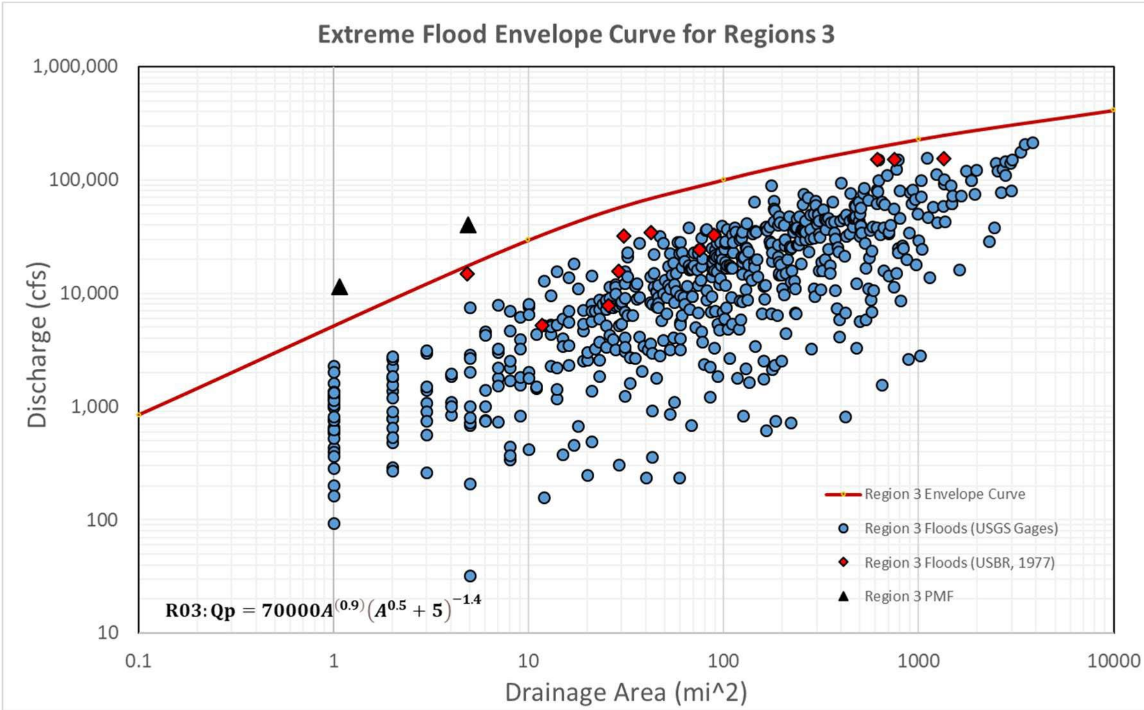

Figure 4. Flood envelope curve for Flood Region 3

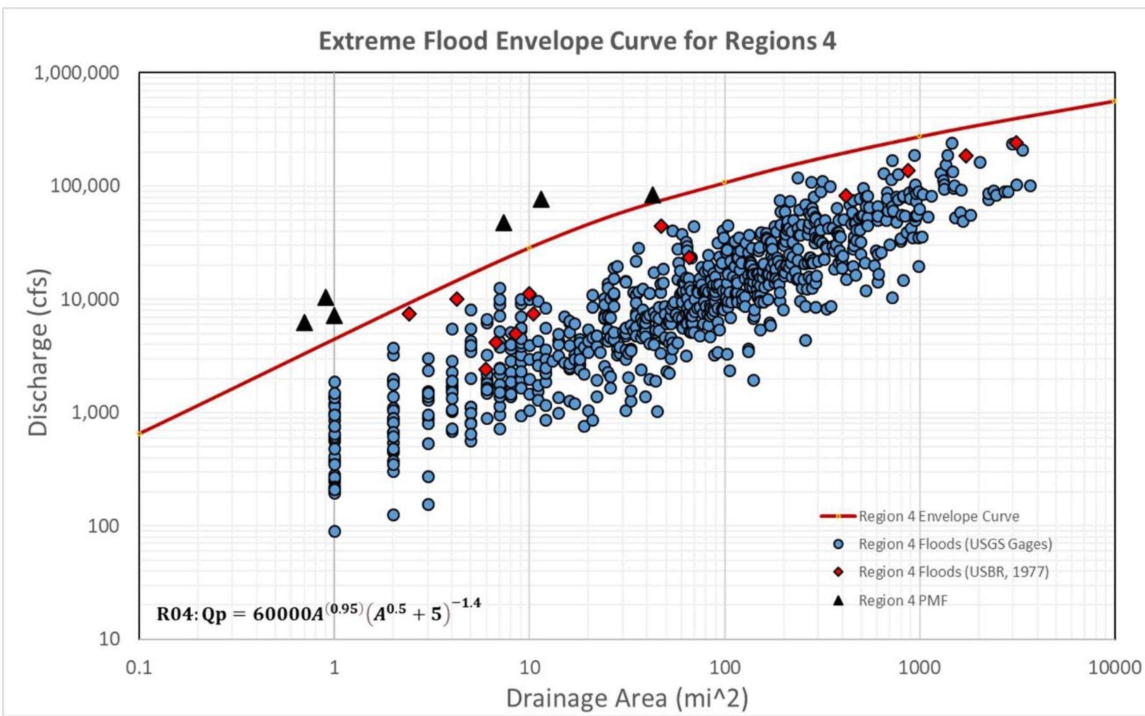

Figure 5. Flood envelope curve for Flood Region 4

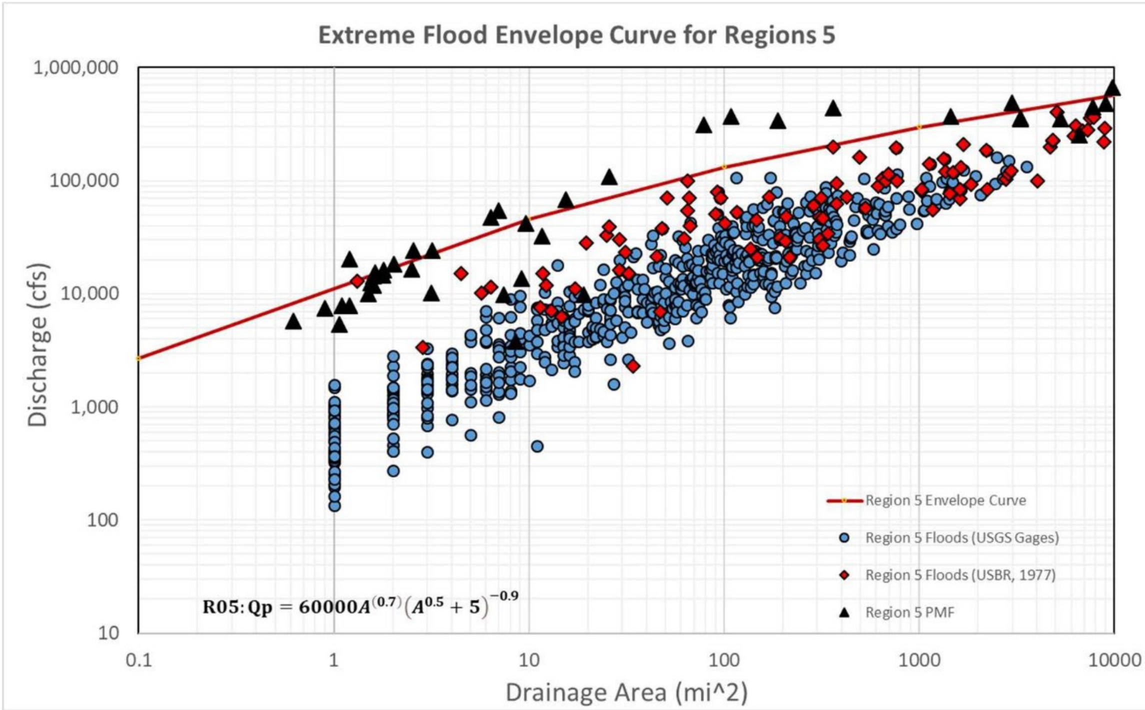

Figure 6. Flood envelope curve for Flood Region 5

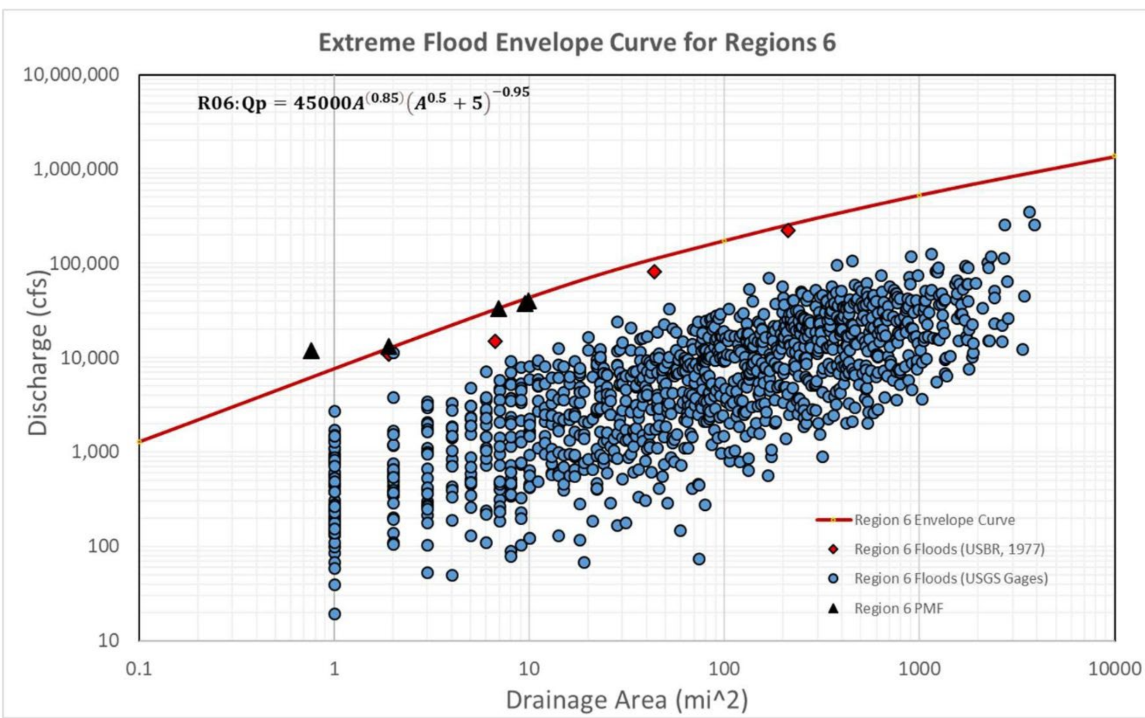

Figure 7. Flood envelope curve for Flood Region 6

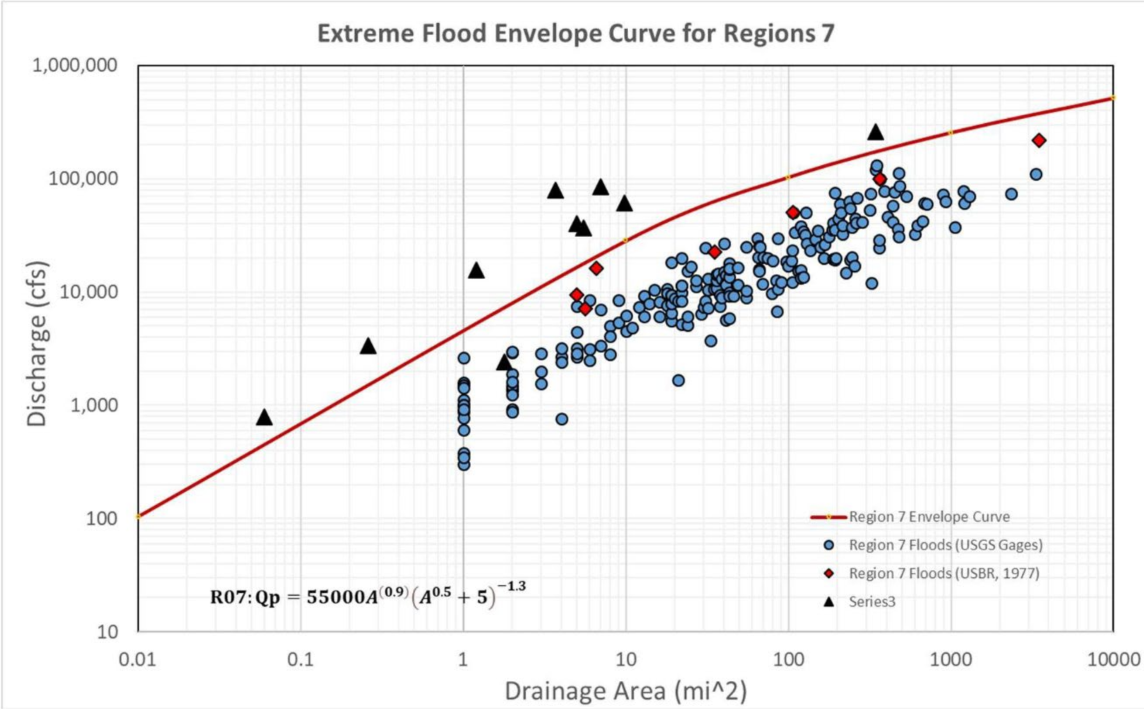

Figure 8. Flood envelope curve for Flood Region 7

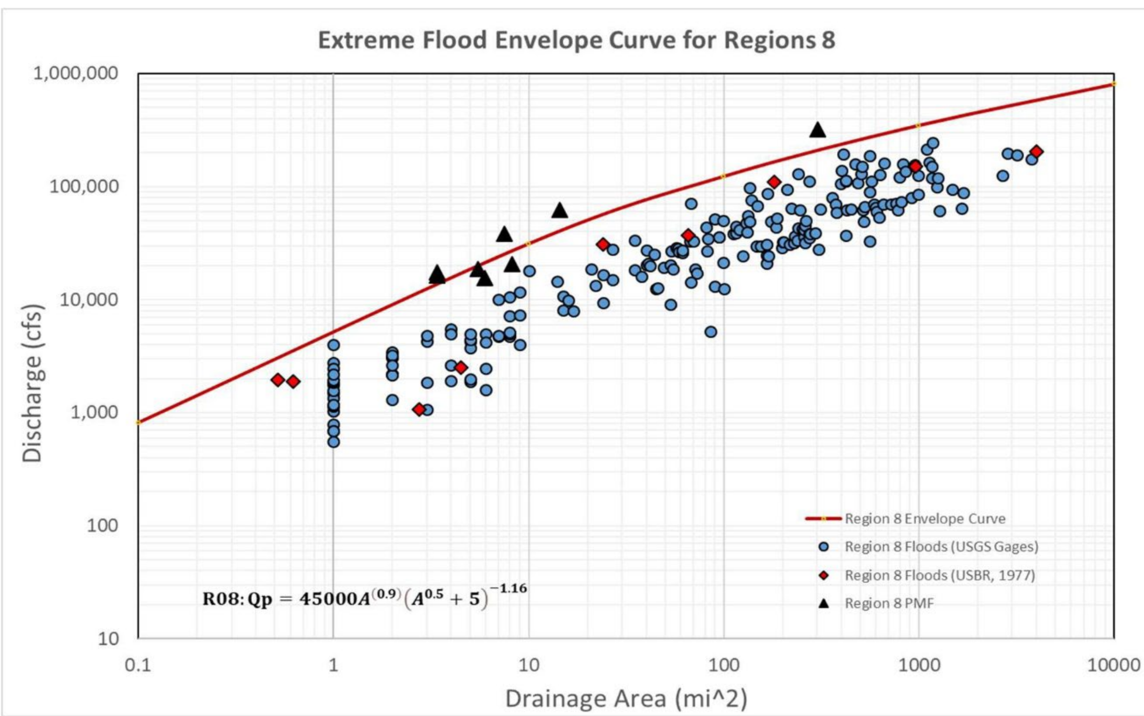

