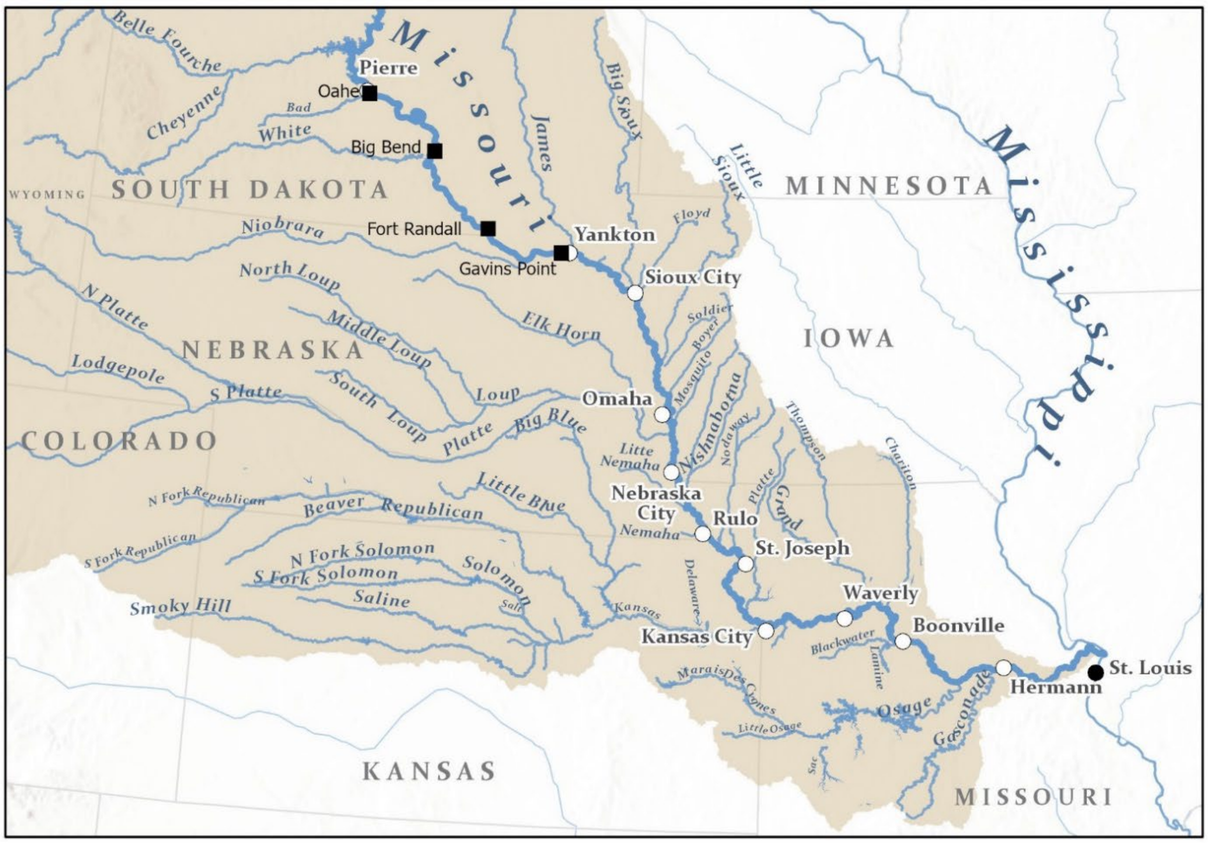
US Army Corps of Engineers®

Missouri River Flow Frequency Study

Yankton, South Dakota to Hermann, Missouri



U.S. Army Corps of Engineers
Northwestern Division,
Omaha District, Kansas City District, and
Missouri River Basin Water Management

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Cover Image:

Map of the downstream portion of the Missouri River basin showing the location of the ten study stream gages, namely Yankton, SD, or the Gavins Point Dam outflow, Sioux City, IA, Omaha, NE, Nebraska City, NE, Rulo, NE, St. Joseph, MO, Kansas City, MO, Waverly, MO, Boonville, MO, and Hermann MO in relation to large tributaries. The map also shows the Mississippi River at St. Louis, MO, and the four downstream Missouri River Mainstem Dams including Gavins Point Dam, Fort Randall Dam, Big Bend Dam, and Oahe Dam. The map does not show the full Missouri River Basin, the Garrison and Fort Peck Mainstem Dams, or the many tributary dams included in the hydrologic analysis of this study.

FOREWORD

Significant flood damages in 2019, only eight years after the damaging 2011 flood, led to calls from the lower Missouri River Basin states to better prepare for future floods. As a result, the Missouri River Flood Risk and Resilience Study was initiated. While completed under separate funding from the Floodplain Management Services Program (FPMS), this Flow Frequency Study report provides foundational information, that when combined with future study of stage frequency, will help accurately describe the current flood risk that exists on the Missouri River. The intended use of this data is for current studies and ongoing flood risk management activities.

Similar updates to flow frequencies have been completed in advance of major Federal investments for flood risk infrastructure on the Missouri River in the past. This includes hydrology in the 1932 "308 Report" for the Missouri River, which led to calls for levees in Kansas City, Missouri, several agricultural levees, and a dam at Fort Peck, Montana. Related studies would lead to the 1944 Flood Control Act which authorized Federal levee construction, five more mainstem dams, and tributary dams. Next was hydrology completed in 1946 as part of the overarching 1947 design for a system of Federal agricultural levees on the Missouri River, and a re-study completed in 1962 to incorporate lessons learned from the floods of 1951 and 1952, leading to additional Federal projects. Although interim hydrology updates were completed as needed for various projects, the next full update of the flow frequencies was not completed until 2003, as motivated by the 1993 flood, which currently stands as the post-dam flood of record for the Missouri River downstream of St. Joseph, Missouri. Federal improvements to new and existing levee systems on the Missouri River, some still in construction, were identified using the 2003 study flow frequency data.

This report was prepared by U.S. Army Corps of Engineers staff of the Omaha District, the Kansas City District, Northwestern Division, Missouri River Basin Water Management, and the Cold Regions Research Laboratory in Hanover, New Hampshire. Additionally, Agency Technical Reviews were provided by U.S. Army Corps of Engineers staff of the St. Paul District, Risk Management Center, and Hydrologic Engineering Center of Davis, California, which also provided invaluable support throughout the entire study process. A special thank you is made for the guidance and advice of the Technical Review Group comprised of staff from state and Federal agencies, private industry, and academic institutions who provided feedback on the scope and methodology and provided detailed comments on the report. Formatting of the document was conducted by RTI International, trademark name of Research Triangle Institute.

Advent of Bulletin 17C flow frequency procedures in 2018 highlighted a need to incorporate historic flood peaks, which would not have been possible without the diligent work of state and local historical societies to document and preserve this information. From this flood history research, the development and intended use of flow frequency data in this document is best summarized by John McCoy, a land surveyor and one of the founders of Kansas City, Missouri, during the rise of the April 1881 flood.

"The subject of floods in the Missouri and Kansas River in the past, and the probabilities of their recurrence in the future, is neither a pleasant or popular theme to talk or write about just now." … "Having some knowledge of facts connected with floods in the Missouri River, I will venture, disagreeable as the subject may be to many, to briefly state them." … "The records of the past tell us of only three floods that may be regarded as devastating, viz: in 178[5], 1826, and 1844. (one other in 1843 only partially so, and many others where the overflows caused little or no damage.)" … "I have written these few incidents of the great flood of 1844 not as a sensation, for the facts are just as I have related them without any undue coloring. Neither have I done so to create any unnecessary alarm for I don't know that there are any grounds for any, but simply to communicate some facts that everyone having interests in the river bottoms ought to know."

– John C. McCoy, 1881

The Missouri River Flow Frequency Study was carried out in close coordination and collaboration with other state and Federal agencies, private industry, and academic institutions. It received guidance and review from the members of an independent technical review group consisting of nationally and internationally recognized experts in their respective fields. The Corps of Engineers team responsible for the accomplishment of this study included many of the agency's best hydrologists and hydraulic engineers. We have the greatest trust in their abilities, knowledge, experience, and commitment to excellence that was consistently demonstrated throughout the course of this study. We stand behind the rigorous technical review processes they put in place to assure the quality and reliability of the study's results. The product of this study provides updated discharge-frequency relationships at 10 Missouri River gages from Yankton, SD to Hermann, MO. This foundational information will be utilized in the next step to provide updated stage frequency analysis to inform existing flood risk on the Missouri River and to provide the basis for sound flood risk management planning and implementation for many years to come.

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Glossary of Important Terms

Big Bucket	A synthetic flow record developed from the historical period of record (POR). The method of random sampling used to create the 500-year Big Bucket used a bootstrap procedure that re-sampled flows from the 90-year historical POR from four delineated regions of the Missouri River Basin and three seasons.
Event	One year of data produced by a Hydrologic Engineering Center (HEC) Watershed Analysis Tool (WAT) simulation.
Expected Moments Algorithm (EMA)	Flow frequency analysis method that can utilize Systematic (Exact), Historic (Interval Censored), and Perception Thresholds (Left or Right Censored) flood information as well as regional skew information.
Expected Probability	A probability estimate that has been corrected for bias in the computed frequency curve
Historical Depletion	Flow calculated by Reclamation's Regional Depletions Model representing estimates of historical basin development surface water withdrawals due to agricultural, municipal and industrial water supply, transbasin diversions, and tributary reservoir holdouts.
Historical Flow	Flow that was observed and recorded through stream gages or estimated based on other historical data such as monthly volumes, high water marks, etc.
Historical Sample	Sample of events used by the WAT to represent the Historical POR. For this study, the historical sample consisted of the Big Bucket and 90-year historical POR
Incremental Flow	Flow representing all tributary and ungaged flow between two stream gages. Calculated by routing historical flow from a stream gage to a downstream stream gage and subtracted the routed flow from the historical flow at the downstream gage. Incremental flow is used as input for the ResSim model.
Lifecycle	Fifty years of data produced by 1 continuous, HEC-WAT simulation. The 50-years of data are sampled from the 90-year Small Bucket created for each realization using a bootstrapping method.

Missouri River ResSim l	A reservoir model built using the HEC Reservoir System Simulation (ResSim) software. The Missouri River ResSim (MR ResSim) model simulates reservoir operations for the six Missouri River mainstem reservoirs, seven Kansas River reservoirs, and seven Osage River reservoirs.
Historical Period of Record	The period from 1930–2019 whose flow data will be used in this analysis.
Present Depletion	Flow calculated by Reclamation's Regional Depletions Model representing estimates of present (2017) basin development surface water withdrawals due to agricultural, municipal and industrial water supply, transbasin diversions, and tributary reservoir holdouts.
Realization	A group of 50 lifecycles produced by an HEC-WAT simulation.
Regulated Flow	Flow that has been simulated through the MR ResSim model, which uses reservoir operations based on the 2018 Master Manual and incremental flows adjusted to present basin development using present depletions.
Small Bucket	A 90-year flow record sampled from the Big Bucket and scaled events for each realization within an HEC-WAT simulation. The Small Bucket is used to capture knowledge uncertainty.
Transform Method	A method for estimating regulated flow frequency using an unregulated/regulated transform function. This method is the recommended method in EM 1110-2-1415 and was used in the 2003 Upper Mississippi River System Flow Frequency Study (UMRSFFS). The Transform Method does have limitations with complex, highly regulated systems because each event is not transformed in probability space. Transformed events are approximated with the unregulated/regulated transform function.
Unregulated Flow	Flows without regulation from dams or historical depletions. These are equivalent to "no regulation no irrigation" flows and are the closest estimate of "natural" flows. However, natural flows are impossible to compute because we cannot account for channel geomorphology.

WAT Monte Carlo Method	A method for estimating regulated flow frequency through a Monte Carlo simulation using the HEC-WAT software. This method estimates regulated flow frequency by sampling events from a Big Bucket and scaled events. Each sampled event is then simulated through the MR ResSim model to transform flows into regulated flows. In general, Monte Carlo methods are well suited to estimate regulated flow frequency in complex, highly regulated systems

Executive Summary

Lower Missouri River flow frequency was estimated at 10 gages from Yankton, SD, or Gavins Point Dam, to Hermann, MO, thus providing estimates of the Missouri River flow in cubic feet per second (cfs) associated with annual exceedance probabilities. This analysis incorporates new data and statistical analysis and applies state of the practice methodologies. These methods more completely assess risks for combinations of floods impacting portions of the basin downstream of the Missouri River reservoir system. Technological advances in methods, modeling capabilities, and computing power have strengthened the quality of data and analysis.

Previous flow frequency analysis on the lower Missouri River from Gavins Point Dam to Hermann, MO was completed in 2003 as part of the Upper Mississippi River System Flow Frequency Study (UMRSFFS) by the United States Army Corps of Engineers (USACE, 2003). The 2003 study was initiated following record flooding in 1993, updating previous flow frequencies published in 1962 using a period of record of 1898 to 1997. Several pieces of new information and technical advancements have become available since that time which warranted the update. Major flooding occurred on the Missouri River in 2011 and 2019. Bulletin 17C was published in 2018, replacing the previous Bulletin 17B federal guidelines for flow frequency estimation from 1982. Bulletin 17C incorporates methods to incorporate periods in between historical flood observations and gaps in the systematic record by means of perception thresholds, something not possible in 2003. Further, methods to detect non-stationarities in the flow data and qualitatively consider the effects of climate change per Engineering and Construction Bulletin (ECB) 2018-14 have also been developed.

Monte Carlo techniques in hydrology, referenced in Chapter 12 Engineering Manual (EM) 1110-2-1415, have advanced considerably as computing power has improved and have been used successfully for complex studies such as the Columbia River Treaty (CRT). With the creation of the Hydrologic Engineering Center (HEC) Watershed Analysis Tool (WAT), Monte Carlo techniques are being used more often. Hydrologic and hydraulic modeling software for water accounting and hydraulic calculations has undergone major upgrades with the HEC Reservoir Simulation (ResSim) and River Analysis System (RAS) software since 2003. Within the Missouri River Basin, HEC-ResSim and HEC-RAS models have been developed for the 2018 Missouri River Basin Management Plan and the Corps of Engineers Water Management Systems upgrades completed in 2021.

This study replicated the 2003 UMRSFFS methodology to compute unregulated flow frequency based on EM 1110-2-1415, Bulletin 17C, ECB 2018-14, and an updated period of record (POR) daily flows from 1930 to 2019. The POR daily flow record was computed by means of the Mainstem Missouri River Basin HEC-ResSim model, adjusting the flows for consistency with current depletions and for scenarios as if the dams were in place or were not in place the whole time, referred to as the “regulated” and “unregulated” flows, respectively. As part of developing the POR, historical estimates of water usage, or depletions, have been updated by the U.S. Bureau of Reclamation. A 177-year historic period back to 1843/1844 was adopted when computing the Bulletin 17C unregulated flow frequencies. Sensitivity to earlier flood estimates and settlement dates was also considered for a historic period of 200 to 204 years at five study gages with detailed flood history information, and up to 321 years at Hermann and Boonville, MO.

Flows from the HEC-ResSim model with Gavins Point Dam as the upstream boundary condition were re-routed with HEC-RAS hydraulic models to assess the impact of hydraulic versus hydrologic routing methods, ultimately incorporating the HEC-ResSim results. Regulated flow frequencies were computed for this study first by mimicking the 2003 study in a method referred to as the "transform method". Additionally, a Monte Carlo simulation was performed using HEC-WAT controlling HEC-ResSim. The results of the Monte Carlo simulation are recommended for adoption as the estimate of regulated flow frequency on the lower Missouri River as the method more completely assesses risks for combinations of floods impacting portions of the basin downstream of the reservoir systems.

Monte Carlo analysis completed for this study took the CRT techniques and added the use of a "big bucket" synthetic record and a post-processing method. The "big bucket" synthetic record adds 500 events of synthetic data generated externally along with the 90 events in the historical record. Additionally, to improve the sampling at extreme probabilities, 15 synthetic events for the Missouri River Mainstem Reservoir System and 13 for the Kansas and Osage Basin Reservoirs were generated based on scaling of flood events and assigning a probability based on the most representative location for each event. The post-processing method allows the unregulated flow frequency curves produced by the WAT to match the Bulletin 17C frequency curves at each study location.

These results are summarized in Tables ES-1 for the Bulletin 17C unregulated flow frequencies and Table ES-2 for the Monte Carlo regulated flow frequencies. Bulletin 17C is the accepted method for computing unregulated flow frequencies. As shown in Section 6.3.3 and 7.6 of the report, unregulated flow frequency from HEC-WAT as sampled from the "big bucket" and synthetic events and routed through the HEC-ResSIM model is also shown to indicate how close they match the Bulletin 17C curves. Although climate change may already be impacting portions of the basin, results in this study are considered reflective of the existing conditions flows of the Missouri River Basin as detailed in Section 2.6 and 2.7. Results are valid for floods between a 99% and 0.2% annual exceedance probability (AEP) event. Extrapolating the results to estimate floods less frequent than the 0.2% AEP is not recommended without additional study. Conceptual examples showing results of the transform method and Monte Carlo method of computing regulated flow frequency are presented in Figures ES-1 and ES-2, respectively.