Figure 9. Flood envelope curve for Flood Region 8

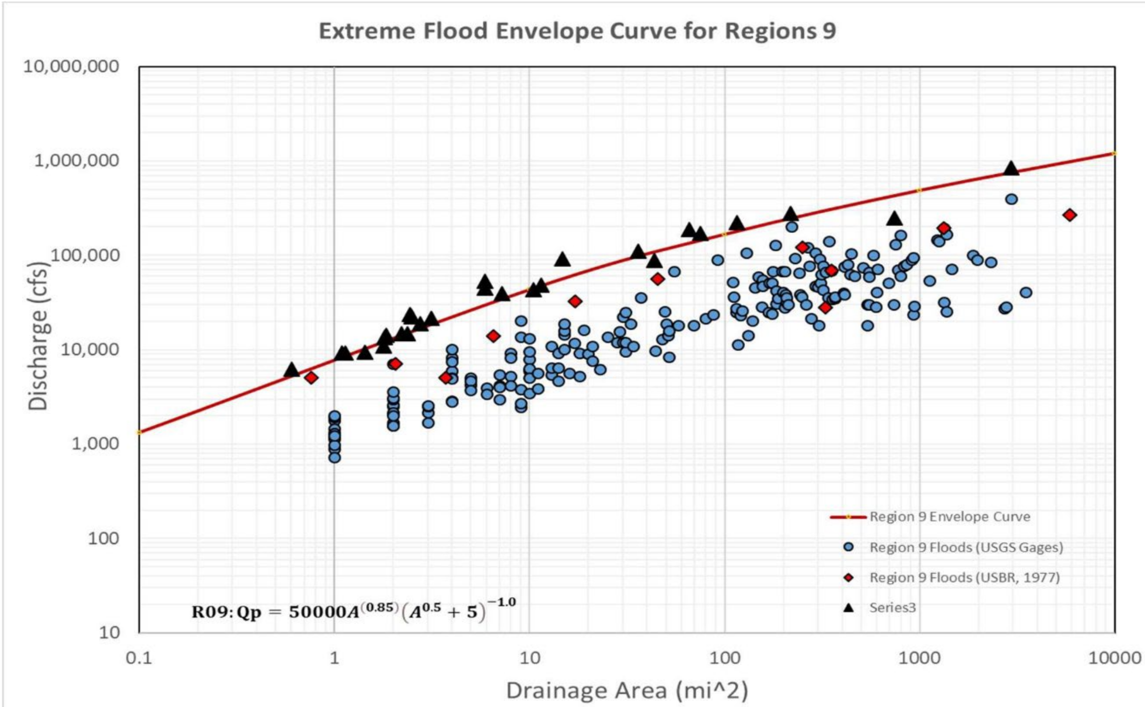

Figure 10. Flood envelope curve for Flood Region 9

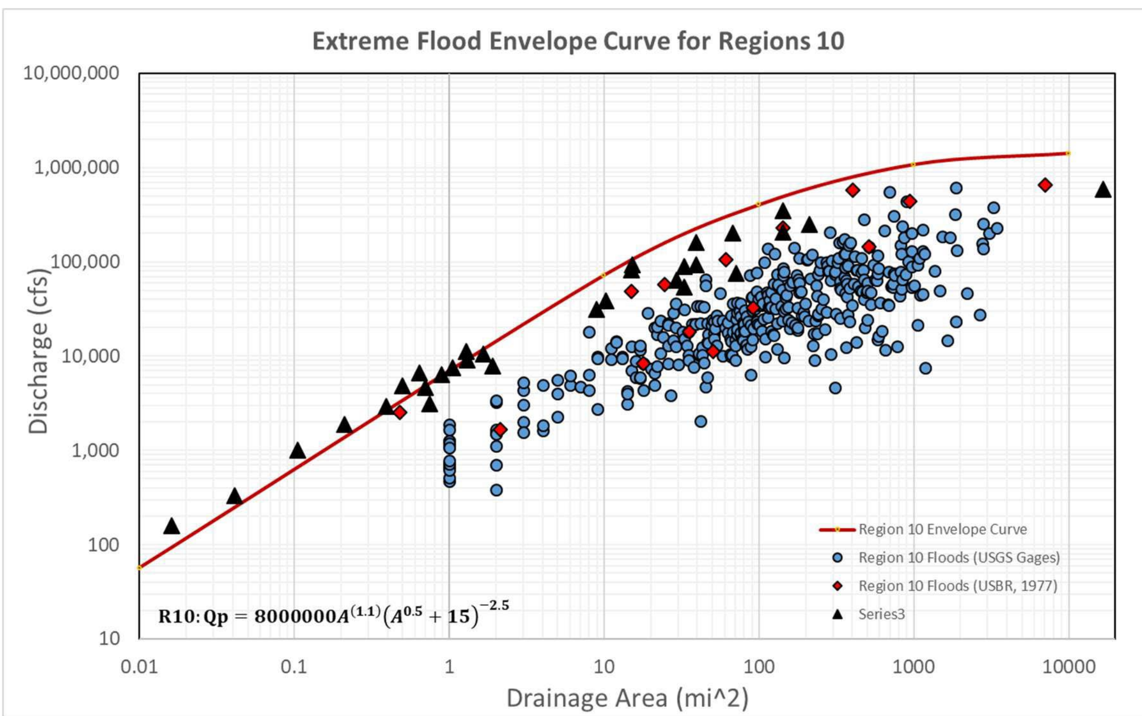

Figure 11. Flood envelope curve for Flood Region 10

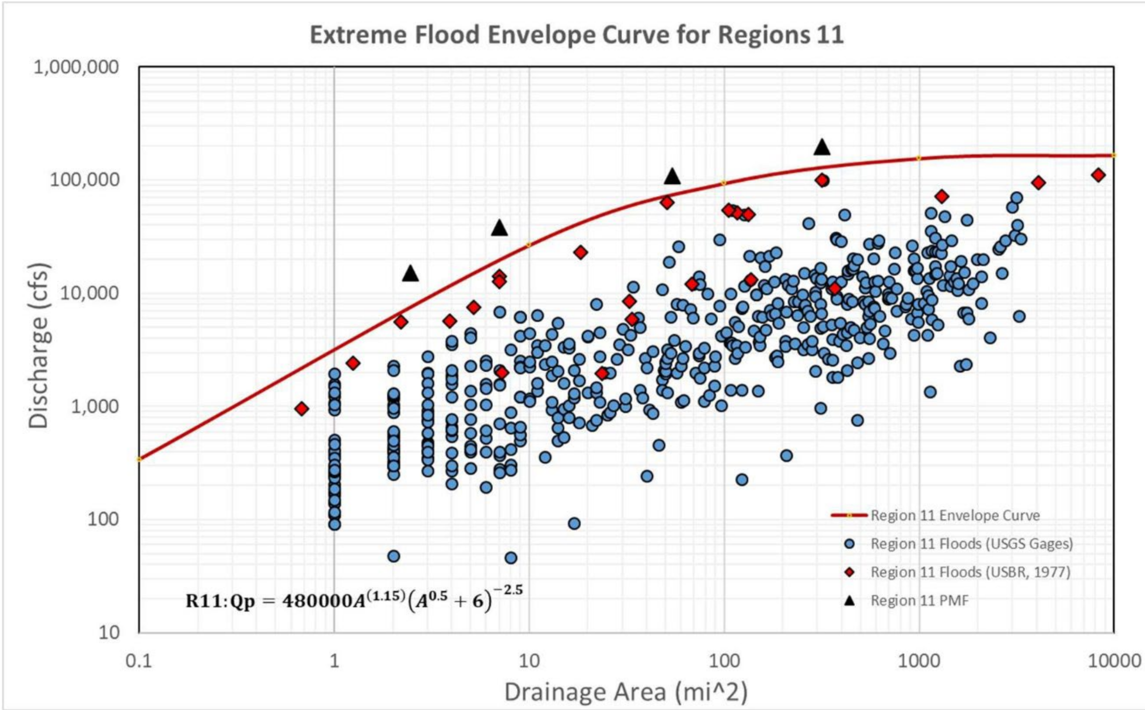

Figure 12. Flood envelope curve for Flood Region 11

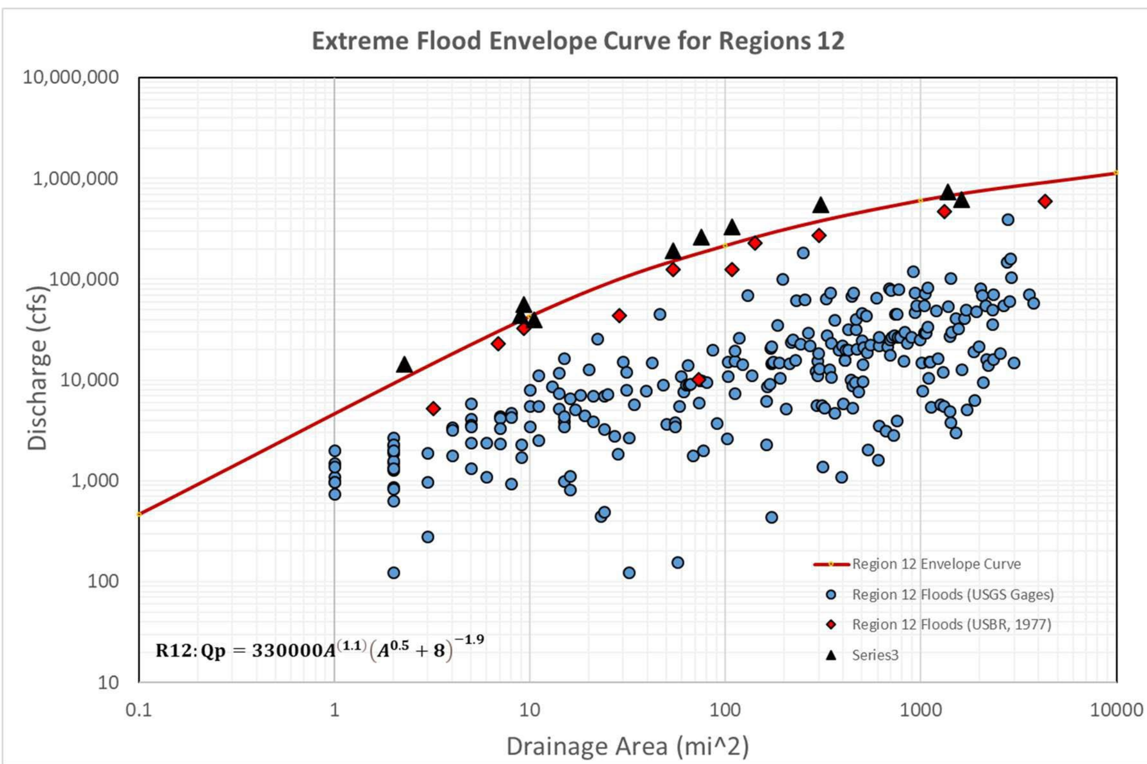

Figure 13. Flood envelope curve for Flood Region 12

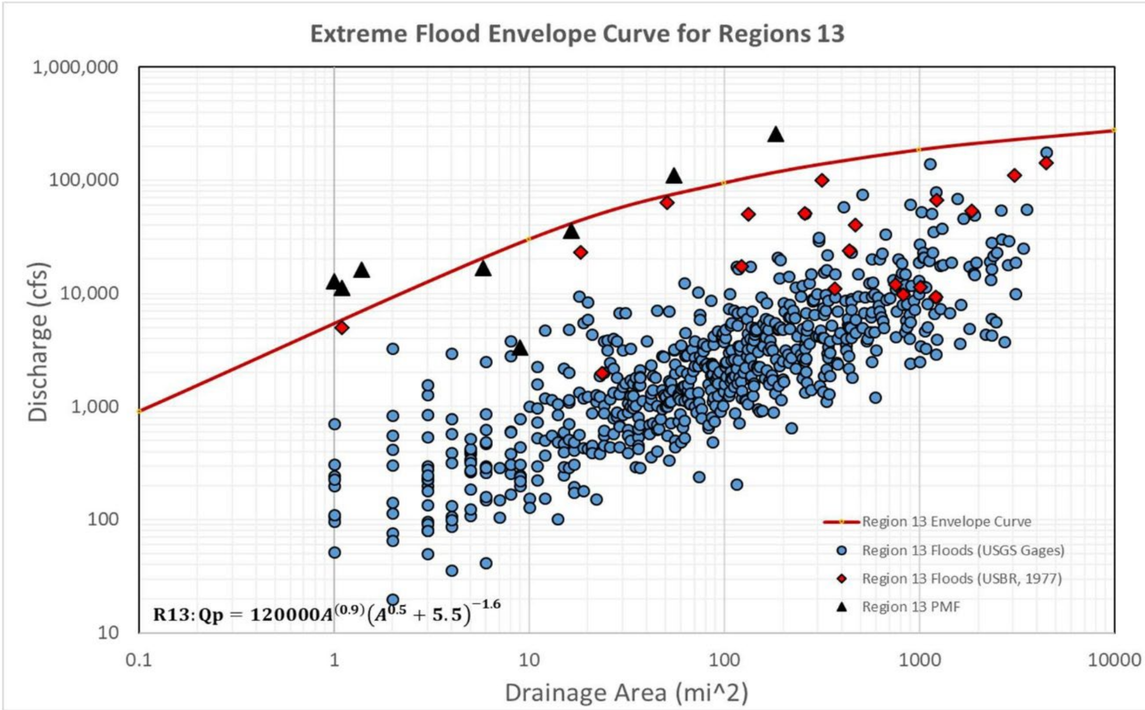