Table ES-1. Final Unregulated Bulletin 17C Flow Frequency Annual Exceedance Expected Probability (Flow in CFS)

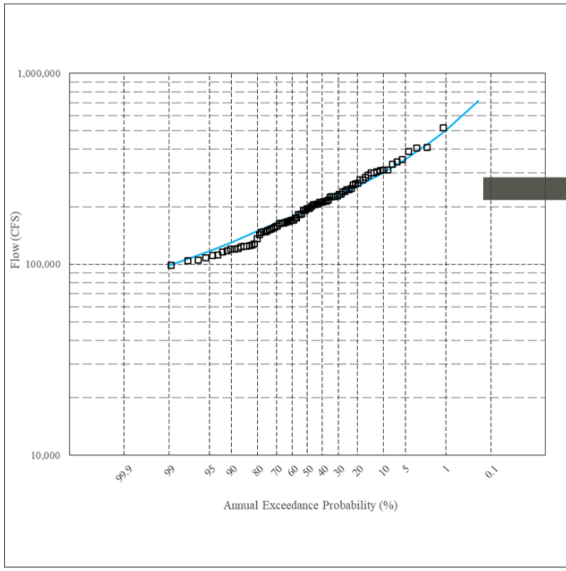
AEP (%)	Yankton	Sioux City	Omaha	Nebraska City	Rulo	St Joseph	Kansas City	Waverly	Boonville	Hermann
0.2	686,000	719,000	727,000	730,000	715,000	707,000	835,000	848,000	924,000	1,230,000
0.4	565,000	591,000	602,000	617,000	608,000	607,000	738,000	751,000	827,000	1,090,000
0.5	531,000	555,000	567,000	584,000	578,000	578,000	709,000	723,000	798,000	1,050,000
1	438,000	458,000	471,000	497,000	497,000	500,000	624,000	639,000	711,000	928,000
2	362,000	378,000	391,000	424,000	429,000	435,000	547,000	562,000	630,000	816,000
4	301,000	313,000	327,000	364,000	372,000	379,000	476,000	490,000	553,000	710,000
5	283,000	295,000	309,000	346,000	356,000	362,000	454,000	468,000	528,000	676,000
10	236,000	246,000	258,000	296,000	307,000	314,000	387,000	401,000	454,000	575,000
20	196,000	203,000	215,000	251,000	262,000	268,000	322,000	334,000	379,000	473,000
50	144,000	150,000	159,000	189,000	198,000	205,000	231,000	239,000	269,000	327,000
80	110,000	114,000	121,000	147,000	154,000	160,000	169,000	174,000	191,000	226,000
90	96,200	99,500	106,000	129,000	136,000	141,000	145,000	148,000	160,000	186,000
95	86,400	89,300	95,500	117,000	123,000	128,000	128,000	130,000	138,000	158,000
99	70,900	73,200	78,600	96,600	101,000	107,000	100,000	101,000	103,000	114,600

Note: Table ES-1 is also Table 3-19; Yankton / Gavins Point, Sioux City, Omaha, Nebraska City, Rulo, and St. Joseph are results of a mixed population analysis. Kansas City, Waverly, Boonville, and Hermann are results of a single population analysis.

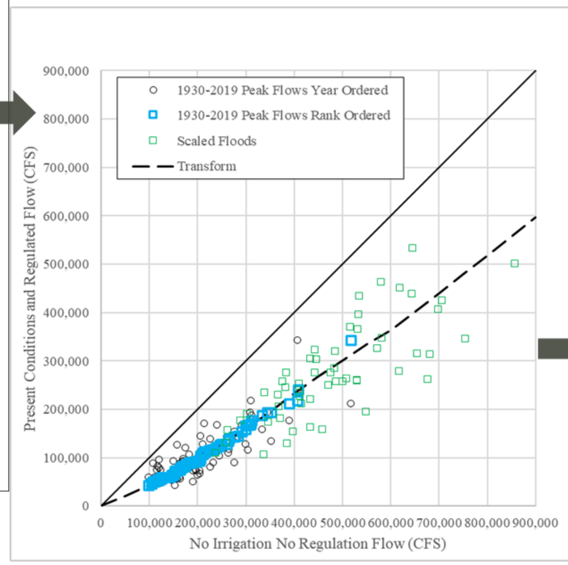
Table ES-2. Summary of Regulated Flow Frequency Annual Exceedance % Probability (Flow in CFS) Produced by the Monte Carlo Analysis.

AEP (%)	Yankton	Sioux City	Omaha	Nebraska City	Rulo	St Joseph	Kansas City	Waverly	Boonville	Hermann
0.2	213,000	285,000	351,000	480,000	510,000	526,000	640,000	674,000	731,000	933,000
0.4	169,000	268,000	312,000	399,000	432,000	444,000	555,000	588,000	702,000	742,000
0.5	164,000	266,000	293,000	382,000	422,000	433,000	546,000	573,000	672,000	722,000
1	164,000	218,000	232,000	329,000	336,000	349,000	467,000	503,000	572,000	666,000
2	104,000	156,000	187,000	244,000	294,000	296,000	393,000	412,000	531,000	571,000
4	81,000	121,000	154,000	220,000	250,000	255,000	312,000	323,000	417,000	506,000
5	77,000	111,000	151,000	212,000	233,000	239,000	293,000	294,000	393,000	473,000
10	64,000	89,000	118,000	171,000	187,000	197,000	247,000	251,000	334,000	416,000
20	54,000	71,000	99,000	132,000	148,000	157,000	197,000	214,000	280,000	345,000
50	44,000	47,000	62,000	88,000	101,000	107,000	136,000	142,000	204,000	262,000
80	38,000	41,000	47,000	61,000	65,000	75,000	97,000	101,000	134,000	175,000
90	35,000	38,000	43,000	54,000	57,000	66,000	82,000	86,000	109,000	142,000
95	33,000	36,000	40,000	49,000	51,000	59,000	72,000	75,000	97,000	123,000
99	28,000	32,000	37,000	42,000	44,000	52,000	58,000	59,000	78,000	100,000

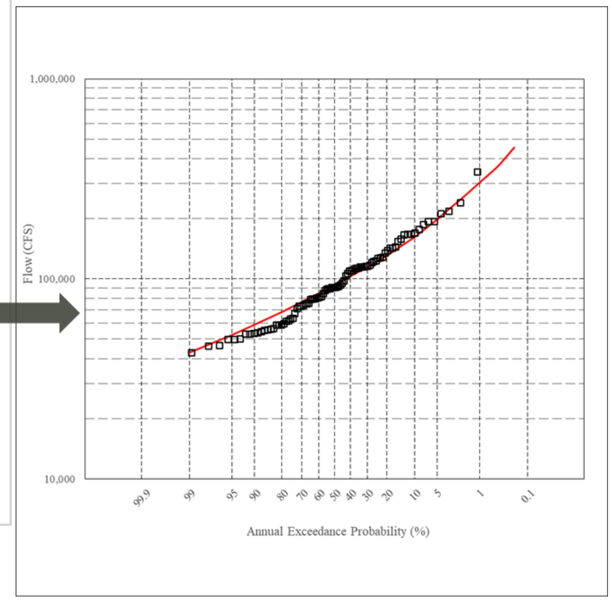
Note: Table ES-2 is also Table 6-18.



Unregulated flow frequency



Transform



Regulated flow frequency

Transform Function (Unregulated Q) = Regulated Q

Figure ES-1. Conceptual Example of Transform Method Results for Computing Regulated Flow Frequency

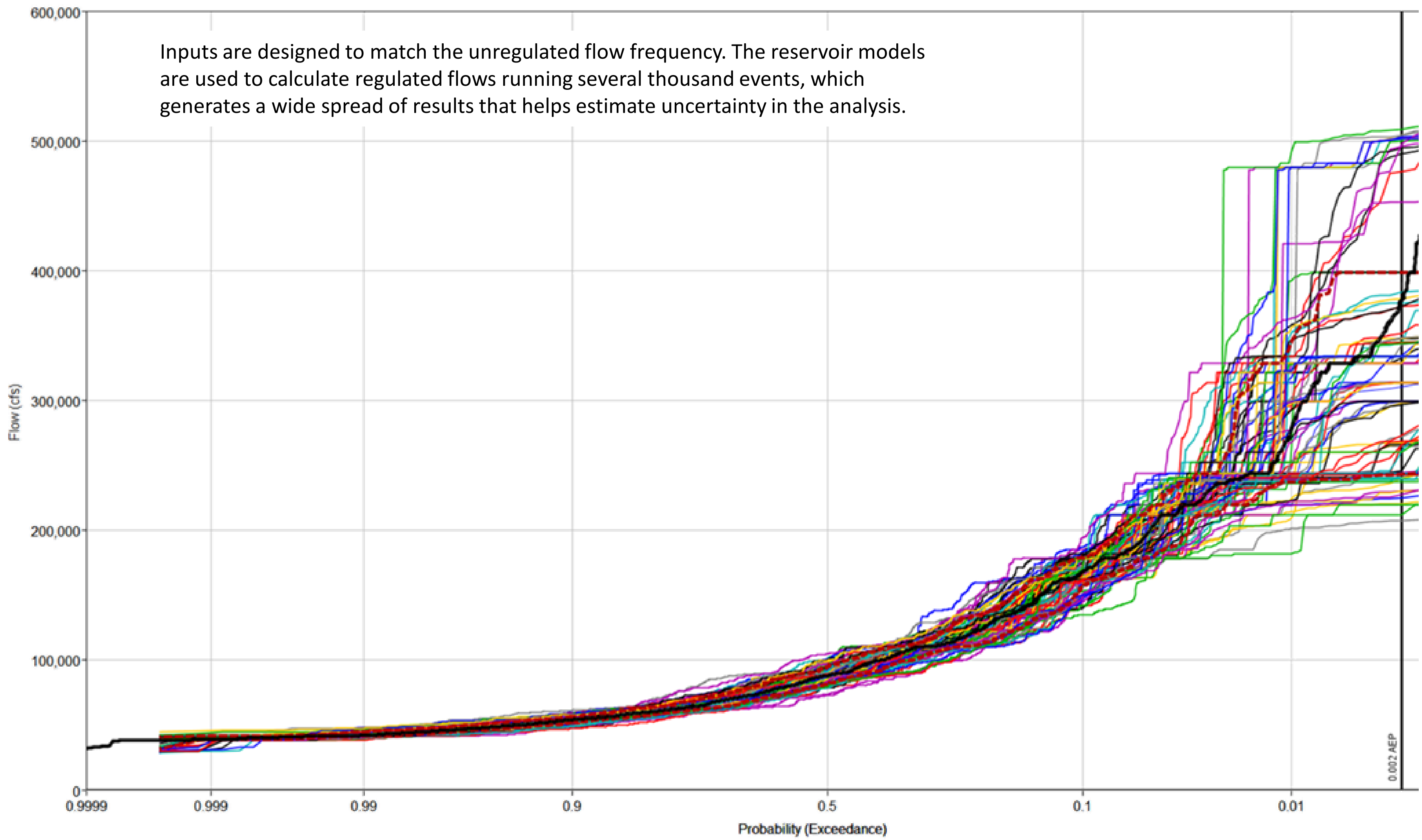


Figure ES-2. Conceptual Example of WAT Monte-Carlo Method Results for Computing Regulated Flow Frequency

The regulated flow frequencies calculated by the Monte Carlo method are compared to the UMRSFFS 2003 results in Figures ES-3, ES-4, and ES-5, representing the common 10%, 1%, and 0.2% AEP. Table ES-3 compiles these results. See Section 7 for an expanded discussion and presentation of flow frequencies at all 14 AEPs.

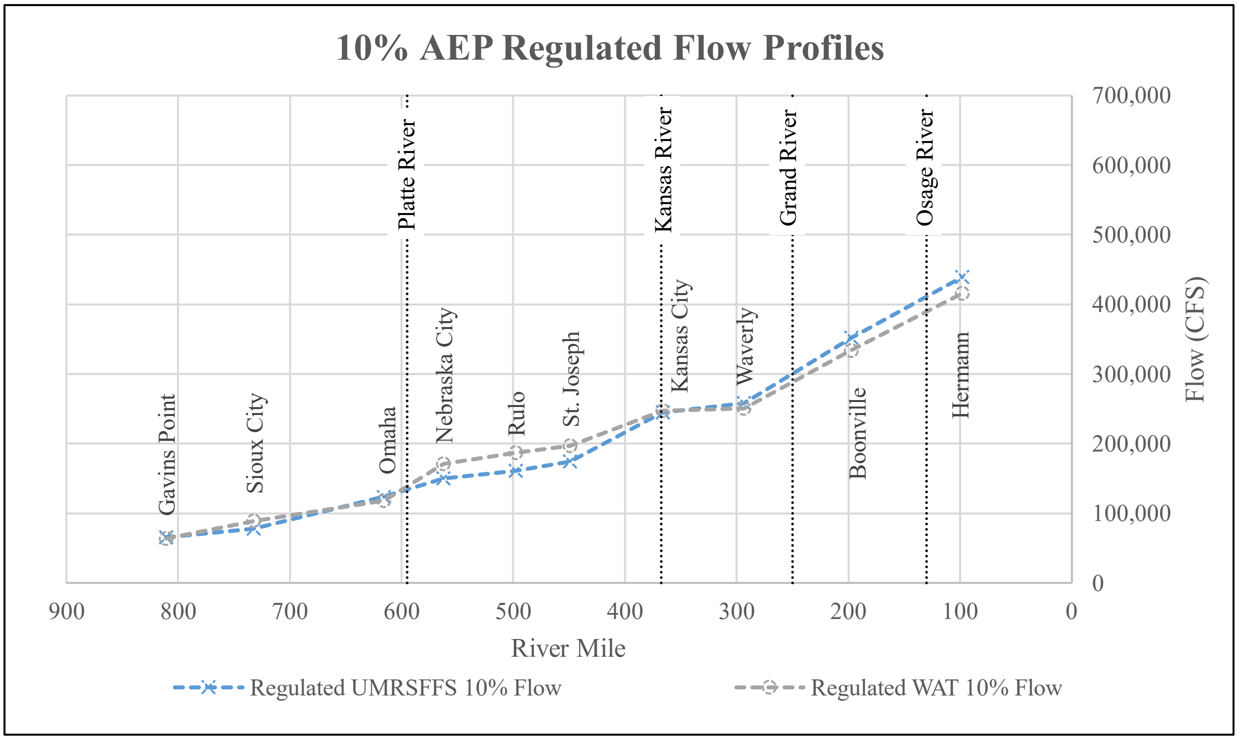


Figure ES-3. Regulated 10% AEP Flow vs River Mile, 2003 UMRSFFS, and Current Study from WAT Monte Carlo (Adopted)

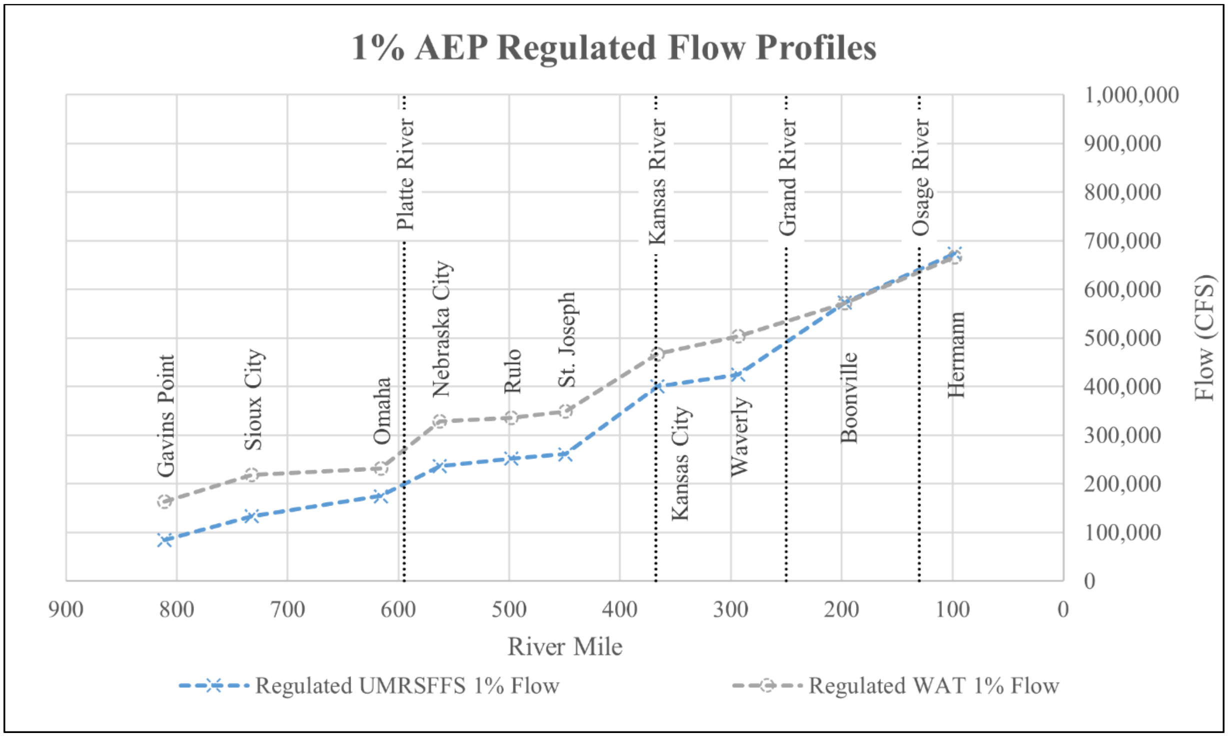


Figure ES-4. Regulated 10% AEP Flow vs River Mile, 2003 UMRSFFS, and Current Study from WAT Monte Carlo (Adopted)

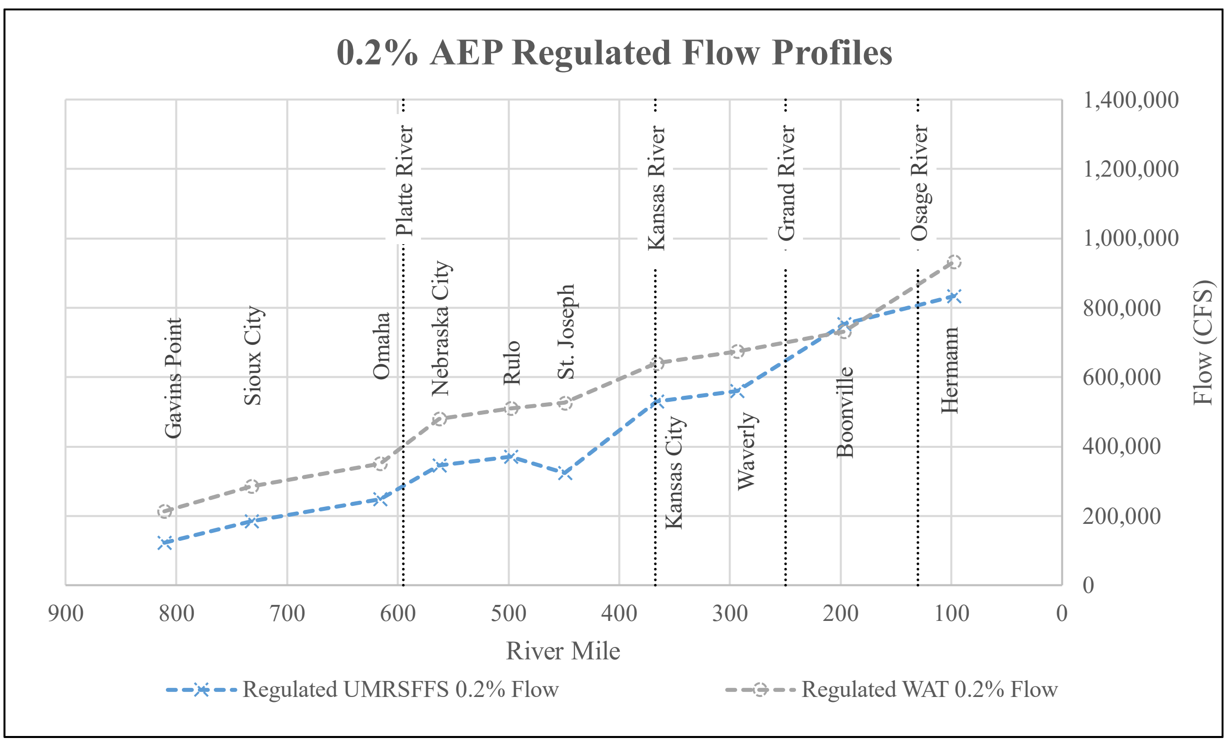


Figure ES-5. Regulated 0.2% AEP Flow vs River Mile, 2003 UMRSFFS, and Current Study from WAT Monte Carlo (Adopted)

Table ES-3. Comparison of Regulated Flow Frequency for 10%, 1%, and 0.2% Annual Exceedance Probability (Flow in CFS), 2003 UMRSFFS and Current Study from WAT Monte Carlo (Adopted)

Gage Location	10% AEP		1% AEP		0.2% AEP	
	2003 UMRSFFS	2023 MRFFS	2003 UMRSFFS	2023 MRFFS	2003 UMRSFFS	2023 MRFFS
Gavins Point	65,000	64,000	84,900	164,000	123,500	213,000
Sioux City	78,300	89,000	133,800	218,000	185,400	285,000
Omaha	123,600	118,000	174,700	232,000	247,900	351,000
Nebraska City	149,800	171,000	236,700	329,000	345,400	480,000
Rulo	160,900	187,000	252,200	336,000	370,700	510,000
St. Joseph	174,000	197,000	261,000	349,000	324,000	526,000
Kansas City	245,000	247,000	401,000	467,000	530,000	640,000
Waverly	258,000	251,000	424,000	503,000	561,000	674,000
Boonville	352,000	334,000	573,000	572,000	753,000	731,000
Hermann	439,000	416,000	673,000	666,000	833,000	933,000

Note: Tabular Summary of Figures ES-3 through ES-5.

1. Introduction

1.1 Purpose

This report documents hydrologic and hydraulic analysis of the Missouri River conducted by the Omaha and Kansas City Districts of the U.S. Army Corps of Engineers (USACE) to update the regulated flow frequencies on the Missouri River below Gavins Point Dam. The previous study for discharge frequency relationships on the Missouri River was completed in 2003 as a part of the Upper Mississippi River System Flow Frequency Study (2003 UMRSFFS) based on a period of record of 1898 to 1997. Additionally, in 2018 USACE completed a model simulation building new reservoir and river models using a period of record of 1930 to 2012 as part of the Missouri River Recovery Program (MRRP) Management Plan and Integrated Environmental Impact Statement (2018 ManPlan).

This update aimed to incorporate newer methodology and models as well as to capture the effects of recent floods on regulated peak flow frequency. Work initiated on this study in 2020 and at that time 22 years of additional data was available, including two major flood events in 2011 and 2019. Unlike the 2003 UMRSFFS, this report does not publish stage frequency profiles for the Lower Missouri River. Nor does it incorporate possible future changes to flows as result of in-depth climate change analysis. These items, which are currently funded and in progress as of the date of this report, are anticipated to be published later under a separate report. The results are considered reflective of the existing conditions of the Missouri River Basin, reporting regulated flow frequencies between a 99% and 0.2% annual exceedance probability (AEP) event.

1.2 Scope

Regulated flow frequencies were computed at ten stream gages between Gavins Point Dam and Hermann, MO on the Missouri River. The scope of the effort was broken into flow data time series development, computation of unregulated flow frequencies, hydraulic routing, and estimation of regulated flow frequencies using two methods, a transform method, and a Monte Carlo method. The period of record (POR) was increased to include data up through 2019 to capture recent high flow events. An unregulated dataset was developed to reflect the "no development, no reservoirs" flows by taking the observed flow at gaging locations and accounting for depletions and holdouts due to reservoir regulation and upstream withdrawals. A regulated dataset was developed by applying the current level of depletions and holdouts to the entire period of record. Applying the current level of depletions ensures that the datasets represent flows that would have occurred under current basin development for the entire period-of-record. These data sets were developed by means of a Hydrologic Engineering Center (HEC) Reservoir Simulation (ResSim) model and additionally routed by means of River Analysis System (RAS) model initially developed in the 2018

Missouri River Recovery Management Plan and Environmental Impact Statement (2018 ManPlan EIS).

For the unregulated dataset, historical incremental flows based on historical gage data were routed downstream from Landusky, MT to Hermann, MO via the Missouri River ResSim Model, which removed regulation effects of only the modeled reservoirs within the ResSim model. The tributary reservoir effects were removed when depletions and tributary reservoir holdouts were added back to the model at each gage location. Estimates of depletions and tributary reservoir holdouts not in the ResSim model were estimated by Reclamation. The regulated dataset was developed by simulating reservoir operations based on the 2018 Missouri River Master Manual.

The unregulated and regulated datasets could also be routed from Gavins Point downstream to Hermann, MO via HEC-RAS models. The HEC-RAS routing used the ResSim unregulated and regulated flows at Gavins Point as the upstream boundary condition. Results from the two models were compared. A Bulletin 17C analysis was then performed on the unregulated data set at ten gage locations and extrapolated out to an annual exceedance probability of 0.2%. The study has picked ten locations of interest to do analysis at: Yankton, SD (Gavins Point Dam), Sioux City, IA, Omaha, NE, Nebraska City, NE, Rulo, NE, St. Joseph, MO, Kansas City, MO, Waverly, MO, Boonville, MO and Hermann, MO. The locations of these stations, or gages, are shown in Figure 1-1, where Gavins Point Dam is located immediately upstream of Yankton, SD and the two locations are often used interchangably in this report.

As detailed in the Bulletin 17C guidelines, historic peak floods were considered and incorporated into the analysis. Literature review was conducted to determine previously published values for historic floods, and uncertainty with these values was incorporated at select gages, including St. Joseph, Kansas City, Boonville, and Hermann, MO, and was used to inform historic peak flows used at other study gages. Additionally, peaking factors were established to convert daily flows used in the routing models to peak flows. Although this study does not publish water surface profiles, some discussion of elevation data was necessary when establishing historical flood peaks. Unless otherwise noted, elevations referenced in this report are to the National American Vertical Datum of 1988 (NAVD88).

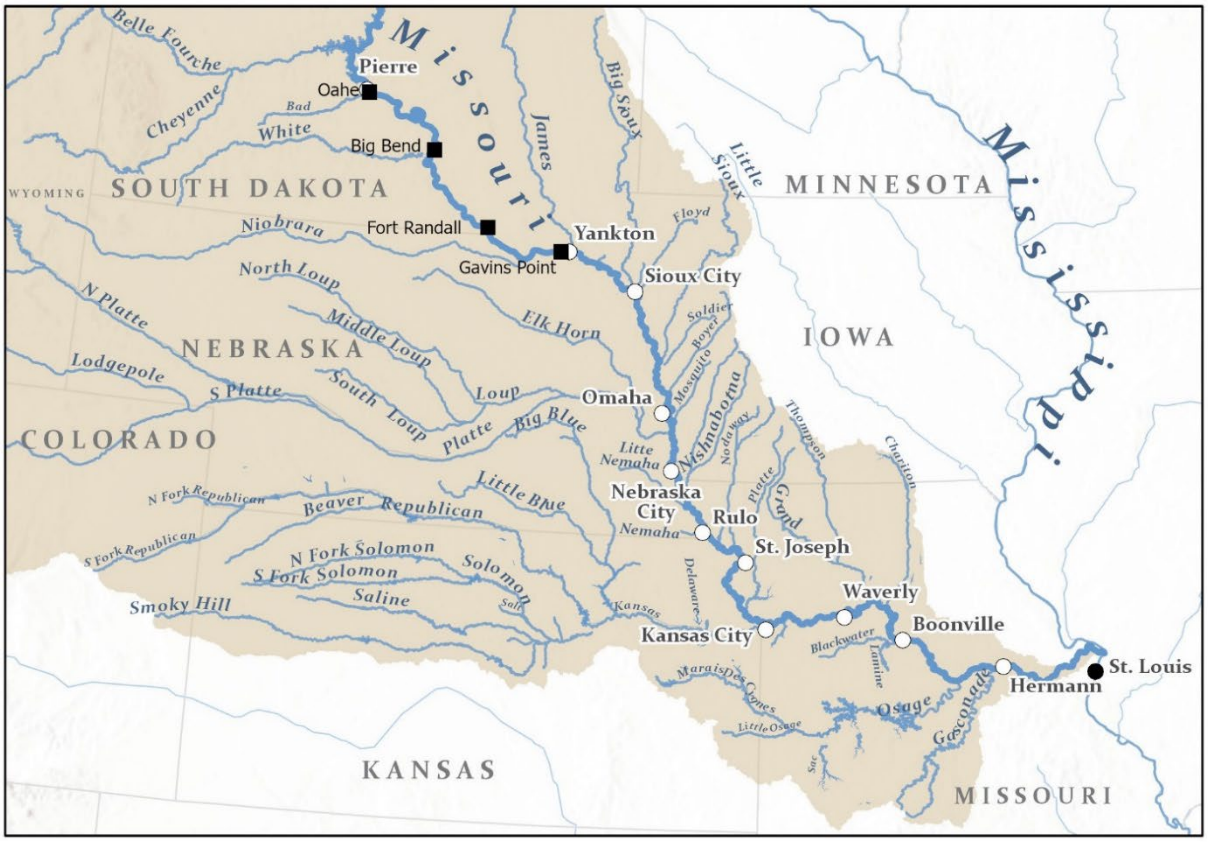


Figure 1-1. Stream Gages used in the Lower Missouri River Frequency Analysis

As stated, regulated flow frequencies were computed using two methods. First, a relationship was developed for each gage location between the unregulated data set and the regulated data set. This relationship was used to transform the unregulated flow frequency from the Bulletin 17C analysis into a regulated flow frequency. To inform this relationship, additional synthetic floods were produced based on scaling up existing flow data from flood years to add additional high flow events larger than observed in the period of record. This method was selected to mimic the 2003 UMRSFFS analysis. Secondly, a Monte Carlo analysis was performed utilizing the HEC Watershed Analysis Tool (WAT) to compute regulated flow frequency directly using a combination of the observed record and synthetic events. To do this analysis, the very large watershed was broken into regions and correlations between regions established to determine a reasonable sampling approach. The methodology results in modeling combinations of events that cannot be checked based only on the analysis of the POR. Outputs of the Monte Carlo analysis were calibrated to the unregulated Bulletin 17C flow frequency curves at the study streamgages.

Prior to initiating Bulletin 17C analysis, the study also included a qualitative analysis on the impacts of climate change on flood risk, and the effect on flood risk management projects within the Missouri River basin. An investigation on non-stationarity was included as part of this effort to identify any trends or changepoints in the data over the period of record and was compared to timelines for overall basin development. The qualitative analysis resulted in a recommendation to complete an in-depth analysis for the basin. While the qualitative analysis informed the study, aside from sensitivity analysis to various periods of record and ways to incorporate historic peaks, no attempt to adjust the records for climate change were made at this time.

1.3 Objectives

The main objective of the Missouri River Flow Frequency analysis is to develop discharge frequency relationships for ten mainstem gage stations on the Missouri River between Gavins Point Dam and the confluence with the Mississippi River. To develop these relationships, unregulated and regulated flows were developed and analyzed using several hydrologic, hydraulic, and Monte Carlo software models.

Additionally, this report aims to better capture the effects of the change in climate. Thus, another objective for the analysis is to perform a qualitative climate assessment. This effort identifies the relative severity of climate change and its effects on precipitation, temperature and flows within the basin. Climate Preparedness and Resilience tools were used to evaluate non-stationarity as well as identify trends in peak streamflow, monthly peak flow, and future hydrology.

1.4 Previous Studies

Over the history of the Corps of Engineers there have been numerous studies on the Missouri River. Previous studies include the 308 Report in 1932, Flood Control Act of 1941, Flood Control Act of 1944, 1947 Missouri River Levee System Definite Project Report (USACE 1947), Mississippi Basin Model Studies, Main Stem Flood Control Benefits Re-evaluation of 1956, and Missouri River Agricultural Levee Restudy Program of 1962. A summary of key documents is provided below:

Missouri River Basin "308 Report" of 1932, and Kansas City supplement of 1935. This document reflected the first major planning effort for flood risk reduction at a national scale motivated by the devastating flood of 1927 on the Mississippi River as authorized by the 1928 Flood Control Act. The study recommended levees to be constructed at Kansas City, considered multiple alternatives for flood risk reduction, and contains a wealth of information and original documentation for estimates of several historic floods.

Missouri River Levee System Definite Project Report of 1947. The 1947 study recommended design flows for the agricultural levees and included flow frequency information and estimates of several historic floods in Appendices A and I, Hydrology, for Kansas City and Omaha District, respectively, both completed in 1946.

Missouri River Agricultural Levee Restudy Program of 1962. The 1962 study, which considered a period of record back to 1898, was the primary source of flow frequency information until flows were updated in 2003. The effort included analysis of adjusting flows for the impact of levees that had been constructed at that time and in estimating future impacts of levees on flood routings.

Upper Mississippi River System Flow Frequency Study (UMRSFFS) of 2003. As previously discussed, this study reflects currently published flow and stage frequencies for the Missouri River below Gavins Point Dam. The study analyzed the Missouri River as a major tributary to the Mississippi using the 1898 to 1997 POR. Additional information on previous studies can be found in the 2003 UMRSFFS Appendices E and F to include published unregulated and regulated flow frequencies and stage frequency profiles for the Kansas City and Omaha Districts, respectively. The effort included developing several unsteady flow models for different time periods using the UNET software, which was later incorporate into HEC-RAS. Appendix D contains analysis of the St. Louis District, and Appendices A and G provide information on basin development and meteorology.

Kansas River Flow Frequency Study, 2002. A similar effort using the same data as the 2003 UMRSFFS was completed by the Kansas City District in 2002 for the Kansas River regulated flow frequencies, however, no stage frequencies were published. Previous flow frequency studies were completed in the 1970's for the Kansas River.

Post 2011 Flood Report. Following the 2011 flood, the flow frequency results from the 2003 UMRSFFS were reevaluated in a cursory analysis for several gages between Gavins Point Dam and Hermann, MO. Generally, the report concluded that differences between the hydrologic statistics using the additional 14 years of record available through 2011 were of a small magnitude (<5%). However, the Kansas City District flagged that the St. Joseph, MO unregulated to regulated transform relationship warranted further investigation as result of the cursory analysis after seeing how the 2011 flood plotted with the data. Unregulated values were extended using flows from USACE Annual Damages Prevented Calculations, whereas regulated records were extended using observed USGS peak flows.

Lower Platte River Flow Frequency Analysis, 2018. The Omaha District completed a flow frequency study for the Lower Platte River, using post-Kingsley Dam records of 1942 to 2016. Due to regulation impacts, no attempt to incorporate historical peak information was undertaken.

Kansas City Levees, Supplemental Hydrology and Hydraulic Analysis, 2018, as Awarded Version, August 2021. Bulletin 17C computations were made for the Missouri River at Kansas City, MO, and Kansas River at DeSoto, KS. The 2003 UMRSFFS period of record of 1898 to 1997 was extended initially to 2017 and later to 2019 using values from the USACE Annual Damages Prevented publications for unregulated flows and the observed flows for regulated flows. Kansas River flow records were similarly extended from 1917 to

1997 to 1891 to 2019 by incorporating older flow records at upstream gages and translating them to DeSoto, KS. Additionally, stage records and historic peaks were used to derive older historic peak flow information for periods back to the 1844 flood, 1826 flood, 1785 flood, and to 1699 as sensitivity analysis. Additional flood routings using rain-runoff models for the Lower Kansas River Basin were used to fill in additional data in the 2003 UMRSFFS unregulated to regulated flow transform equations.

Missouri River Recovery Program (MRRP), Management Plan and Integrated Environmental Impact Statement, 2018 (Man Plan EIS, 2018). This study developed existing conditions unsteady flow river hydraulic models, reservoir simulation models, and timeseries flow data to compare various management alternatives using an 82-year period of record simulation from 1930–2012. All documentation for the Man Plan EIS, which was heavily leveraged for this study, is posted on the Missouri River Recovery Program Website at: https://www.nwo.usace.army.mil/mrrp/mgmt-plan/.

Kansas River Basin Watershed Study, post ATR draft, 2023. Using the same data as this study, and flood history research expanded upon from the Kansas City Levees Report, updated regulated flow frequencies for Kansas River gages and tributaries below dams have been developed. The report uses the transform methodology as in the 2002 Kansas River Basin Study, as validated against the HEC-WAT Monte Carlo analysis from this current study at the DeSoto, KS gage.

2. Basin Description

The Missouri River rises along the Continental Divide in the northern Rocky Mountains and flows generally easterly and southeasterly to join the Mississippi River near St. Louis Missouri. Maps of the basin are presented in future sub-sections for reference. The river drains approximately 9,700 square miles of Canada and 513,300 square miles or one-sixth of the contiguous United States. Its headwaters begin near Three Forks, Montana where the Madison River, the Jefferson River, and the Gallatin River join to form the Missouri River. From there it travels 2,315 miles to its confluence making it the longest river in the United States. Basin topography varies from the 56,000 square miles in the Rocky Mountain area in the west, where many peaks exceed 14,000 feet in elevation, to the approximately 370,000 square mile Great Plains area in the heartland of the basin, to the 90,000 square mile Central Lowlands in the lower basin. The elevation of St. Louis, Missouri, near the mouth is 466 feet. The Black Hills in South Dakota and the Ozarks in Missouri, consisting of 13,000 square miles, are isolated dome like uplifts that have been eroded into a hilly and mountainous topography. Stream slopes vary from about 200 feet per mile in the mountains, to about 4 feet per mile in upper reaches of the Missouri River above Zortman, MT, to about 0.9 foot per mile in the Great Plains and Central Lowlands from the Yellowstone River to the mouth at St. Louis, Missouri.