Figure 14. Flood envelope curve for Flood Region 13

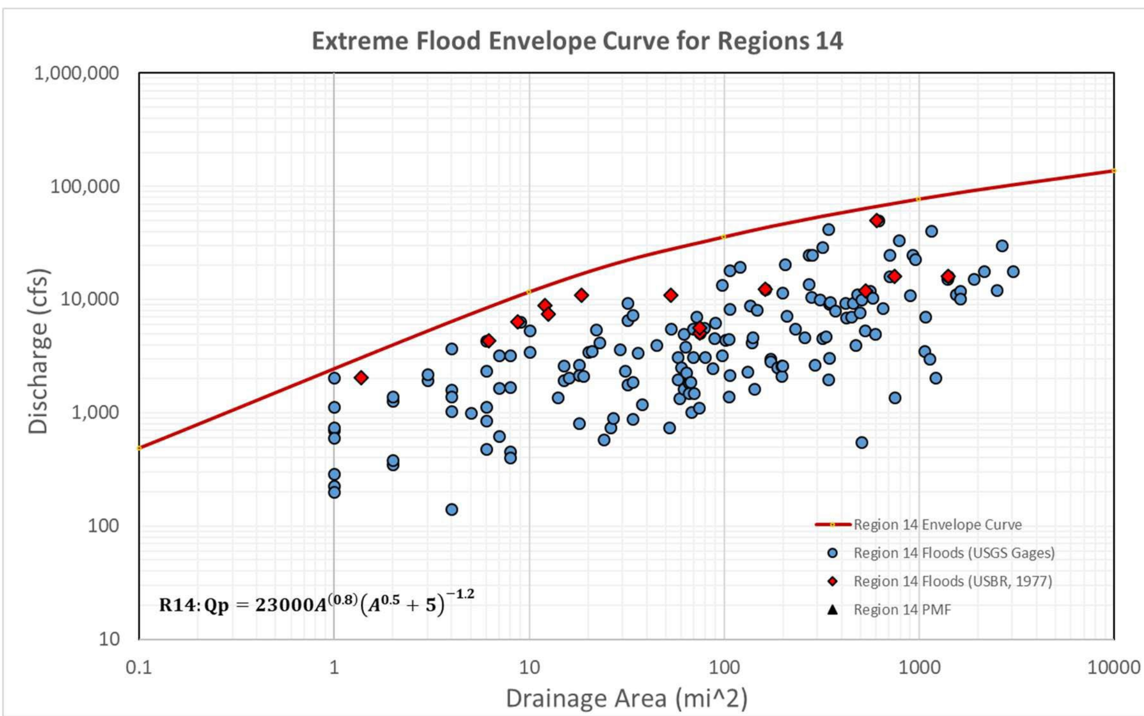

Figure 15. Flood envelope curve for Flood Region 14

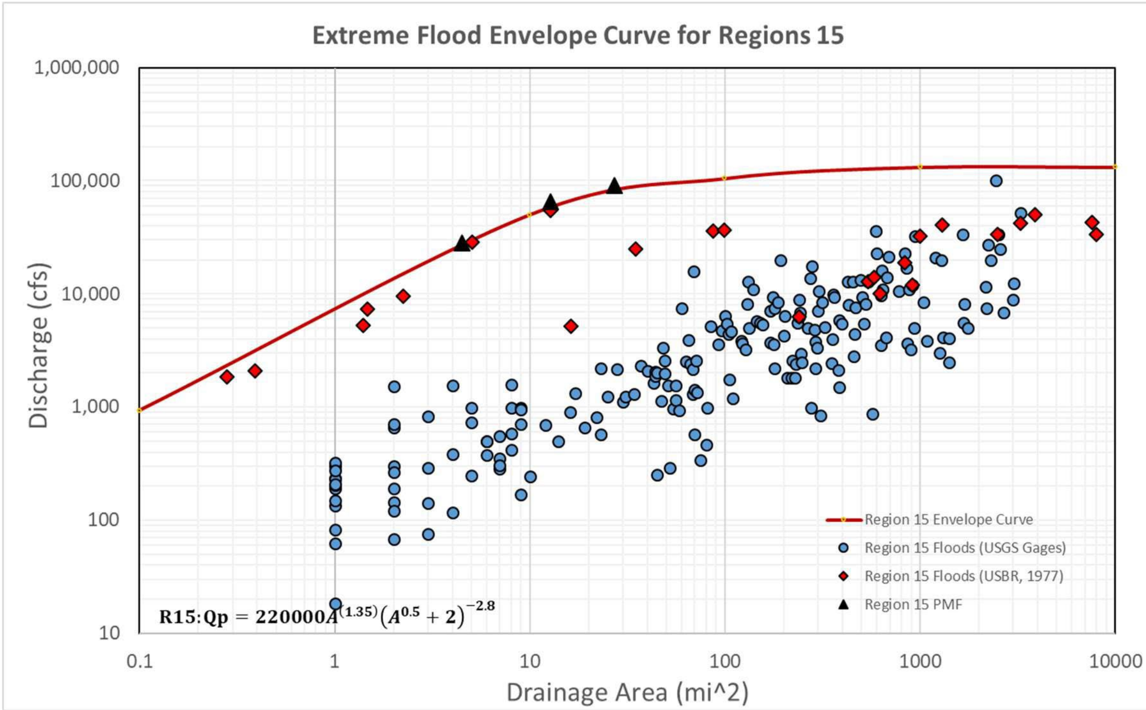

Figure 16. Flood envelope curve for Flood Region 15

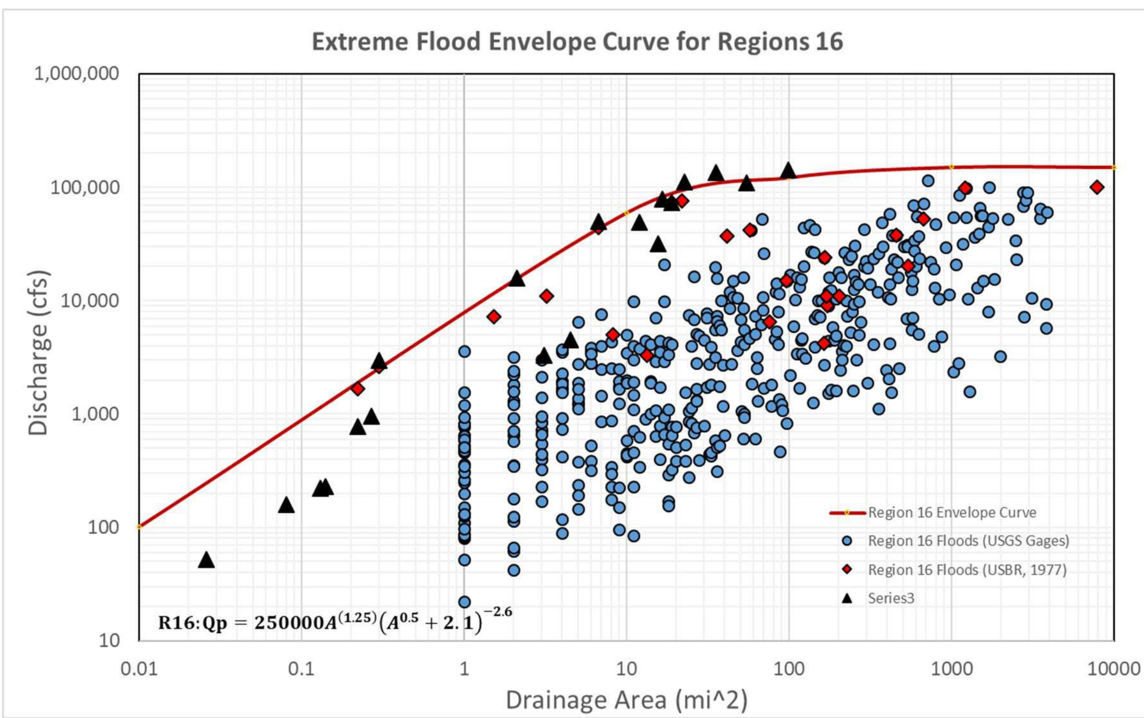

Figure 17. Flood envelope curve for Flood Region 16

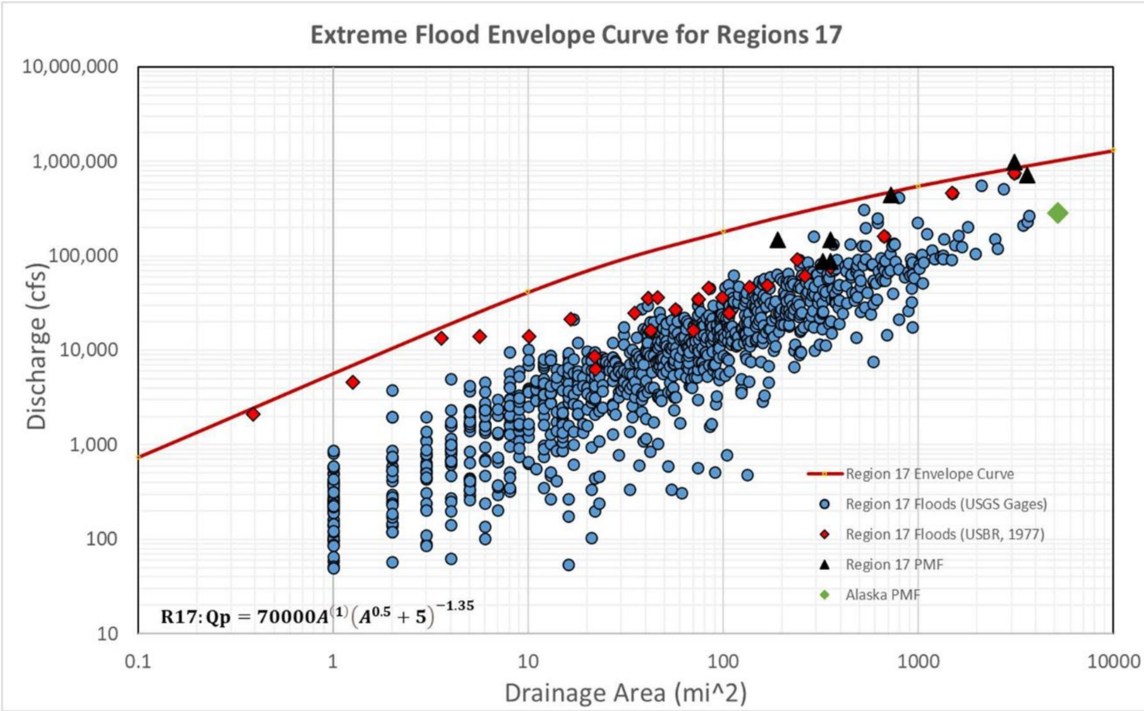

Figure 18. Flood envelope curve for Flood Region 17

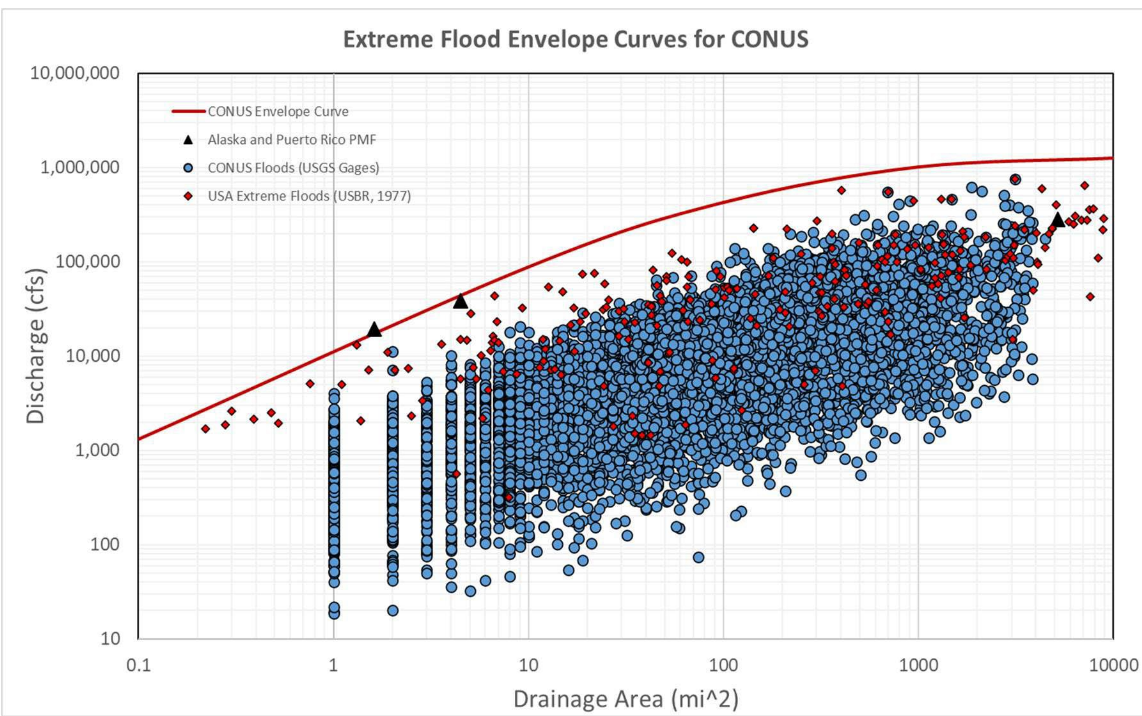

Figure 19. Flood envelope curve for region CONUS