Major Missouri River tributaries are the Yellowstone River, which drains an area of 70,000 square miles, joining the Missouri River near the Montana-North Dakota border; the Platte River with a 90,000 square mile drainage area entering the Missouri River in eastern Nebraska; the Kansas River which empties into the Missouri River in eastern Kansas at Kansas City and drains an area of approximately 60,000 square miles; and the Osage River which drains approximately 15,000 square miles of the Ozark Plateau and Ozark Plains of Missouri and eastern Kansas. The Osage River joins the Missouri River on the right bank 130 miles above St. Louis with an average annual streamflow comparable to the Yellowstone River and higher than the Platte and Kansas Rivers.

A prominent feature in the drainage pattern of the upper portion of the basin is that every large tributary, except for the Milk River, is a right bank tributary flowing to the east or to the northeast. During high plains snowpack years significant flow can be contributed from left bank tributaries just downstream of Gavins Point Dam such as the Vermillion, James, and Big Sioux Rivers. Only in the extreme lower basin, below the mouth of the Kansas River, is there a reasonably fair balance reached between left and right bank large tributaries as in the Grand and Chariton Rivers of the left bank and Osage, Gasconade, and Lamine/Blackwater Rivers of the right bank. The direction of flow of the major tributaries is of particular importance from the standpoint of the potential concentration of flows from storms that typically move across the basin in an easterly direction. It is also important in another respect on the Yellowstone River, since early spring temperatures in the headwaters of the Yellowstone and its tributaries are normally from 8 to 12 degrees Fahrenheit higher than along the northern most reach of the Missouri near the Yellowstone confluence. This ordinarily results in ice breakup on the Yellowstone prior to the time the ice goes out of the Missouri River, thereby contributing to ice jam floods along the Missouri River downstream from the confluence to near Williston, North Dakota.

Streams having their source in the Rocky Mountains are fed by snowmelt. They are clear flowing and have steep gradients with cobble-lined channels. Stream valleys often are narrow in the mountains onto the outwash plains. Flood flows in this area are generally associated with the snowmelt runoff period occurring in May and June. Occasionally, summer rainfall floods having high, sharp peaks occur in the lower mountainous areas, such as the Rapid City flood in June 1972 and the Big Thompson River flood in July 1976. However, these types of events, including also the Colorado floods of 2013 and Yellowstone National Park flood of 2022 are independent from flooding on the Missouri River due to distance and attenuation from these western portions of the Platte and Upper Missouri River Basin watersheds.

Streams flowing across the plains area of Montana, Wyoming, and Colorado have variable characteristics. The larger streams with tributaries originating in the mountain areas carry sustained spring and summer flows from mountain snowmelt, and they have moderately broad alluvial valleys. Streams originating locally often are wide, sandy-bottomed, and intermittent, and they are subject to high peak rainfall floods. In the plains region of North Dakota, South Dakota, Nebraska, and Kansas streams generally have flat gradients and broad valleys, except for the Nebraska sand hills area. Except for the Platte River, upstream of Nebraska City, NE, most of the streams originate in the plains area and are fed by snowmelt in the early spring and rainfall runoff throughout the warm season. Further downstream, such as in the Kansas River Basin, while snowmelt can contribute to stream flows, the largest events tend to be driven primarily by rainfall events due to warmer temperatures often allowing snowmelt between events during the winter. In the Osage Basin, large winter floods driven by rainfall are relatively common. Stream flow is erratic. Stream channels are small for the size of the drainage areas, and flood potentials are high. When major rainstorms occur in the tributary area, streams are forced out of their banks onto the broad flood plains.

In the regions east of the Missouri River above Sioux City, IA, streams have variable characteristics. Those in the Dakotas, such as the Big Sioux and James Rivers, are meandering streams with extremely flat gradients and very small channel capacities in relation to their drainage areas. These areas are generally covered with glacial drift and contain many pothole lakes and marshes. Rainfall in the spring often combines with the annual plains snowmelt to produce floods that exceed channel capacities and spread onto the broad flood plains. Streams in the Ozark Highlands of Missouri as characteristic of much of the Osage, Gasconade, and portions of the Lamine River Basins can resemble mountain streams with their clear, dependable base flows. Much of the area is underlain by limestone, and there are cavernous underground springs. The hilly terrain contains high content of rock and clays, thus producing high peak runoff, which contributes to frequent floods with large volumes due to this area's higher annual rainfall. While average annual streamflow of the Osage River is comparable to the Yellowstone River, in dry years the Osage can have considerably lower flows, whereas in wet years, the Osage can produce much higher stream flows. This indicates increasing variability of flows for eastern portions of the basin compared to the western mountain fed streams, or even the sand hills region of Nebraska as in the Niobrara River.

2.1 Watershed Characteristics

Because the basin is so vast and was influenced by a variable geologic historical development, it is best to describe the basin in sections. There are

major physiographic divisions within the Missouri Basin, the Interior Highlands, the Interior Plains, and the Rocky Mountain System. The Rocky Mountain System division includes parts of the Northern Rocky Mountains, Middle Rocky Mountains, Wyoming Basin, and Southern Rocky Mountains provinces. The Interior Plains division includes parts of the Great Plains and Central Lowlands provinces. Sections and subsections within the Great Plains province include such distinct topographic features as the Black Hills in South Dakota and Wyoming, and the Sand Hills in Nebraska. The Interior Highlands division is characterized by the Ozark Plateaus province. See Figure 2-1 for a map outlining the physiographic divisions within the Missouri Basin.

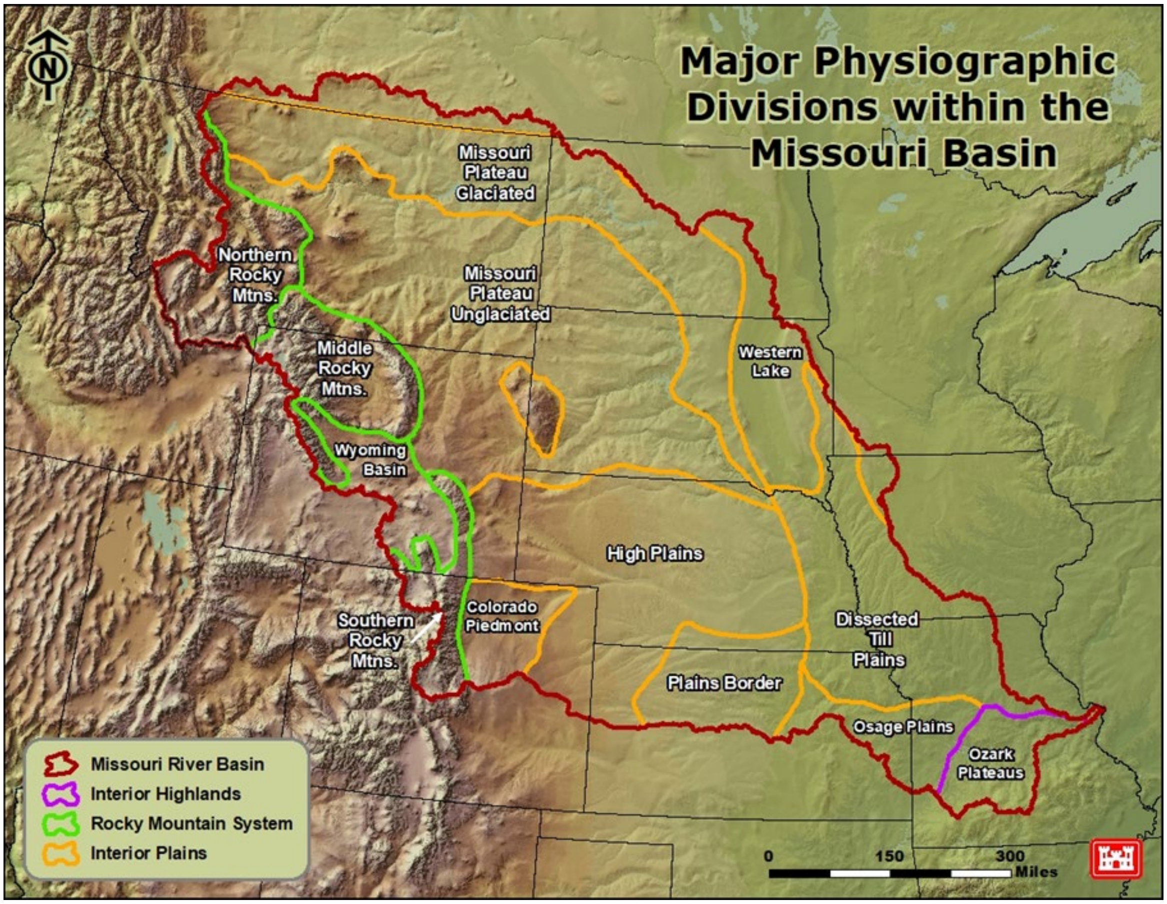


Figure 2-1. Major Physiographic Divisions within the Missouri Basin

The Rocky Mountain System forms the western boundary of the basin and reflects an exceptionally rugged topography, with numerous peaks surpassing 14,000 feet in elevation. The approximately 55,000-square-mile mountainous area is punctuated with many high valleys, but the peaks and mountain spurs dominate the physical features.

Extending eastward from the Rocky Mountain System division is the Interior Plains division that characterizes the major portion of the Missouri Basin. The Interior Plains division can be divided into two areas - the Great Plains and Central Lowlands provinces. The Great Plains province is a 360,000-square-mile area that forms the heartland of the basin. The eastern boundary of this province lies approximately along the 1,500-foot contour, and the western boundary lies at the foot of the Rocky Mountain System, averaging about 5,500 feet in elevation. Average slopes from west-to-east are about 10 feet to the mile. South and west of the Missouri River the surface mantle and topography have been developed largely by erosion of a fluvial plain extending from the mountains. The alluvial outwash laid down a heterogeneous mixture of mantle material. Combinations of water and wind erosion cause varying topographical changes, depending on climate and erodibility of the mantle. That portion of the Great Plains province north and east of the Missouri River, and at places extending south of the river, has been influenced by continental glaciation. Here the topography was shaped mainly by erosion of the glacial drift and till. Morainic drift belts are in evidence and large boulders abound. Some relatively uneroded glacial debris remains as the ice left it, piled in hummocks without order and enclosing many shallow basins, ponds, and swamps.

Within the Great Plains province are isolated mountainous areas developed by erosion of dome-type uplifts. Principal among these is the Black Hills in western South Dakota and northeastern Wyoming, an elliptical-shaped area 60 miles wide and 125 miles long. Another distinctive area within the province is the Sand Hills in north-central Nebraska, covering about 24,000-square-miles.

The Central Lowlands province, within the Interior Plains division, borders the Great Plains province to the east, but generally there is no perceptible line of demarcation between them. This roughly 88,000-square-mile area extends between a line from Jamestown, North Dakota, to Salina, Kansas, and the Mississippi River drainage divide. This entire area has been developed by erosion of a mantle of drift and till deposited by the continental glaciers. An abundance of rainfall and stream development has created a hilly topography in many places, but especially in the southern portion of the province.

2.2 Basin Regulation

The Missouri River Mainstem Reservoir System is comprised of six dam and reservoir projects, Fort Peck, Garrison, Oahe, Big Bend, Fort Randall and Gavins Point, authorized by the Rivers and Harbors Act of 1935 and the Flood Control Act of 1944. Section 9 of the 1944 Flood Control Act authorized the System to be operated for the purposes of flood control, navigation, irrigation, hydropower, water supply, water quality control, recreation and fish and wildlife. In addition, operation of the System must also comply with other applicable Federal statutory and regulatory requirements, including the Endangered Species Act. The System is regulated using guidelines published in the Master Manual. The Master Manual presents the water control plan and operational objectives for the integrated regulation of the System. Annual water management plans (Annual Operating Plans) are prepared each year, based on the water control criteria contained in the Master Manual, to describe potential reservoir regulation of the System for the current operating year under a variety of runoff conditions. The System contains 71 percent of the installed capacity in the basin's Federal hydroelectric power system, provides almost all of the reservoir support for downstream flow support on the Missouri River during drought periods and contributes greatly to flood risk reduction for over 2 million acres of land in the floodplain of the Missouri River. At normal pool levels, these reservoirs provide an aggregate water surface area of 1 million acres for recreation and fish and wildlife enhancement.

Since the System was designed, the Master Manual has been updated several times. Reservoir modeling for the 2003 UMRSFFS was based on the guidelines published in the 1978 Master Manual. Since the 2003 UMRSFFS was completed, two main updates were made to the Master Manual. In the 2004 Master Manual, drought conservation measures, non-navigation flows, and unbalancing of the upper three reservoirs were added. The drought conservation measures stated that the navigation service level and season length would be reduced based on "guide curves" to conserve water. When the guide curves indicate that navigation will not be supported, non-navigation flows will take effect. Non-navigation flows are releases made to support water supply to the thermal powerplants and other municipal and industrial intakes on the river or reservoirs. Intra-system unbalancing is a three-year rotating process among the upper three reservoirs where one of the upper three reservoirs is drawn down to benefit resident fisheries. Also, in the amended 2003 Biological Opinion (BiOp) issued by the United States Fish and Wildlife Service (USFWS), criteria for a bimodal spring pulse for the benefit of the pallid sturgeon was included. The bimodal spring pulse was added as a guideline to 2006 Master Manual. Based on additional science and the completion of the Man Plan EIS, it was determined the reservoir unbalancing and bimodal spring pulse were no longer needed, so those guidelines were removed from the 2018 Master Manual.

The six mainstem dams were constructed starting in 1933 at Fort Peck, which was in operations for navigation and flood control by 1938, with the other five dams constructed, filled, and placed into operations between 1946 and 1967. The mainstem dams have a combined total storage of 72.4 million acre-feet (MAF) comprised of 17.6 MAF of permanent storage, 38.5 MAF of carryover / multiple use, and 16.3 MAF of flood control storage split between 11.6 and 4.7 MAF of flood control / multiple use and exclusive flood control, respectively (USACE 2018 Master Manual). During dry periods, the carryover / multiple use can provide additional storage for large floods. While the total storage is periodically updated to reflect storage lost due to sedimentation, the flood control storage space of 16.3 million acre-feet has remained unchanged since the system filled and became operational in 1967. The system flood control space is based on flow routings of the 1881 flood, whereas the carryover / multiple use storage is based on the record drought of the 1930's.

The flood control storage zones in the Missouri River main stem reservoirs were designed in a series of Detailed Project Reports in the mid-1940's to provide control of the severe 1881 flood, with maximum releases of about 100,000 cfs from all projects other than Fort Peck and with maximum pools at or near the top of the exclusive flood control storage space. The 1881 flood inflows, estimated at 325,000 cfs at the Fort Randall Dam site, were based on estimates of what actually occurred, without reduction to allow for operational effects of upstream tributary reservoirs or for consumptive use by upstream irrigation and other purposes. If the flood runoff were to recur today, its severity as far as the main stem reservoir designs are concerned would be significantly reduced by these factors. On the other hand, regulation criteria used in the 1881 reservoir design studies were based largely on hindsight, with little regard for downstream runoff conditions. Releases of approximately 100,000 cfs were assumed to be made from mid-April to mid-July from the five lowermost reservoirs, without any requirement for reducing releases to desynchronize with downstream flood peaks (USACE 2003, Appendix F). Current flood operations of the System include the use of several downstream control points as detailed in the 2018 Master Manual. In times of flooding, releases are scheduled to evacuate the flood pools by a certain date but may be temporarily reduced during times of high downstream tributary flows. During extreme events, as the exclusive flood control pool fills flood operations transition to preserving the integrity of the dams to prevent overtopping, which could have catastrophic downstream consequences. This operation may require releases when downstream flooding is occurring.

USACE Omaha District and Kansas City District also own and operate 43 tributary reservoir projects along with directing flood regulation at 22 US Bureau of Reclamation (Reclamation) reservoirs with authorized flood control storage according to Section 7 of the 1944 Flood Control Act. Other authorized purposes of these tributary projects vary by project and can include water supply, water quality, fish and wildlife, recreation, irrigation, and hydropower, with limited navigation flow support at a few Kansas River Basin projects. Most of the dams were constructed between the 1940's and 1980's, providing approximately 15.7 million acre-feet of flood storage (USACE 2003, Appendix F), with the 22 Reclamation dams representing 3.9 MAF of this total. Approximately 78% of the tributary flood storage is within the 18 Kansas and six Osage River basins projects which have a flood storage of 6.7 and 5.7 MAF and total storage of 9.2 and 8.2 MAF, respectively. In the Kansas River Basin, the lower seven dams of Tuttle Creek, Milford, Perry, Clinton, Waconda (Reclamation), Kanopolis, and Wilson combine for 5.1 MAF of flood storage, representing 76% of the Kansas River Basin flood storage, and 6.5 MAF of total storage. Of these, Milford, Waconda, and Kanoplis have eight, two and one additional federal dams upstream of them, respectively. Upstream storage projects in the Kansas River basin are situated in drier portions of the basin that also have soils with higher infiltration capacity and significant irrigation demand, entering their flood pools much less frequently than the eastern dams. The multi-purpose pools of all 11 upstream Kansas River Basin dams are operated by Reclamation for irrigation, including the USACE Harlan County Dam upstream of Milford, the largest upstream project. Of the remaining 3.3 MAF of flood storage in these tributary projects outside of the Kansas and Osage Basins, 1.6 MAF are in dams upstream of the Mainstem Dam Reservoir System. Most notably, these include four Reclamation dams in the Missouri and Yellowstone River basins of Canyon Ferry Dam, Tiber Dam, Boysen Dam, and Yellowtail Dam.

The design of the flood control pools at each project varies but is usually based on the analysis of a large observed flood at the dam site or the computation of hypothetical flood hydrograph. The lower Kansas Basin Reservoir flood pools are operated for flow targets on the Kansas River and Missouri River at Kansas City and Waverly, MO, with flow targets at Waverly usually limiting releases during extended wet periods. The Waverly, MO flow targets are 90,000 cfs, 130,000 cfs, and 180,000 cfs when the reservoirs are at Phase I, II, and III pools, respectively. During extended wet periods, the Kansas Basin Reservoir pools can remain high for extended periods, unless deviations are approved to allow evacuation ahead of a rise or on the falling limb of the hydrograph. In the upper Kansas River Basin, Harlan County was sized based on the record devastating 1935 flood which caused 110 deaths in Nebraska. The 1935 flood produced a peak of 280,000 cfs on the Republican River at Cambridge, NE on May 31, but attenuated to 122,000 cfs on the Kansas River near the mouth at Bonner Springs, KS on June 6. Had the upper Republican River Reservoir System been operational during the 1935 flood, the maximum discharge at McCook, Nebraska, would have decreased from 245,000 cfs to 49,340 cfs (USACE 2021, KC Levees).