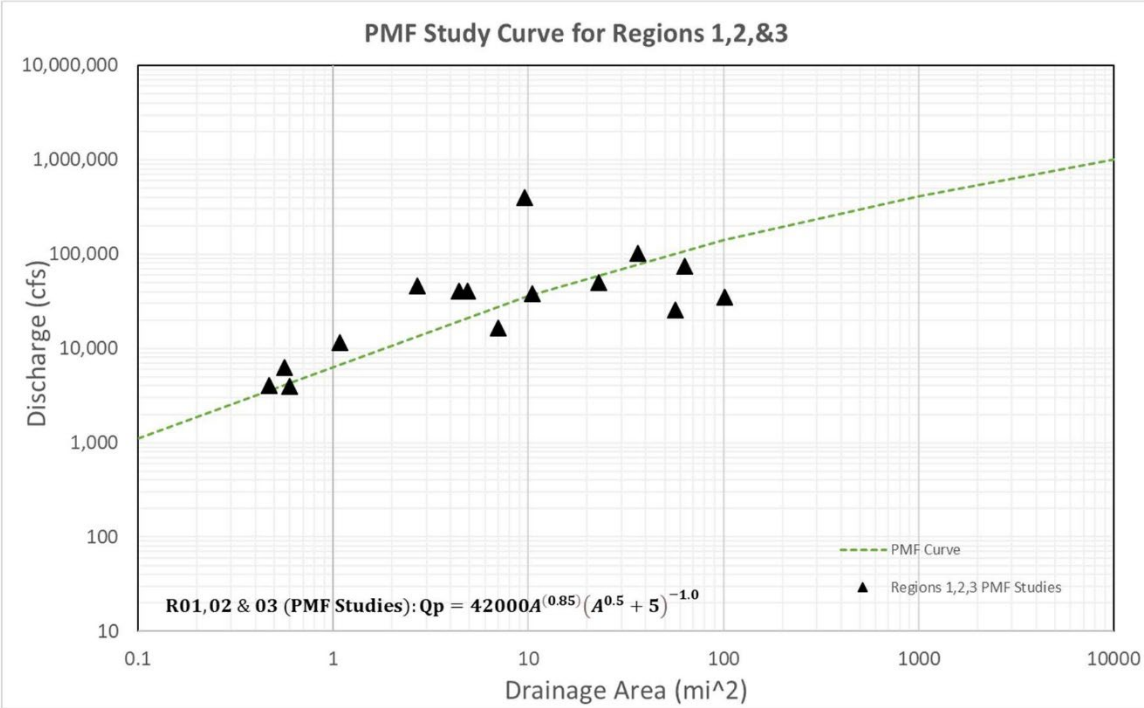

Figure 20. PMF study curve for Flood Regions 1, 2 and 3

Table 1. Flood Envelope Curves Coefficients

Region	K_1	K_2	K_3	K_4
1	110000	1.30	-2.20	7.0
2	23000	0.85	-1.10	6.0
3	70000	0.90	-1.40	5.0
4	60000	0.95	-1.40	5.0
5	60000	0.70	-0.90	5.0
6	45000	0.85	-0.95	5.0
7	55000	0.90	-1.30	5.0
8	45000	0.90	-1.16	5.0
9	50000	0.85	-1.00	5.0
10	8000000	1.10	-2.50	15.0
11	480000	1.15	-2.50	6.0
12	330000	1.10	-1.90	8.0
13	120000	0.90	-1.60	5.5
14	23000	0.80	-1.20	5.0