For the Osage River Basin, the flood pools are operated for a flow target on the Osage River at St. Thomas, MO as 34,000 cfs, 54,000 cfs, and 80,000 cfs for Phase I, II, and II pools, respectively. Additionally, the Osage Basin is operated a for the Missouri River at Hermann, MO, holding releases on the rising limb for flows above 260,000 cfs, and the allowing releases up to 90% of the peak that just occurred on the falling limb. This falling limb criteria has been similarly implemented on the Kansas River Basin as an approved deviation in recent floods, as in May–June of 2019. In the Kansas City District, the Phase I, II, and III target flows are generally set with Phase I as a percentage of the bankfull or non-damaging flow, with Phase II being near the threshold of damaging, and Phase III having slight damages. Water Control Manual (WCM) updates were initiated at several dams in the Osage and Kansas Basins in 2022. Their current operations follow the original project and basin master WCM’s as written between the 1960’s to 1980’s.

Figure 2-2 demonstrates the large storage capacity of the Missouri River mainstem dams relative to other USACE dams. In the figure, the largest Kansas and Osage Basin Projects are also labeled at Tuttle Creek and Truman. Tuttle Creek Dam is located on the Big Blue River with 1.9 MAF of flood storage and approximately 2.1 MAF of total storage. The second largest Kansas River Basin project is Milford Dam on the Republican River immediately west of Tuttle Creek Dam 0.76 MAF of Flood Control storage and total storage of 1.1 MAF. Truman Dam is located on the Osage River downstream of the other five dams and has 4.0 MAF of flood storage and a total storage of 5.2 MAF. Figure 2-3 shows a map of the USACE and Reclamation dams and other major dams in the Missouri River basin. Figure 2-4 graphically shows the relative flood control storage space of all 71 Missouri River Basin USACE and Reclamation dams grouped by watershed.

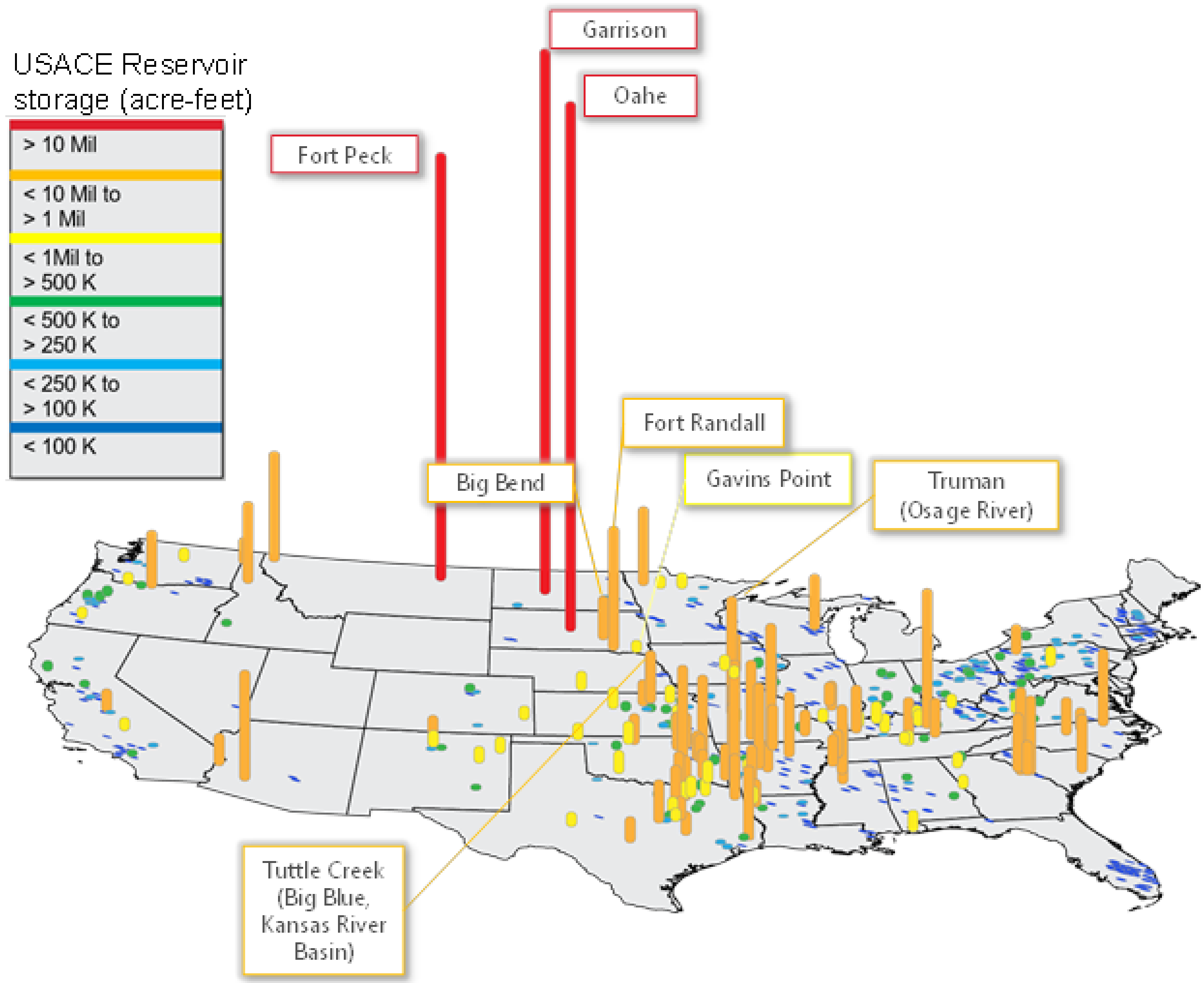
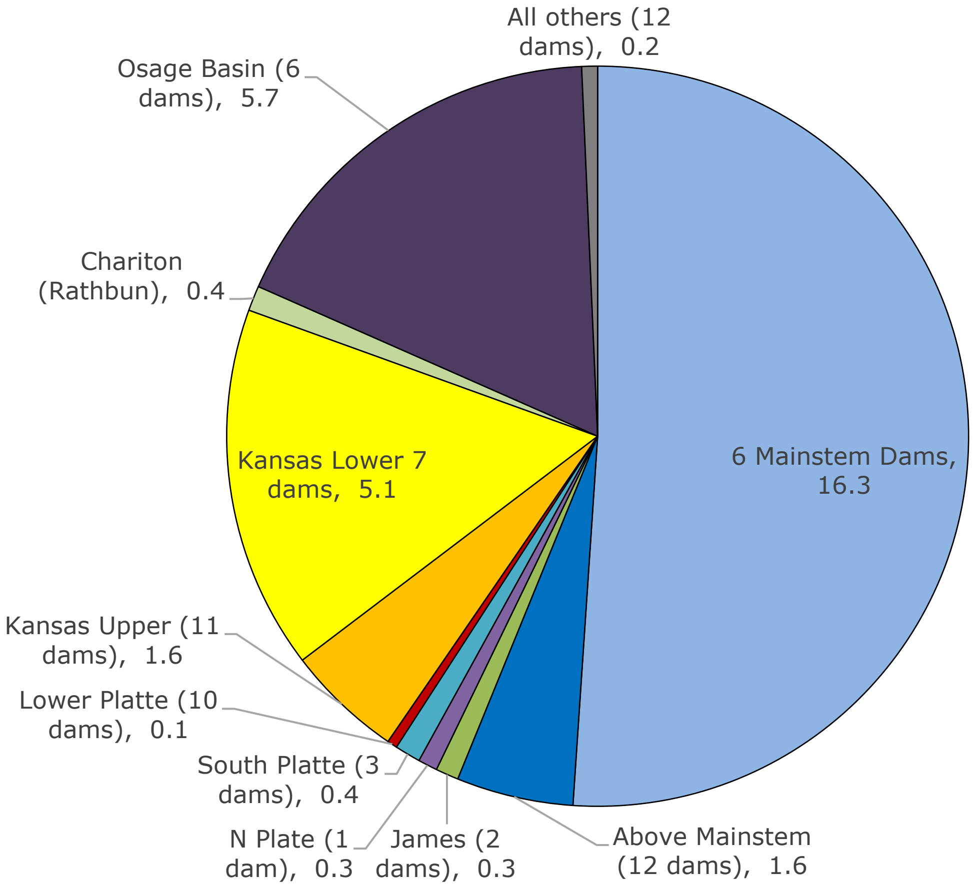


Figure 2-2. USACE Reservoir Storage Map for the Lower 48 States

Figure 2-3. Missouri River Basin Mainstem and Tributary Reservoirs



Numbers for each grouping of dams (71 total dams) are total flood control storage in millon acre-feet. The total for all 71 dams is 32 million acre-feet. This does not include multi-purpose storage or permanent pools.

Figure 2-4. Missouri River Basin Mainstem and Tributary Reservoir Flood Control Storage Space by Watershed

The drainage pattern of the Missouri River basin along with a map of regulated drainage areas in the basin are shown on Figure 2-5. As seen in the figure, aside from the Kansas and Osage River systems, the tributary reservoir drainage areas are generally small relative to the full basin, with the largest situated in the far upstream reaches of the watersheds long distances from the Missouri River. The largest tributary projects in terms of drainage area below the Mainstem Reservoir System aside from the Kansas and Osage Basin systems include projects in the James River Basin in North Dakota, North Platte and South Platte River Basins in Wyoming and Colorado, and the Chariton River in southern Iowa. Two other dams without federally authorized flood control storage are also highlighted on the figure as in Kingsley Dam (Lake McConaughy) completed in 1941 on the North Platte River in Nebraska, and Bagnell Dam (Lake of the Ozarks) completed in 1931. An accounting of regulated and unregulated drainage area is provided in Section 3.1 for each study gage.

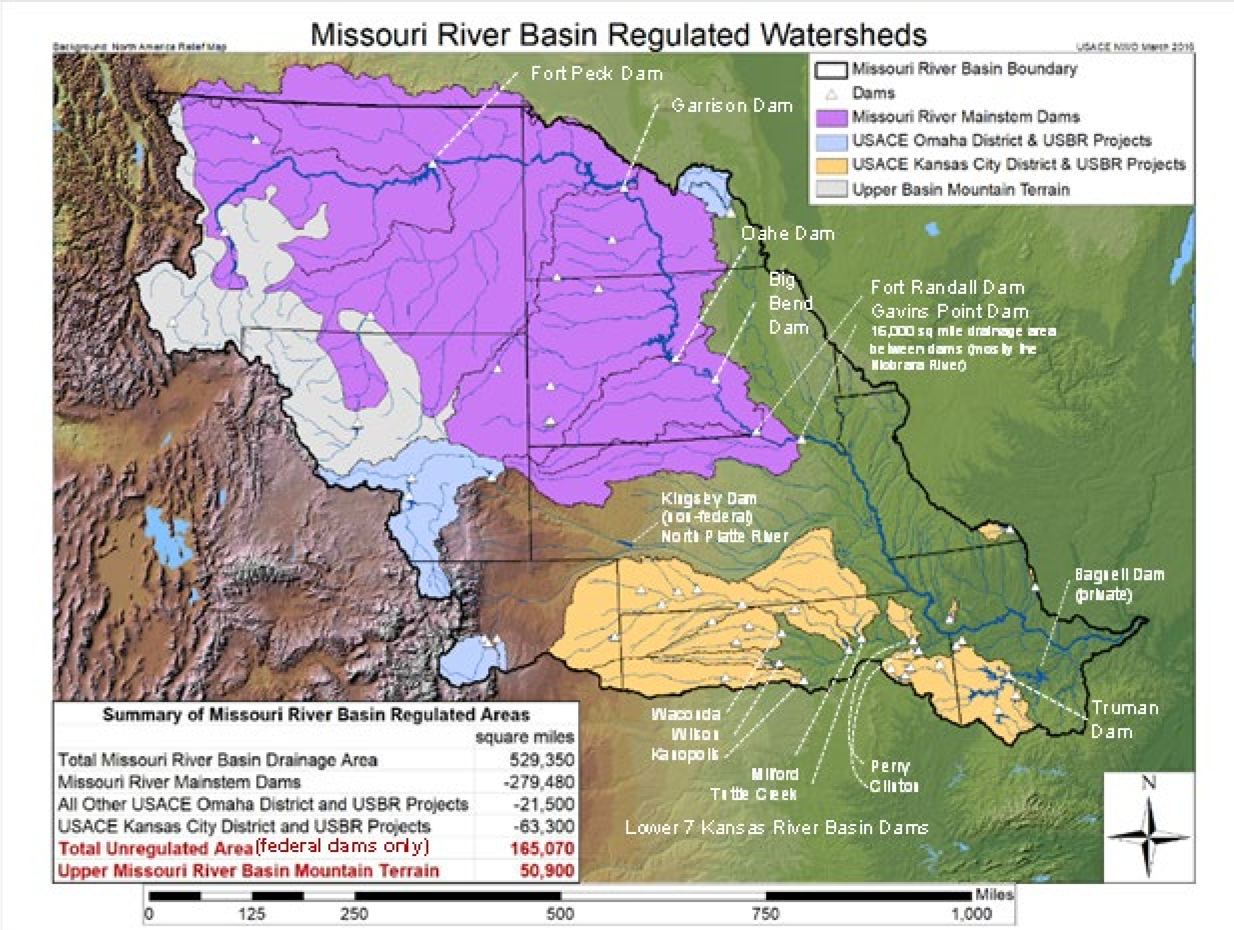


Figure 2-5. Missouri River Basin Regulated Watersheds

2.3 Climatology

The climate within the basin is determined largely by the interaction of three great air masses that have their origins over the Gulf of Mexico, the northern Pacific Ocean, and the northern polar regions. They regularly invade and pass over the basin throughout the year, with the gulf air tending to dominate the weather in summer and the polar air dominating in winter. It is the seasonal domination of the air masses and the frontal activity caused by their colliding with each other that produces the general weather regimens found within the basin.

A major factor affecting the climate is the remoteness of the basin from the source areas of the air masses. This means that the air masses must cross vast areas before they reach the basin. In crossing these areas, they leave much of their available precipitation, and their air temperatures are changed considerably by radiation from the land surface. Potential for intense rainfall combining with snowpack also presents a challenge for the Missouri River Basin.

Primarily because of its midcontinental location, the basin experiences weather that is known for fluctuations, extremes, and variability within the basin. Winters are relatively long and cold over much of the basin, while summers are fair and hot. Spring is cool, moist, and windy; autumn is cool, dry and sunny. Weather tends to fluctuate widely around annual averages, with the occurrence and degree of the fluctuations being unpredictable. Thus, the climatic averages must be thought of as generalizations of the more common occurrences over a period.

Average annual precipitation varies from over 40 inches in parts of the Rocky Mountains and southeastern parts of the basin, to as low as 6 to 12 inches immediately east of the Rocky Mountains until reaching eastern portions of the watershed. For example, the average annual precipitation of the Kansas River Basin varies from less than 20 inches in western Kansas to approximately 39 inches at its mouth near Kansas City, MO, generally increasing with distance from the Rocky Mountain rain shadow. Eastern portions of the basin in Missouri can receive over 40 inches of precipitation on average. There is a wide variation in the basin wide pattern of monthly precipitation.

In the upper to middle portions of the basin, precipitation received from November through March generally is in the form of snowfall. This can transition to mixed rainfall and snow in middle portions of the basin, whereas in southern portions of the Missouri River Basin, such as the Osage and Gasconade Rivers, late fall and winter floods from rainfall are relatively common, and snowmelt events are a smaller portion of the total runoff. Thunderstorms are prevalent in May through August and often are localized, with high-intensity rainfall. Prolonged droughts and lesser periods of deficient moisture may be interspersed with periods of abundant precipitation. Southern portions of the basin in Missouri often experience high-intensity rainfall in the fall months, as can other portions of the basin, although it is less common.

There are periods of extremely cold winter and hot summer temperatures in the basin. Extremes range from winter lows of - 60 F in Montana to summer highs nearly up to 120 F in Iowa, Nebraska, Kansas, and Missouri. The basin regularly experiences over 100-degree temperatures in summer and below-zero temperatures in winter over most of its area.

Winds in the basin are the rule rather than the exception, particularly in the plains area. Average wind velocities of 10 miles per hour are prevalent over much of the basin. In the plains area strong winds accompanied by snow sometimes create blizzard conditions. High winds occasionally prevail during periods of high temperatures and deficient moisture that can destroy crops and desiccate rangeland within a few days.

An outstanding climatic rarity in the basin was the severe drought of the 1930's when excessive summer temperatures and subnormal precipitation continued for more than a decade.

2.4 Flood History

Summary details of the two largest floods that have occurred since the publishing of the 2003 UMRSFFS report, select major floods covered in the 2003 report, and a summary of historic floods and evidence used to estimate their magnitude in this study is provided in this section. Additional flood history information may be viewed in the UMRSFFS Appendix F (USACE, 2003) and the 2018 Missouri River Master Manual. Much of the flood history research summarized is covered in detail in the Kansas City Levees, Supplemental Hydrology and Hydraulic Report (USACE 2021, KC levees). Additional details of how the historical flood information was incorporated in the study are included in Section 3. Many other floods occurred that are not written about in detail here but were factored in as historic peak flows as documented in Appendix A, or in the systematic records.

2.4.1 Flood of 1785

Based on limited written records citing stories heard from French and Native American eyewitnesses, coupled with high water marks documented on the Mississippi River at St. Louis, and damages at St. Genevieve, MO, a large flood impacted at least the downstream portions of the Missouri River in 1785. The flood is likely to have occurred in April and was reported to be bigger than the 1826 flood, to perhaps comparable to 1844 based on information on the Mississippi River. The 1785 flood is the largest known flood dating back before European settlement of the Mississippi River floodplain below the Missouri River in 1699. On the Mississippi River, estimates of its height range from April 1, 1785, being 0.68 feet higher than 1844 at St. Louis based on National Weather Service records, to 2.4 feet lower than 1844 based on high water marks at Kaskaskia (Chappell 1908).

2.4.2 Flood of 1811

The first flood on the Missouri River with written record from eyewitness accounts is that of July 1811 and earlier high flows of that year based on the journals of John Bradbury, a naturalist, and Henry Brackenridge, an author and statesman. They ascended the Missouri River separately leaving St Charles, Missouri (river mile 27.8) on March 14 and April 2, 1811, respectively, each documenting frequent rains and multiple high-water events. They ascended to the original Fort Lisa at the Mandan village near river mile 1357.5, 38 miles north of present Bismarck, North Dakota, by June 22, then descended together beginning July 17 thus reaching Fort Osage below Kansas City on July 27, 1811. The authors documented flows "higher than any previous point" beginning at the Omaha Tribe village near present river mile 720 below Sioux City, IA, and on downstream of the Platte River which covered the lowlands and often had strong currents that was forcing them into the woods. Continuing their descent, when they stopped at a farm near present Boonville, likely on the high ground of the natural levee near the river, corn 14 feet high was noted, indicating the high bottoms were not overflowed as they were in 1844. Other documents indicate that 1811 may have been comparable to the flood of 1826 in St. Louis, MO, likely reaching its peak in mid-June (Gould 1889). Aside from the loss of stored food at Mandan and Arikara villages due to the wet weather, which eliminated the usual surplus the tribes used for trade, no accounts of flood damages were located. No information to reliably relate the magnitude of this event to previous floods could be located on the Missouri River. For the lower river below Kansas City, since it was not noted by French and Indian sources, nor did Bradberry or Brackenridge note significant flooding in their journals, it can be assumed that the flood magnitude was smaller than that of 1785 and likely also that of 1826.

2.4.3 Flood of 1820

The first documented flood damages on the Missouri River occurred in 1820 at Fort Atkinson, its initial camp of wood buildings established in 1819 just upstream of Omaha, NE at present day Fort Calhoun, NE, on the "low bottoms". The flood was reported to partially destroy US Army facilities, which were relocated mostly to the bluffs, though drawings show some buildings at the base of the bluffs. Based on flood damages described in 1826, it is possible that some barracks facilities of the original camp remained in service.

2.4.4 Flood of 1826

A large flood in late April in Kansas City and upstream to early May 1826 downstream produced overflows throughout the Missouri River and Middle Mississippi River floodplains from the Omaha / Council Bluffs to St. Louis. The flood caused damages at US Army facilities at Fort Atkinson above Omaha, NE, which was rebuilt mostly on the bluffs after the flood of 1820. The fort was abandoned in 1827 and relocated to present Fort Leavenworth, KS. On May 2, 1826, then Major Stephen Watts Kearney wrote from Fort Atkinson just before leaving on his trip down river to St. Louis that "the River, which has been higher this spring than ever before known, appears to be falling fast". James Kennerly, Sutler at Fort Atkinson, wrote of rising waters through April, and on April 26 "now in my yard and 10 feet from store door", and "finding water 5 or 6 feet deep in the Quarters [of the first regiment]." The river started falling on April 26, 1826 according to Kennerly's journal. Kearney reported overtaking the crest of the flood between Jefferson City, MO and the Osage River on May 8, 1826 (Kearney and Kennerly's diaries, Fort Atkinson State Historical Site Website, viewed in March 2023 at https://www.fortatkinsononline.org/history). According to William Clark's 1826-1831 diary, the Mississippi River in St. Louis crested on May 16-17, 1826, then fell through July. Clark noted "Mississippi and Missouri both of them above their junction higher at this time, than they have been since the recollection of the oldest inhabitants." (Barry 1948, Kansas State Historical Society Website, viewed in April 2023 at https://www.kshs.org/p/william-clark-s-diary/15491).

The 1826 flood provides the first documented flood damages at Kansas City, MO with the destruction of a Choteau Family trading post on the north bank approximately three miles below the current USGS gage, established around 1822, with the family living in the area since 1819. The flood inundated Harlem Bottoms, present North Kansas City, and the bottoms below the post, and motivated the Choteau Family to purchase land near the river in present day East Bottoms in Kansas City, MO that did not flood in 1826 to build their home, steamboat landing, and trading post facilities that were later flooded in 1843 and destroyed and abandoned in 1844 (Marra 2001, McCoy 1881). At St. Louis, 1826 flood damages motivated the establishment of the St. Louis Directrix, an early vertical datum also used on the Missouri River, as residents wanted its height established so that development would not occur below that line (Scharf 1883). At Franklin, MO, which was in the floodplain on the "high bottoms" directly across from Boonville, MO, the May 12, 1826 Missouri Intelligencer newspaper and Kearney's journal documented the flood was just into low-lying areas of the town, which escaped with little damage. The Intelligencer also stated it was the biggest flood known for 30 years, similar to Kearney's May 2, 1826 statement at Fort Atkinson, however, it is unknown if either author was aware of the 1811 or 1785 floods, or if there was another larger flood around the turn of the century. Overall, the 1826 flood was later considered as moderate when compared to the 1844 flood by the Choteau family (Marra 2001). Best estimates of its height relative to 1844 were 10 feet below 1844 at Kansas City, consistent with a June 18, 1844 Lexington Express article, located between Kansas City and Waverly, and 8 feet below at Boonville, MO. The event could also be considered up to approximately 5–6 feet above flood stage at Omaha, NE, however the exact location of the flooded barracks referenced by Kennerly would be difficult to discern as it would not have been on the bluffs with most of the site. Limited written sources referencing a "June flood" indicate the peak at Kansas City, MO may have coincided with an out of bank flood on the Kansas River when the Missouri River was already at or above its banks (See USACE 2021, KC Levees Report). However, information at Omaha, Kansas City, and Boonville indicates the Kansas River did not significantly add to the peak. Other than Fort Atkinson, and a few trading posts on the bluffs, the 1826 flood pre-dated development upstream of Kansas City in Platte or Holt County, MO.

2.4.5 Flood of 1843

The flood of April 1843 is sometimes overlooked in historical documents as it was overshadowed by the Great Flood of 1844 (McCoy 1881). Flood damages were reported by a land surveyor and one of the founders of Kansas City, MO, John McCoy, who saw buildings he erected wash away in the floodplain in Harlem, which is in the vicinity of present-day North Kansas City, MO, reporting its height as 6 or 8 feet below 1844. Several newspaper articles contain a description of high water that year to include the St. Charles, Missouri, Advertiser (see Section 3.8.6) and the Boonslick Times. Additionally, in 1842 the US Army had temporarily established a new base called Fort Croghan near present Council Bluffs, Iowa, which experienced at least four feet of water in the barracks based on journal of John Audubon, a naturalist as he ascended the river. According to Babbit 1916, on April 17, 1843 "Captain Burgwin reported the greatest rise in the Missouri River known within seventeen years [1826]" as he prepared the post to remove to the bluffs.

Earlier on his trip, John Audubon also documented that water had been two feet deep in Mrs. Chouteu's home near Kansas City, which was built on land that did not flood in 1826. He visited the home on May 2, reporting the house still abandoned when river had fallen by six feet. The Holt (established 1841) and Atchison (established 1845), County, Missouri History book places the April 1843 event in the same class as 1844 and 1881, representative of gages in the vicinity of Rulo, NE and St. Joseph, MO. Peak stages upstream of Kansas City all occurred in April, whereas at Kansas City and downstream, the river crested in very late April or early May. Best estimates of its height considering all information is approximately six feet below 1844 in Kansas City. Available information suggests the 1843 flood was only accompanied by a moderate flow on the Kansas River at or below bankfull, with likely minor added flow below Kansas City. After the flood, Fort Croghan was abandoned and the soldiers returned to Fort Leavenworth, KS. The exact location of Fort Croghan, let alone the flooded barracks, is of some debate in literature, but could be considered at least four feet above flood stage (see Appendix A). Following the flood of 1826 and a high flow event in 1827 which washed several homes into the Missouri River due to bank erosion, the original town site of Franklin, MO across the river from Boonville had largely been relocated to new Franklin before the flood, thus providing no information for 1843. However, it was reported that what was left of the original Franklin townsite was completely destroyed by 1844, with many of the building foundations remaining until they were destroyed due to scour in the 1993 flood.

2.4.6 Flood of 1844

The flood of 1844 was of great magnitude throughout much of the Missouri River basin, however, information largely leveraging the logbook of the steamboat Nimrod suggests the river was low that year upstream from the Platte River (see USACE 2018, Master Manual). Extensive research was conducted for the Kansas City Levees Project which cross referenced literature describing approximately a dozen accounts of high water on the Kansas River, despite very limited development at that time in Kansas. Indicators of high water were cross-referenced, largely leveraging several eye-witness accounts clustered in present-day Topeka, KS, and extending west to present Rossville, KS. These included the Kansa Tribe "Fools Chief Village" located on a terrace of the floodplain not flooded in 1903 or 1951 which was reported to have been surrounded by water by the nearby Pottawattamie Tribe, and a ferry operated by the Pappan's, who's house floated away when water reached the eves. These were coupled with a 1930's interview of an early settler documented in the 308 report (USACE 1932, 1935) who remembered seeing the 1844 high-water mark when he arrived in Topeka in 1854 and its height above the 1903 flood before the mark was destroyed, and observations of James Clyman. From this information, a range of credible flows was established and cross-checked using other high-water marks along the Kansas River. These included three accounts in present Wyandotte and / or Shawnee Counties in Kansas, with the destruction of a Choteau Trading Post, the Grinter Ferry, which was established in 1831, and destruction of a Delaware Tribe town and just reaching a Delaware Baptist Mission near present day Edwardsville, KS according to Missionary Ira Blanchard. Homes and facilities destroyed were relocated to Choteau, KS, a future railroad station, now abandoned, and the current Grinter Place Museum, owned and operation by the Kansas State Historical Society, both located in the bluffs. The Delaware Tribe also relocated their town to high ground after the flood, and the Mission operated by Ira Blanchard was moved to the new town site.

The information shows that the peak stages in Kansas City occurred on June 15–16, 1844 coinciding with the rise of the Kansas River. The credible Kansas River flow ranges established were a low of 345,000 cfs to a high of 555,000 cfs and a best estimate of 437,000 cfs at Topeka, KS. The Journal of James Clyman, who meticulously logged the weather each day, documented 80 hours of continuous rainfall near the Kansas River just upstream of Topeka, Kansas between June 10–13, 1844. The river was reported as cresting in Topeka, Kansas on June 14, which has approximately a two-day travel time to Kansas City. This rainfall fell after a few months of wet weather that had driven the Kansas River to bankfull. The river at St. Joseph was documented as rising several feet on June 13. The peak at St. Joseph likely occurred on June 14, 1844 (Wilder 1886, page 950) about 2.7 feet below 1881, which has approximately a one-day travel time to Kansas City. This indicates Missouri River flows likely slightly preceded those of the Kansas River. John McCoy reported a rate of rise of eight to ten feet in twelve hours in the Kansas River floodplain near the confluence with the Missouri River on the morning of June 14, 1844 as he was evacuating belongings from his mother-in-law's house in West Bottoms, present CID leveed area. At the Chouteau Farm, which was completed destroyed and abandoned, a steamboat pulled up to the house to evacuate belongings from the second story. Pierre Menard Choteau in an 1872 interview (Marra 2001) reported a similar rate of rise as John McCoy, stating "the family awoke to find themselves surrounded by four feet of water."… "The family had barely time to escape to the main shore when the current became quite rapid and rose to the second story of the house." Essentially all structures at the Town of Kansas, present day Kansas City, MO, and those of the Chouteau family, were destroyed by the flood, except the Chick Warehouse, which had water near the foot of the building (McCoy 1881).

While driven largely by the flows of the Kansas River combined with those of the Missouri River upstream of Kansas City, other tributaries were also documented as having high flows. In the history of Platte County, MO, Paxtun in 1897 reported the Platte River of MO/IA as having its highest known stages since settlement in the county which was after the Platte Purchase of 1836. Historic peak flows are estimated on the USGS website for 1844 on the Osage River at Warsaw, MO, present Truman Dam site and at Bagnell, MO as 185,000 cfs and 164,000 cfs, respectively, each in June. Additionally, further upstream in the Osage Basin, Missionary John Meeker recorded flood damages to his facilities near present day Ottawa, KS and consistent rainfall and flooding timing as James Clyman. While large flows were described on tributaries near Glasgow, MO, the floods of 1851 and 1858 may have rivaled 1844 on the Grand and Chariton Rivers and exceeded it on the East Fork of the Chariton (Glasgow Weekly Times articles of June–July of 1851 and 1858). The 1844 crest exceeded flood stage at various points along the Missouri River from 12 to 17 feet. Estimated peak discharges were St. Joseph 350,000 cfs, Kansas City 625,000 cfs, Boonville 710,000 cfs, and Hermann 892,000 cfs (USACE 2003, Appendix F). These discharges were the greatest ever estimated from Kansas City to Hermann in terms of observed flows. Variations of these flow estimates in other documents are further discussed in Section 3 and Appendix A. High water marks for 1844 are very reliably recorded and estimated at the Kansas City, MO gage and locations further downstream, with moderately reliable estimates of high-water marks located at St. Joseph and Rulo, NE. However, for upstream gages, no reliable estimates of the height of 1844 are available (USACE 2003, Appendix F).

2.4.7 Flood of 1851

Details of the height of 1851 are limited along the Missouri River, but available accounts coupled with records of its height on the Mississippi River at St. Louis (see Humphries 1867) indicate the flood was significant on the lower Missouri River. Phil Chappell, a steamboat captain, and author who wrote about early floods and remembered the flood as seven-year-old boy, reported 1851 being up to 6–8 feet below 1844 in the vicinity of Jefferson City, MO. Similarly, the Palmyra Whig, June 12, 1851 reposted a statement from the Republican from Jefferson City, MO of June 8th stating the flood had reached within 5 feet of the 1844 high water mark, a location possibly impacted by Osage River backwater. The history of Fremont County, IA indicates the 1851 flood produced record stages and significant damages on the "smaller streams" in the county in May. Additionally, the Glasgow Weekly Times indicated the river reached within 10 feet of 1844 then commenced falling the previous Saturday on June 12, 1851. Other Glasgow Weekly Times articles indicated the Grand and Chariton Rivers which enter just upstream of Glasgow, MO produced large flows. At Kansas City, information from Chanute 1870 suggests 1851 was lower than 1858 and did not coincide with a Kansas River flood. With a range of 5-10 feet below 1844, best estimate flows assumed 7 feet below 1844 for Boonville and Hermann as further discussed in Section 3.5.

2.4.8 Flood of 1858

Flooding in 1858 had at least two peaks, one of June corresponding the flow of the upper Missouri River, and one in mid-July corresponding to the largest Kansas River flow between the floods of 1844 and 1903. Peak stages upstream of Kansas City occurred in June, whereas downstream, the largest peak was in July. In his 1870 report, Engineer O. Chanute, who designed and oversaw construction of the first bridge across the Missouri River, documented 1858 as the largest event since 1844 being at least 12.29 feet lower than 1844 at Kansas City. Just upstream of Kansas City, the flood of June was placed in a similar class as 1883 or 1881 in Platte County, MO, by Paxtun, 1897, a reach often impacted by Kansas River backwater. Paxtun also reported the Platte River of MO/IA reaching its second highest known stage 10 inches behind 1844 on June 10, with a second smaller peak on July 1, 1858 (Paxtun, 1897). The port of Weston, MO in Platte County was damaged and temporarily taken out of service by the June 1858 flood but was put back into operations until the flood of 1881 moved the river away from the town (City of Weston, MO website). The Kansas River flood washed out the first railroad bridge built over the Kansas River near Topeka, KS between July 17–19 after only a few months of operation. Credible ranges of flows for the Kansas River in 1858 were established as a best estimate of 175,000 cfs, and high estimate of 225,000 cfs in Topeka, Kansas (USACE 2021, Kansas City Levees). Though relative differences could not be discerned, the Glasgow Weekly Times articles indicate that the July 1858 flood was likely comparable to the flood of 1851 at that location, with high flows reported on the Grand and Chariton Rivers, and a new record on the East Fork of the Chariton exceeding 1844. However, Phil Chappell described 1858 as lower than 1851, likely near Jefferson City, whereas 1858 was 0.45 feet higher than 1851 and 4.3 feet lower than 1844 at St. Louis (see Section 3.6.2). The best estimate of the peak flow at Kansas City is 301,000 cfs on July 20, 1858, coinciding with the Kansas River peak.

2.4.9 Flood of 1867

Floods of note between 1859 and 1872 before stage records began include 1862, 1865, 1866, 1867, and 1869, with April 1867 as the most significant of these on the Missouri River as the likely maximum flow upstream of the Kansas River since 1844 or 1843. April 1867 flood levels were documented at 4.0, 4.9, and 4.8 feet below 1881 at Omaha, Fort Leavenworth, KS, and Kansas City, respectively, nearly four feet above current flood stage at Omaha and one foot above at Kansas City (see MRC 1875 and 1887, TP23 1954, Chanute 1870). At Omaha, 1867 stage was just below the lower bound estimate for 1843 and was otherwise the second highest stage behind 1881 until the 1952 flood. Chanute 1870 reported April 29, 1867 as 14.99 feet below 1844 at Kansas City, approximately 237,000 cfs based on the historic rating curve in Section 3.8.3. Information was compiled to compare its height with other floods of 1858 to 1872, and to generate flow estimates at Kansas City, St. Joseph, and Omaha for 1867 as follows.

Phil Chappell, a steamboat captain from the Jefferson City area, placed 1858, 1862, and 1867 in the same class below the Kansas River as being high enough to fill the sloughs and low-lying areas but not high enough to cause significant damage (Chappell 1908). At St. Louis between 1862 and 1872, April 26, 1862 produced the highest annual peak flow at 712,000 cfs, July 24, 1869 second highest at 615,000 cfs, May 1, 1867 third highest at 568,000 cfs, and April 25, 1866 tied for fourth highest with July 28, 1865 at 513,000 cfs. Flood history shows Missouri River annual peak flow has not exceeded St. Louis (see Section 3.6.2). According to the July 1, 1862 The Morning Herald of St. Joseph, the 1862 flood peaked on June 30, 1862 and motivated the removal of the Great Western Hotel at Elwood, KS near the current USGS gage due to bank erosion concerns. Elwood, KS was founded in

1856 and requires a stage above 23.7 feet to flood low-lying areas of the town. On April 24, 1867 at Forest City, MO, the day of the peak just downstream at St. Joseph, the flood exceeded 1862 by two inches and was still rising, making it the largest flood since 1844 (April 26, 1867 Holt County Sentinel). A flood in 1866 was referenced in the 1867 Union Pacific Railroad Report at Omaha and April 1867 issues of the St. Joseph Morning Herald as being lower than 1867, by about one foot at St. Joseph. Floods of July 1869 were just after Chanute stopped recording stages at the new bridge in Kansas City, however, no newspaper articles were found denoting its height on the Missouri River. The Kansas River produced a historic peak flow of 72,000 in 1869 at Topeka, likely in late June based on numerous newspaper articles detailing severe flood damages and 13 deaths west of Junction City.