15	220000	1.35	-2.80	2.0
16	250000	1.25	-2.60	2.1
17	70000	1.00	-1.35	5.0
CONUS	7000000	1.00	-2.30	15.0
1,2,3	42000	0.85	-1.00	5.0

References

Crippen, J.R., Bue, C.D., 1977. Maximum flood flows in the conterminous United States. US Geological Survey Water Supply Paper.

Meyer, R. W. 1994. Potential hazards from floodflows within the John Muir House National Historic Site, Franklin Creek drainage basin, California. U.S. Geological Survey Water Resources Investigation Report 93-4009.

Appendix C. *Annual Exceedance Probability Estimation Methodology*

This appendix outlines the methodology used to estimate the annual exceedance probability (AEP) for spillway discharge capacity and PMF inflow for a given dam.

AEP Calculation

The annual exceedance probability (AEP) is calculated by interpolating or extrapolating along the trendline of the flow frequency data input by the user. Flow frequency data follows and asymptotic relationship where less change in the magnitude of the inflow occurs as the return year increases. This relationship that can be estimated using a power function. Figure 1 shows the flow frequency data plotted with the power function regression for the data.

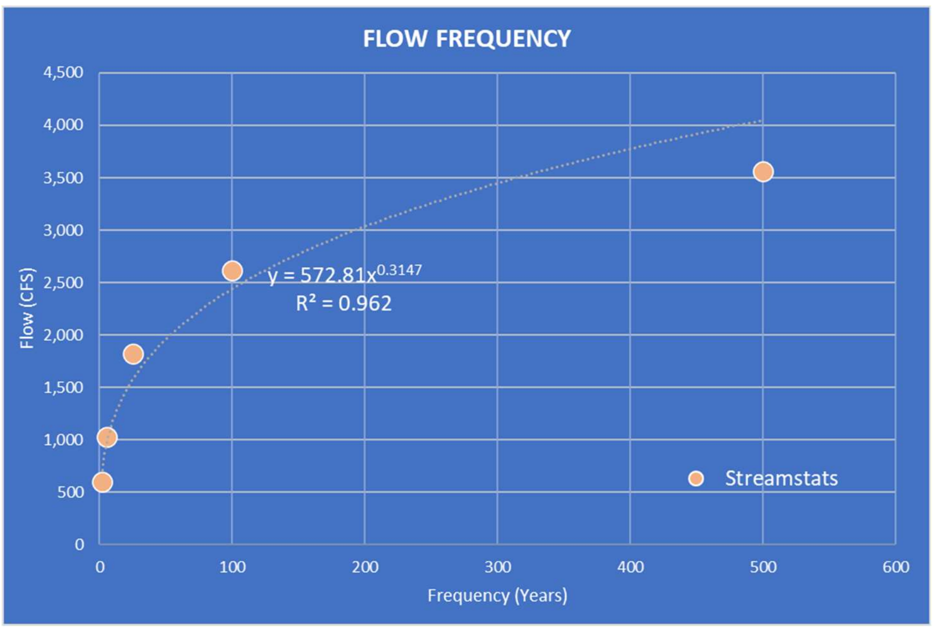

Figure 1. StreamStats Flow Frequency Data Plot with Power Regression Trendline

To interpolate and extrapolate along the power function regression of the flow frequency data, a log-log regression was applied. The flow frequency data is shown on a log-log plot in Figure 2.