Analysis of Chanute's surveys at Kansas City in March and May, the month before and after the 1867 flood, digitized within approximately 0.5 feet elevation, show a cross-sectional area of 32,400 and 42,000 square feet below the 1867 flood, respectively. Chanute noted significant scour occurred during the flood and reported accurately measuring a maximum velocity of 12 ft/s in April 1867. Pre-navigation project (pre-BSNP) velocities were significantly higher in maximum and comparable to slightly lower on average than measurements of 1993 to 2002, with a 12 ft/s maximum consistent with pre-BSNP flows of about 240,000 cfs at Waverly (Blevins 2006). Based on analysis of the timing of 9 feet of observed bed scour on the Kansas River in the 1951 flood, in that event stages within one foot of the peak occurred before scour initiated, peak stage coincided with the peak flow, and much of the scour progressed on the falling limb of the hydrograph (USACE 2021, KC Levees). An average velocity of 6.4 ft/s using the average area of the two surveys yields a flow estimate of 237,000 cfs from the historic rating curve, plotting as expected for this flow. Analysis using reasonable average velocities with each survey yields a flow range of 200,000 to 300,000 cfs as shown in Appendix A. While Chanute described 1867 as a "united freshet of the Kansas and Platte Rivers", the highest Kansas River flow was likely in June when a pontoon bridge at Topeka was damaged and it was within its approximate 100,000 cfs channel capacity (USACE 2021, Kansas City Levees).

Compilation of 1867 St. Joseph Morning Herald articles indicate the peak occurred on April 24, 1867, 22-24 feet above the low water mark of an unknown point near St. Joseph, threating homes on the high bottoms in Elwood, KS. The April 25, 1867 Kansas Chief at White Cloud, KS upstream of St. Joseph stated "The low bottoms are all overflowed, and if the rise continues much longer, the high bottoms will likewise be inundated." Similarly, the April 26, 1867 Holt County Sentinel described depths of one to six feet over farms at Forest City, MO. At St. Joseph, the "low bottoms" visible with LiDAR are overflowed at a moderate flood stage of 21 feet, flood stage being 17 feet. A best estimate of 22.3 feet was assumed using the 4.9 feet depth below 1881 at Fort Leavenworth, approximately 290,000 cfs, making 1867 higher than 1877 as at Kansas City, lower than Elwood and 1844, and below 1883 which was highlighted in Platte County, MO history along with 1858, but 1867 wasn't.

The April 21, 1867 The Morning Herald of St. Joseph stated "At Omaha the river has overflowed the landing and submerged houses and considerable quantities of Union Pacific Railroad property." Homes and railroad facilities are shown in the present Omaha leveed area on the 1868 birds eye map near Chicago Street, where the landside elevations match flood stage at the current USGS gage just downstream. Best estimates using the stage from MRC 1875 and TP23 1954 yield 4 feet below 1881, approximately 275,000 cfs (see Section 3.7.3). Based on flood history, it is possible but rare the flow at Omaha was higher than at Kansas City. In 1952, Sioux City produced approximately 9% higher flows than Kansas City, and Yankton about 20% higher. Still, based on the likely largest events of June-July 1858 and April 1867, maximum flows of 1845-1872 did not likely exceed 300,000 cfs above Kansas City. Information assembled for the 1867 event is included in Appendix A and in Section 3 for some individual gages.

2.4.10 Flood of 1881

Flood damages were experienced at multiple communities throughout the Missouri River in April 1881. Following a wet year in 1880, the winter of 1880–1881 was marked by below normal temperatures and heavy snows, resulting in an exceedingly heavy snow blanket over the plains area of the upper Missouri River Basin by spring and resulting in river ice thickness of 24 to 32 inches in the vicinity of Yankton and Omaha. Spring thaws and ice breakup began in the upper basin while the lower river was still frozen, resulting in huge ice gorges in the Dakotas. Two distinct peaks occurred in April, the second producing the highest flows, still the first peak produced higher stages at Omaha than any recent flood (Omaha Bee, April 9, 1881). At Omaha the instantaneous peak of April 9^{th} was 323,000 cfs, and of April 24-25^{th} was 372,000 cfs (USACE 1946, 1947 Levee DPR Appendix), the first peak 1.8 feet lower (TP23, 1954). The first peak on April 5^{th} near Yankton was especially devastating as an ice jam estimated to be over 30 miles in length produced a peak stage 15 feet higher than the next highest flood in 1952 of 480,000 cfs. The late April 1881 peak discharge from Sioux City to St. Joseph was the highest of record until 1952 when it was exceeded by another plains snowmelt flood. Estimated peak discharge was 325,000 cfs at the Fort Randall Dam site, 360,000 cfs at Sioux City, and at St Joseph was 370,000 cfs; the volume of the flood was estimated at over 40 million acre-feet at Sioux City, Iowa. This flood became the basis for sizing the flood control pool of the Mainstem Dams as discussed in Section 2.2. While still producing high stages at and downstream of Kansas City, the flood did not coincide with high discharges of the Kansas or Osage Rivers. Additionally, the flood led for calls for flood protection, for example the City Engineer of Council Bluffs called for a levee at least five feet above 1881 (April 26, 1881 Omaha Bee), similar to the height of the current levees completed in the 1950's. For additional information on 1881, please refer to the 2003 UMRSFFS, Appendix F, and the 2018 Missouri River Master Manual.

2.4.11 Flood of 1903

Floods of May–June 1903 were severely damaging throughout the Kansas and Missouri Rivers, second perhaps to only 1951 for damages in Kansas City, with 19 lives lost and over 20,000 people rendered homeless. The flood was caused by prolonged and heavy rainfall over the lower Kansas River Basin, coinciding with the June rise in the Upper Missouri Basin. Flooding along the Kansas River in May 1903 was the largest since the Kansas “Big Water” of 1844 (Juracek and others, 2001). Tributary inflow below Kansas City materially increased the discharges, but the principal tributaries, such as the Grand, Osage, and Gasconade, were considerably below the maximum stages of record. Very little overflow occurred between St. Joseph, Missouri, and Atchison, Kansas. Below Atchison the flooding increased to where below Kansas City, Missouri, the flood waters extended from bluff to bluff. Approximately 615,000 acres of agricultural land were inundated. Estimated peak discharges were St Joseph 252,000 cfs, Kansas City 548,000 cfs, Boonville 612,000 cfs, and Hermann 676,000 cfs. While stage and precipitation were well documented for the 1903 flood compared to past floods, measurements of the rivers flow were not collected. Estimates of the 1903 flood flows were derived from early rating curves of limited measurements and careful study of the drainage areas along the rivers. Earlier estimates of the magnitude of the flow on the Kansas River in 1903 were revised significantly upward after flow measurements became available during the 1951 flood, bringing the estimate made in the 308 Report (USACE 1932, 1935) of 220,000 cfs up to 337,000 cfs at the mouth. However, estimates of the Missouri River flow in Kansas City, MO in 1903, and 1844 from the same rating curves, have remain unchanged or little changed for 1903 since the 308 Report (see Appendix A). The 1903 flood was the primary motivation for levee construction in Kansas City, MO and Kansas City, KS.

2.4.12 Flood of 1951

The spring and summer of 1951 was a period of excessive rainfall over the Kansas River basin which culminated in an exceptionally heavy downpour during the 4-day period of 9-13 July. The Kansas River crest of 510,000 cfs at Bonner Springs, KS, fortunately coincided with a low flow out of the upper Missouri River, and there was no flooding, except from backwater, on the Missouri River above Kansas City. Federal levee units of Argentine, Armourdale, and Central Industrial District (CID) along the Kansas River at Kansas City, KS were overtopped and breached, some parts still in construction. The Fairfax levee failed at a conduit resulting in backwater flooding of the district from the Kansas River. New federal levees on the Missouri River of North Kansas City, East Bottoms and Birmingham all held. Below Kansas City, MO the entire Missouri River valley was flooded to depths up to 20 feet. The peak discharge at Kansas City of 573,000 cfs was the highest since the 1844 flood, and the highest observed flow since. During this flood, only Kanopolis Dam which was completed in 1948 and its upstream project, Cedar Bluffs were in operations, with minimal impact on streamflows at the mouth. Fort Peck Dam in Montana was also in operations at the time.

2.4.13 Flood of 1952

The following spring, in March–April 1952, a flood of exceptional magnitude and severity on both the Missouri River itself and most of its plains area tributaries at and above Sioux City, Iowa, was generated from rapid snowmelt over the plains areas of the upper basin. On the Missouri River, flooding was continuous from the Yellowstone River in Montana to the mouth. At and below Kansas City, because little water was being added from tributary areas, the flood, although still severe, became less than the maximum of record. Peak discharges at Sioux City 441,00 cfs, Omaha 396,000 cfs, Nebraska City 414,000 cfs, and St Joseph 397,000 cfs were the highest discharges ever recorded, compared to 400,000 cfs at Kansas City, significantly lower than in 1951. The 1952 event was generally a single peak hydrograph moving from upstream to downstream, peaking at Sioux City on April 14, Omaha on April 18, St. Joseph on April 23, Kansas City April 24, and Hermann, MO on April 28. During this flood, Fort Peck Dam was in operation, providing a reduction in peak streamflows. Other Mainstem Dams closed later that year that could have further reduced flows, as the System would have been highly effective at regulating this flood event.

2.4.14 Flood of 1986

The flood of October 1986 produced record inflows to Truman Dam of 445,000 cfs, resulting in the only Phase III release for the project to date with a peak outflow of 70,000 cfs. Five dams upstream of Truman, and the private Bagnell Dam downstream were also in operations during the flood. Peak flows on the Missouri River at Hermann, MO reached 549,000 cfs on October 5, 1986. This flow at Hermann has only been exceeded two times since the upstream dams were completed as in July 1993 and May 1995. Peak flows at Boonville reached 334,000 cfs, exceeding flood stage by over 10 feet during the peak also on October 5, 1986. Flooding was not as prevalent in reaches of the Missouri River upstream of the Lamine/Blackwater River which enters the Missouri River on the right descending bank at river mile 202, about five miles upstream of Boonville, MO.

2.4.15 Flood of 1993

The great flood of 1993 was caused by a complex mix of meteorological conditions described in detail in the 2003 UMRSFSS Appendix F, leading to the most severe flooding since either 1951 or 1952 from the Platte River to the mouth between July 23–31. Rain fell somewhere in the Missouri River basin every day from March 14 through July 29. During the period of June 1 to July 27, rainfall occurred on 34 out of 57 days at Omaha, Nebraska. On July 23–24, a then record crest of the Missouri River overtopped federal levee L-550 near Brownville, Nebraska. On July 24, the Elwood, KS, and St. Joseph Airport Levee Unit R-471-460 overtopped and soon after breached. On July 26, levee units L-400 and L-246 overtopped. Additionally, essentially all non-federal levee units were overtopped from near Rulo, NE to the mouth. To date, based on USGS peak flows, the 1993 flood still has the highest flows on the Missouri River from St. Joseph, MO to the mouth since the dams have been completed. Flooding was a result of precipitation falling downstream of the Mainstem Dams. Annual peak flows were Yankton 24,300 cfs, Sioux City 72,200 cfs, Omaha 115,000 cfs, Nebraska City 197,000 cfs, St. Joseph 335,000 cfs, Kansas City 541,000 cfs, Boonville 755,000 cfs, and Hermann 750,000 cfs.

During the worst of the flooding release from Gavins Point Dam was reduced to minimums for other regulation objectives of 6,000 cfs in early July and did not exceed 9,000 cfs for the rest of the month. The Mainstem Reservoir System stored nearly 10 MAF during June, July, and August, taking advantage of the additional 14.2 MAF of carry storage available due to the previous six-year drought in addition to the 16.3 MAF of flood storage (USACE 2018, Master Manual). Although the resulting damages totaled nearly $12 billion, the flood damages prevented by the System were a record level at the time. The System prevented over $4.4 billion in damages (original price levels) during 1993. A total of $15 billion in damages were prevented for all reservoirs and levees in the Missouri River basin, mostly from preventing overtopping of urban levees in Kansas City and St. Louis, MO (USACE 2018, Master Manual).

2.4.16 Flood of 1997

At the time of the 2003 UMRSFFS, the 1997 flood had produced the record post-dam flows below Oahe, Fort Randall and Gavins Point Dams, and significant flooding in several upstream reaches near or above record stages. Runoff upstream from Sioux City totaled 49.6 million acre-feet during calendar year 1997, the highest annual runoff in the 100-year period of 1898 to 1997, nearly double the average runoff and nearly 20 percent higher than the previous record runoff in 1978. At Yankton, the highest discharge since the construction of the main stem dams of 70,000 cfs was experienced through much of the fall during October, November and early December while evacuating the flood storage from the Main Stem Reservoir System. At Sioux City and Omaha, the Missouri River remained well below flood stage. However, low lying agricultural areas adjacent to the river experienced flooding and drainage problems throughout the spring, summer and fall. Without the Missouri River Main Stem Reservoirs, the peak stage at Omaha of 26.4 feet on April 15 would have been about 13.1 feet higher which would have been only 0.7 feet below the record stage set in 1952 (USACE 2003, UMRSFFS Appendix F).

Below the confluence of the Platte River, the Missouri River exceeded flood stage for much of the April through July period. At Nebraska City, NE, the peak stage of 21.06 feet occurred on April 18, about 3 feet above flood stage. Without the main stem reservoirs, the peak stage would have been about 10 feet higher at Nebraska City which would have exceeded the record stage set in 1952 by more than 3 feet (USACE 2003, UMRSFFS Appendix F). Annual peak flows were Yankton, SD 70,000 cfs in the fall, with USGS peaks flows of Sioux City, IA 100,000 cfs on April 10, Omaha, NE 110,000 cfs on April 15, Nebraska City, NE

113,000 cfs on April 18, St. Joseph, MO 134,000 cfs on April 15, Kansas City, MO 190,000 cfs on April 12, Boonville, MO 281,000 cfs on April 14, and Hermann, MO 303,000 cfs on April 15. These dates show how tributaries contributed to the peak flows at each location prior to the then-record outflows from Gavins Point Dam, as opposed to a single peak moving downstream, which can take several days as in 1952. Flood fight efforts and Advance Measures projects constructed by the corps prevented $100 million in flood damages. The Missouri River Main Stem Reservoirs prevented $5.2 billion in flood damages, with other USACE Projects preventing over $300 million in flood damages (USACE 2003, UMRSFFS Appendix F, and USACE 2018, Master Manual).

2.4.17 Flood of 2011

Heavy snowfall in the Rocky Mountains and upper basin plains along with large amounts of rainfall in the upper basin during the spring of 2011 resulted in long duration, record releases from the System dams, combined with additional precipitation falling downstream in June and July of 2011. The 2011 event exceeded the volume of the 1881 flood used to size the Mainstem Dam flood control pools. Flows increased to 150,000 cfs out of Gavins Point Dam on June 14, peaked at a record 160,700 cfs in late June of 2011, and remained at or above 150,000 cfs for 62 days. The 2011 flood produced post-dam record flows of 192,000 cfs and 217,000 cfs at Sioux City, IA, and Omaha, NE, respectively. At St. Joseph, MO, peak flows of 277,000 cfs occurred on June 28, exceeding the published 1% annual exceedance probability (AEP) flood from the 2003 UMRSFFS for the second time in 18 years. Peak flows at Kansas City, MO were 245,000 cfs on July 10, 2011, at a time when the Kansas River was contributing less than 4,000 cfs. At Kansas City, MO and downstream, while the duration was long and impacted interior drainage, peak flows were considered as a more minor flood event due to the very dry summer. All six Mainstem Dams along the Missouri River released large amounts of water to prevent dam overtopping as the System set a record storage of 72.8 MAF on July 1, occupying 98% of the 16.3 MAF of flood control storage space. Outflows threatened towns and communities between the Mainstem Dams as well as downstream of the system below Gavins Point Dam but would have been significantly higher without the dams in operation. Total damages were estimated at $8.41 billion. The Mainstem Reservoir System was credited as preventing $5.4 billion of damages at the original price levels (USACE 2018, Master Manual).

2.4.18 Flood of 2019

Flooding in 2019 drove portions of the Missouri River into flood stage from early March 2019 to December 2019, an unprecedented duration. The 2019 flood primarily occurred between February and June and consisted of two unique events that impacted different geographical areas within the Missouri River Basin. The first event crested in March of 2019 and primarily impacted the Missouri River upstream of Kansas City, MO. The March event initiated due to the continually cold February of 2019 which led to 2–4 inches of snow water equivalent across the entire lower Missouri River Basin. A sudden increase in temperature and 2 inches of rain caused snow melt to happen rapidly. Additionally, the cold temperatures caused the ground to have over a foot of frost depth, preventing the runoff from infiltrating into the ground. These factors combined to cause huge volumes of water to flow into streams throughout the Missouri River basin. Many rivers were frozen on the surface, and experienced ice jams from chunks of ice breaking off and getting stuck downstream.

Although the large urban levees in Omaha and Council Bluffs did not overtop, essentially all Federal levees between Omaha and Rulo, NE, did overtop and or breach. The federal levees which overtopped and or breached in the Omaha District include Missouri River Levee System (MRLS) Units R-616, R-613, L-611-614, L-601, L-594, L-575, R-573, R-562, R-548, L-550, and L-536. Continuing into the Kansas City District, all non-federal levees upstream of Kansas City were overtopped and or breached, along with MRLS Unit R-500. Overtopping of MRLS Unit R-471-460 near St. Joseph, MO and Elwood, KS, which was in construction for levee raises during the flood, was prevented by sandbagging. Downstream of Kansas City, damages from the March peak were limited as the flow did not coincide with a large flow from the Kansas River or downstream tributaries. Peak flows at St. Joseph were 317,000 cfs on March 22, slightly breaking the record stage set in 1993, and exceeding the previously published 1% AEP flow from the 2003 UMRSFFS for the third time in 26 years. March peak flows reached 294,000 cfs at Kansas City on March 24, showing attenuation and minimal flow inputs between Kansas City and St. Joseph. The March event set a post-dam record flow of 342,000 cfs on March 16 at Nebraska City, coinciding with a record flow of 250,000 cfs from the Platte River on the same day at Louisville, NE, 56% higher than the previous record Platte River flow of 160,000 cfs in 1993. Additionally, the second highest record daily average release from Gavins Point Dam of 90,000 cfs also occurred near this time due to record flooding on the Niobrara River. Peak hourly inflows into the Gavins Point reservoir exceeded 180,000 cfs and the March 14 average daily inflow, with Fort Randall releases at 0 cfs, was 125,000 cfs, which is a daily volume of 250,000 acre-feet. For six hours, the Gavins Point release was set at 100,000 cfs to prevent overtopping of the spillway gates with the pool 2.3 feet above the top of the exclusive flood control pool.