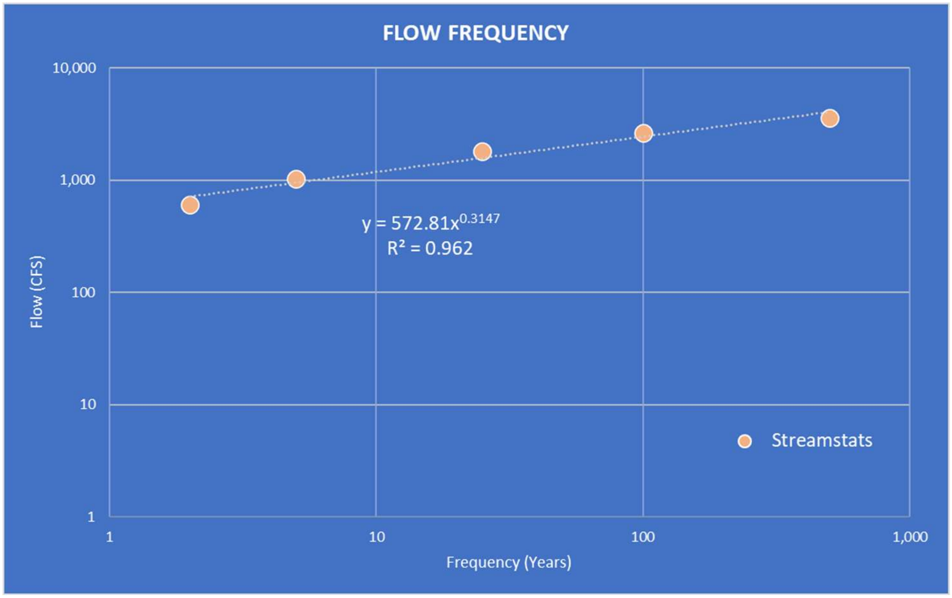

Figure 2. StreamStats Flow Frequency Data Plot with Log-Log Axes with Power Regression Trendline

Power function regression can be accomplished by taking the log of both X and Y data points and applying linear regression. This method was used for the interpolation and extrapolation of the spillway capacity and PMF inflow data to produce an AEP. The tool has five return years (2-,5-,25-, 100-, and 500-year) for the user to input flow frequency data. The AEP regression calculation uses all five return years unless the R-squared value is less than 0.95. When the R-squared value is less than 0.95 the regression is only applied to the 25-, 100-, and 500-year data points). Figures 4 shows a case where the R-squared value is less than 0.95. The data point regression adjustment for the same flow frequency data is shown in Figure 5.

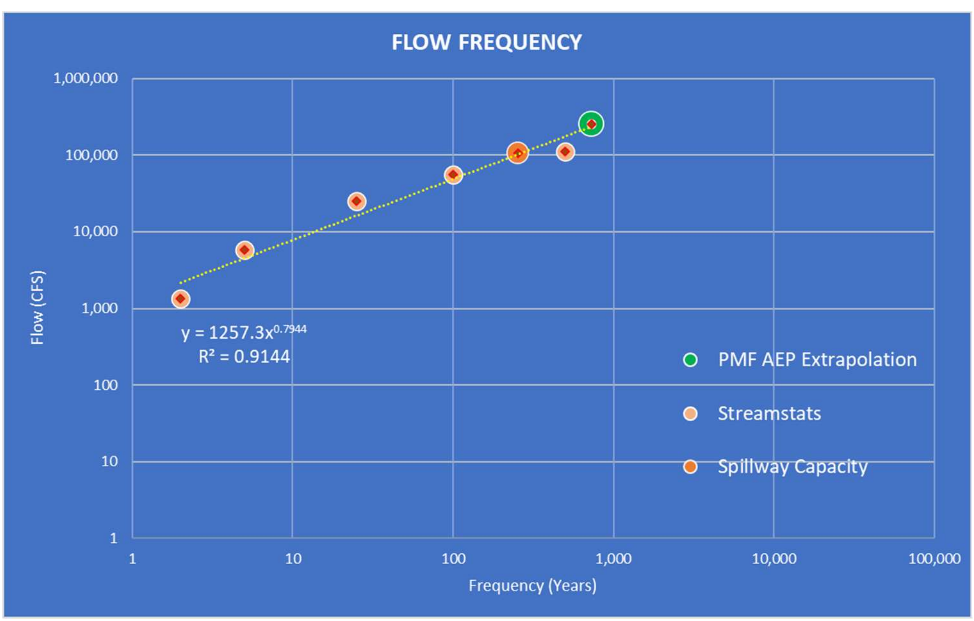

Figure 3. Flow Frequency Plot Where R-Squared Value of Data is Less than 0.95

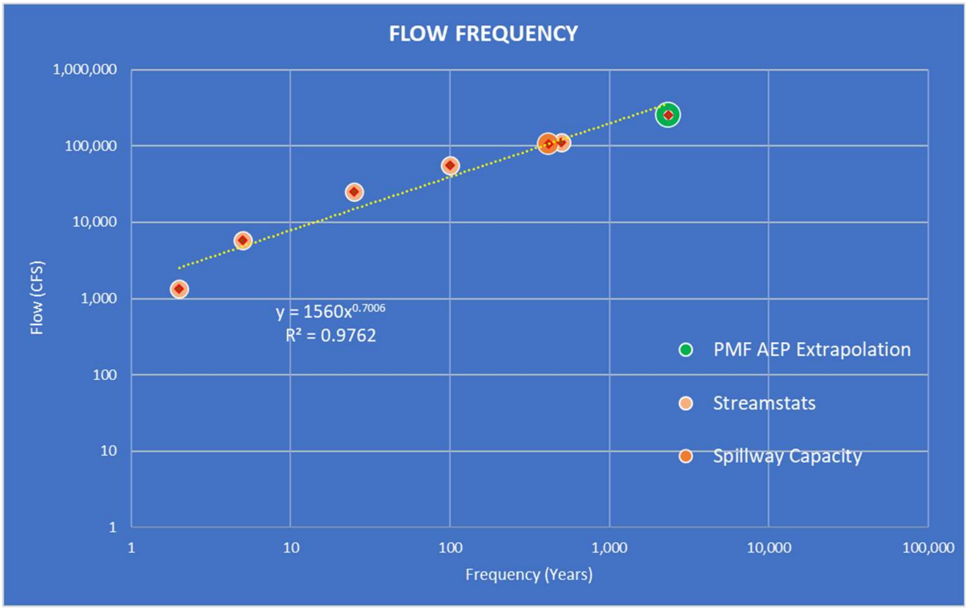

Figure 4. Flow Frequency Plot where Amount of Data Points for Regression was Reduced when R-squared of Data was Less than 0.95

The figures show that the return year of the PMF inflow is increased and the trendline more closely follows the data for the larger return year data. Table 1 below shows the frequency flow data for both the StreamStats input data and the spillway capacity and PMF inflow estimations.

Table 1. Flow Frequency data for StreamStats Data and Spillway Capacity and PMF Inflow Estimation

Source	Frequency (Yrs)	Discharge or Inflow (cfs)	Log (Yr)	Log (Discharge)
Streamstats	2	1350	0.301	3.130
Streamstats	5	5780	0.699	3.762
Streamstats	25	24900	1.398	4.396
Streamstats	100	56100	2.000	4.749
Streamstats	500	112000	2.699	5.049
Spillway Capacity Estimation	413	106069	2.6	5.026
PMF Inflow Estimation	2335	254000	3.37	5.405