The second "event", or events, crested in late May into early June of 2019 and impacted areas between Kansas City, MO and Hermann, MO. This included near record stages on the lower Grand River, which peaked at 109,000 cfs on May 30 at Sumner, MO, and record flows of 44,000 on the Chariton River on May 31 at Prairie Hill, MO. On the Missouri River at Kansas City, Missouri, three flood peaks exceeded the 32 feet flood stage, March 24, June 2, and June 25, with the largest being on June 2 at 308,000 cfs. Peak flows at Boonville and Hermann, MO were 363,000 cfs and 403,000 cfs on May 31, corresponding to the peak of the Grand and Chariton Rivers, and June 7, respectively. Several non-federal levee systems and MRLS Unit L-246 were overtopped in the vicinity of Waverly, MO, the mouth of the Grand and Chariton Rivers, and Boonville, MO. Additionally, a few of the smaller non-federal levees were overtopped between Jefferson City, MO and the Osage River. Several tributary projects reached critical surveillance levels with several reaching record pools to include Harlan County, Perry and Clinton in the Kansas River Basin, and five of six projects in the Osage Basin including Truman Dam. Storage peaked on June 1, 2019 in the lower 7 Kansas River Basin dams at 5.1 million acre-feet, representing 75% of the multi-purpose and flood pools. Reservoir storage dropped to 4.6 million acre-feet before reaching a second peak of 5 million acre-feet on June 24, 2019. Kansas River Basin reservoir levels remained 2 million acre-feet above normal through September 2019 when the Missouri River at Waverly, MO, dropped enough to begin to evacuate the remainder of the flood pools.

2.5 Water Resources Development

Water resources development in the Missouri River basin has been extensive over the past 150 years. Significant periods of development were prior to 1910 and since 1949. Early water resource developments were oriented largely towards single-purpose improvements to meet specific needs without substantial regard for other potential functions. However, as the region's demand for water resources grew, and technology improved, multi-purpose programs became more prevalent. Detailed information on water resource projects is contained in the 2018 Missouri River Master Manual. A summary of the development of 71 federal reservoirs and two select non-federal dams is also provided in Section 2.2. This section summarizes pertinent information for the flow frequency study.

The Federal dam and reservoir projects were built between the 1930’s and 1990’s and serve multi-purpose uses to include flood control, navigation, water supply, irrigation, water quality, fish and wildlife, recreation, and hydropower. Thousands of smaller private dams have also been constructed throughout the basin over time, some beginning in the early 1900’s. Generally, the effects of the older dams are seen in the observed streamflow records for a significant portion of the observed flow records which became widespread by 1930. Effects of other dams began to impact the observed flow records gradually over time as projects were completed. A secondary impact of the dams is that for the river below Gavins Point Dam, storage of sediment in upstream reservoirs has led to channel bed degradation over time. This has served to increase channel capacity in upstream reaches. Historically this impact is greatest just downstream of the dam and has tapered to being more minor in the vicinity of Omaha, and more recently, the mouth of the Platte River.

Irrigation first appeared in the Missouri Basin about 1650 by the Taos Indians along Ladder Creek in northern Scott County, Kansas. 'Modern' irrigation appeared in the basin in the 1860s, and water use for irrigation and other uses grew rapidly through the remainder of the 19th century and into the early 20th century as agricultural uses of water grew, especially in the more arid western plains. Estimates of irrigation, public and industrial water supply, trans-basin diversions, as well as Reclamation reservoir holdouts are produced by Reclamation’s Regional Depletions Model and updated every 5 years. The latest dataset (2017) shows depletions equal to approximately 5–6 million acre-feet (MAF) annually above Sioux City, IA in 1930 and slightly increasing to 6–7 MAF annually by the 1980s and around 7 MAF by the 2000s. Depletions reduced post 2010 and are currently estimated around 5.5 MAF annually. Depletions in the Sioux City to Omaha reach were around 3–4 MAF annually during the 1930s but have been steadily increasing since the late 1940s. Depletions are currently estimated around 4.5 MAF annually in the Sioux City to Omaha reach. The latest depletions dataset showed steady annual depletions during the 1930s in the St. Joseph to Hermann around 0.15 MAF. Depletions in this reach have also been steadily increasing since the late 1940s and are currently estimated around 1.1 MAF.

The Missouri River has served as a form of transportation for centuries used first by Native Americans, then various periods of French, Spanish and eventually the United States as a conduit for trade and economic development. The first river navigation development work consisted of snagging and clearing to remove obstructions beginning in the 1800’s. Several River and Harbor Acts between 1912 and 1945 resulted in authorization for a 9-foot channel from Sioux City, Iowa to the mouth, with large scale work initiating in the 1920’s in a project known and the Missouri River Bank Stabilization and Navigation Project (BSNP). The navigation project is not accomplished by using locks, as is the case on most of the inland waterway systems, but by using river structures called dikes and revetments placed to confine and control the navigation channel. The use of these structures produces velocities high enough to prevent the accumulation of sediment in the navigation channel and permits an open condition for the entire length of the project with no regular dredging required under normal water supply conditions.

As river training structures were constructed, typical of the 1930’s was rapid accretion of sediment and a narrowing of the channel, followed by early successional tree growth, then timber clearing and conversion to agricultural purposes, and levee construction. Most of the accretion had occurred by the 1940’s, started to decline as work slowed during WWII and floods of the 1940’s and large floods of the 1950’s, then continued until completion of the BSNP in 1981. Channel cutoffs were also constructed to improve channel alignment, mostly in the vicinity of Kansas City, MO, St. Joseph, MO, and throughout several locations in the portion of the river between Sioux City, IA and Rulo, NE. Overall changes in channel flow capacity as result of the BSNP have been mostly minor below flood stage based on monitoring of stage trends at gages. However, some changes were observed in the first few years following construction in response to intense construction, and gradual changes have been observed over time.

Prior to development, the Missouri River floodplain was largely forested, with several areas of wet prairie in wide areas of the floodplain such as near the mouth of the Grand and Chariton Rivers, near Waverly, Missouri, and at and upstream of the Nodaway River. A mix of early successional forests and mature forests tended to be near the river in the meander belt, with the bluffs heavily forested throughout the river. In the wide areas, wet prairies would be located closer to the bluffs. Other than small patches for agriculture cleared by Native Americans, the floodplain was minimally developed upon arrival of the first permanent European settlers in the early 1800's. Clearing and drainage improvements for agriculture started as small patches in the lower Missouri River in the early 1800's and gradually expanded. According to Bragg and Tatschl, 1977, "Land surveys along the Missouri River in Missouri from 1826 to 1972 indicated a decline in floodplain forest from 76% to 13% of total land area, while cultivated area increased from 18% to 83% over that time; about 80% of the floodplain was in cultivation by 1958" (Heitmeyer 2015).The Federal Government had no official role in the construction of flood control projects on the Missouri River during the 19th century. However, landowners, municipalities, and the railroads, built dikes and levees to protect their properties. After floods of the early 1900s, states in the Missouri River basin authorized local drainage districts to construct flood protection works. The first authorization for federal levees on the Missouri River was for 7 levee systems in Kansas City in the 1936 Flood Control Act. However, federally funded construction in Kansas City other than some Works Progress Administration work to build portions of the levees in the late 1930's, did not begin in earnest until the mid-1940's. In the 1944 Flood Control Act, additional federal levee systems as part of the Missouri River Levee System (MRLS) Units were authorized and constructed between the 1940's and early 2000's. Other Federal Levees were constructed under different authorities, such as the Omaha and Chesterfield-Monarch Levees. Federal levee construction has slowed in recent years but is expected to continue in the future. No Federal levees have been constructed from Gavins Point Dam to the Omaha, Nebraska / Council Bluffs, Iowa, area due to the significant protection afforded this reach by the Missouri River Mainstem Dams. However, various private levees provide some protection in this reach.

From Omaha, NE to the mouth, levees exist continuously along the Missouri River with very few exceptions. A total of 580 miles of Federal levees constructed by USACE and 680 miles of non-federal levees participating in USACE repair and inspection programs exist along the river between the Omaha, Kansas City, and St. Louis Districts areas of responsibility. These numbers reflect that levees are often on each bank and include tributary tiebacks. At least 200 more miles of private levees exist along the Missouri River that do not participate in USACE programs, although this number from the National Levee Database is considered greatly under counted. The largest urban levees are in the Omaha, NE / Council Bluffs, IA, Kansas City, MO and Chesterfield, MO areas, which is a suburb of St. Louis, MO. Following construction of the Federal levee system, farming of the lands riverward of the Federal levees became more extensive. Farmers often constructed secondary levees at or near the riverbank to prevent crop damages caused by normal high flows on the Missouri River. Private levees have also been built in those areas where Federal levees were not built and improved over time. These levees can alter the flow of the river by minimizing floodplain storage except when overtopped or breached. Impacts of levee construction on stage versus flow rating curves for stages above bankfull can be seen on many gages throughout the lower Missouri River. The USACE Northwestern Division, Missouri River Basin Water Management Office routinely publishes stage trend information for major gages on the river, the latest being in 2021 at https://www.nwd.usace.army.mil/MRWM/Reports/.

Other development along the river includes habitat development for endangered native species and for the mitigation of the Missouri River BSNP beginning in fiscal year 1992, but with much more limited work since approximately 2016. These types of projects are managed under the Missouri River Recovery Program (MRRP), and have included side channel chutes, dredging backwaters, river widening, levee setbacks or abandonments, notching or modification of river training structures, wetland development, and native vegetation development. The total authority, if implemented, could restore up to approximately 32% of the habitat losses that occurred between Sioux City, IA and the mouth as a result of the BSNP. While some localized impacts, such as stage reductions, can be seen from these projects, they tend to be minor in the context of the full river unless strategically designed for that purpose at a large enough scale. The projects are also designed to have no adverse impacts to flood stages.

Another factor in the stage discharge relationship at certain locations along the Missouri River involves mining of sand and gravel materials from the bed for construction materials. Historically, USACE and transportation departments have at times leveraged materials from the bed for constructing levees and highways. These periodic extractions have not been documented to cause significant, lasting change to river-bed elevations, have been the subject of analysis as part of the National Environmental Policy Act Documentation for each project, and have been minimally used on the Missouri River since 2011. Downstream of Rulo, NE in portions of the river regulated by the Kansas City and St. Louis Districts of USACE, commercial sand and gravel mining for construction materials has been ongoing with annual extractions dating back prior to the 1930's. Until the 1980's and 1990's, no major impacts had been observed, however, as extraction rates increased especially in the vicinity of Kansas City, MO in the 1990's, over 10 feet of bed lowering, or bed degradation was observed. Smaller amounts of bed degradation were observed in other locations where sand and gravel mining had occurred by the early 2000's. In 2011, an Environmental Impact Statement (EIS) was prepared that recommended an adaptive management strategy to manage dredging locations and rates to minimize future degradation, limiting amounts to no lower than 2009 levels in Kansas City, and two feet below 2009 levels elsewhere in the nearly 500 miles below Rulo, NE. While dredging has had an impact, large changes to bed elevations are also possible during floods as observed in 1993, 2011 and 2019 when sediment was lost to the floodplain or transported downstream.

Future water resources development may undergo significant challenges, especially in times of extended floods and droughts. For example, areas of increasing flood risk have been identified within the Missouri River, resulting in several studies initiating to determine ways to reduce flood risks and to increase resilience against a future of increasing flood risks. (R.T., 2018) Results for the qualitative assessment are summarized in Section 2.6.

2.6 Climate Assessment

A qualitative analysis based on changes in precipitation, streamflow, and temperature was conducted following current United States Army Corps of Engineers USACE policy (ECB 2018-14). This analysis aims to determine effects of climate change on the study area. To qualify these effects, trends are examined in peak streamflow, peak monthly flow, and future hydrology, as well as checking for non-stationarities. Climate Preparedness and Resilience (CPR) tools are used to perform a series of statistical tests which determine changes in mean, variance, and distribution of the underlying data sets. The Missouri River basin climate's qualitative assessment is based on scientific literature, streamflow trends, analysis of 96 downscaled GCM model predictions through 2100, and a vulnerability assessment of the flood risk reduction business line. Streamflow data were analyzed for statistical change points and monotonic trends using 19 flow locations on the mainstem Missouri River. Historical peak streamflows were evaluated using n-day centered moving average duration peaks (e.g., 7-day, 15-day, 31-day, etc.) Projected trends in streamflow were based on zonal statistics of five HUC-4 watersheds that contain USACE dams. The vulnerabilities of the flood risk reduction USACE business lines were analyzed using the VA tool. The complete climate assessment is provided in Appendix J. A summary of the findings is presented here.

1. Scientific literature relevant to the Missouri River Basin climate is presented in continental-scale assessments (Vose et al. 2017, Easterling et al. 2017) to regionally focused reports (USACE 2015, Conant et al. 2018, **Kloesel et al. 2018**). A full list of references can be found in Appendix J.

2. Temperatures have increased over the 100-year observed recorded and are projected to continue to increase through the end of the 21st century (Section 2 Appendix J). The warming trend is projected to increase the largest in minimum temperature, which will lead to less SWE accumulations in the mountainous western regions of the basin. Increases in average and maximum temperatures are projected to be the largest in the southern part of the basin. Higher temperature will result in more evapotranspiration.

3. There is not a consensus in the literature about trends in the observed precipitation records (Section 2 Appendix J). A trend analysis using National Weather Service precipitation records indicates the majority statistically significant increases for annual precipitation are in areas downstream of Oahe Dam (Section 4 Appendix J). Extreme precipitation events (> 1 in) are projected to increase across the basin. There is a strong consensus that streamflow has increased over the observed record for lower portions of the Missouri River Basin, but future projections have a low consensus with variable directions. All the flow locations had a statically significant change point in the historical flow records in at least one of the n-day duration time series analyzed.

4. The most common change point across all the flow locations was identified around 1941. Other common change points occurred around 1946, 1961, 1984, 1999, and 2007. The statistical tests for changes to the mean and distribution of the data were the most common types of change points detected. A monotonic trend analysis of the peak streamflow found flow locations below Omaha had an increasing trend for all n-day duration time series. Longer n-day duration timeseries resulted in increasing trends downstream of Sioux City. No irrigation, no regulation (NRNI), or unregulated (see Section 3.2) flow locations above Sioux City commonly had a decreasing trend, but none were found to be statistically significant. Seasonal volume trends resulted in all NRNI flow locations having an increasing trend in winter, with fewer upstream NRNI locations in the spring and annual time series.
5. The combination of statistically significant change points and increasing monotonic trends in flow locations below Gavins Point potentially indicates climate has influenced streamflow in that portion of the Missouri River Basin.
6. The Missouri River Basin climate has observed and projected trends that indicate a vulnerability for the flood risk reduction USACE business line. The flood risk reduction business line has vulnerable watersheds in both future climates (i.e. dry, wet) and scenarios (i.e. 2050, 2085). The most common dominant indicator for flood risk vulnerability is related to a cumulative flood magnification. In the Missouri River Basin, this means there is a potential for flooding or property damage in the future. For the watersheds that contain USACE dams, flood magnification indicates a potential for energy spills during the winter and spring seasons. An indicator relating to the urbanized acreage within the 500-year flood plan was dominant for two southern watersheds in the dry-2050 and dry-2085 scenarios.
7. Over time, the number of vulnerabilities increase in both dry and wet scenarios. The dry scenario has the largest increases in vulnerability in the southern region of the basin. The wet scenario resulted in increased vulnerability across the entire river basin.
8. Based on this assessment, it is likely climate change has already impacted streamflow in the Missouri River basin. Continued changes in peak streamflow are expected as precipitation extremes are expected to be transient through the end of the 21st century.

The data used for evaluating nonstationarities and monotonic trends is based on daily streamflows which have reservoir regulation and irrigation impacts removed. The irrigation impacts are based on information provided by the Bureau of Reclamation. However due to the long history of development in the basin, there are still uncertainties in the streamflow data used with this assessment. For example, many of the major reservoirs were constructed following the Flood Control Act of 1944; however, water storage and irrigation development were occurring for decades prior to the major storage projects which makes identification of nonstationarities challenging. In addition, land use and land cover change is not explicitly removed from the streamflow record which could also introduce additional uncertainty in the analysis. Table 6 in Appendix J provides possible explanations in the identified nonstationarities.

The climate assessment showed increases in historical seasonal volumes and peak flows at all locations in the January through April season. The May through September season showed reductions in the seasonal volumes in only the upper basin and showed increases in peak flow for the mid and lower basins. It is unclear what affect these changes will have on future flow frequency based on the projected streamflows available for the climate assessment in Appendix J. However, with universal concern that changes in future climate may impact operation of these projects, USACE is completing a quantitative non-stationarity study, or in-depth study, for the basin which will examine predicted future rainfall-runoff conditions and could be used to assess future flow frequency variations.

The information provided by the climate assessment demonstrates there are hydrologic changes that are likely occurring in the Missouri River Basin. The flow frequency analysis, while not directly modified, did consider this information which resulted in the instigation of an in-depth evaluation of climate change impacts on flow frequency outside of the current Lower Missouri River Flow Frequency Update study. That study is in progress at the time of publication. Across all flow locations, the most common change point identified in the qualitative assessment was 1941, a similar date as found for the Kansas and Grand River Basins (see Sections 2.7.2 and 2.7.3). Other common change points occurred around 1946, 1961, 1984, 1999, and 2007. Since the systematic period starts at the beginning of a record drought that ended in the early 1940's, a change point around that time is not unexpected. Sensitivity analysis was conducted as part of the unregulated Bulletin 17C flow frequency analysis at representative gages to shorter periods of 1941 to 2019 and 1967 to 2019, as compared to the adopted 1930 to 2019 systematic period. This analysis is documented in Section 3.7.3 for the early spring period at Omaha, 3.8.3 for Kansas City, and 3.8.6 for Hermann, these gages being selected as representative of the varying hydrology along the river. A summary of the results for these three gages is as follows:

- Effects of shortening the systematic records from 1930 to 2019 to 1941 to 2019 had variable impact on the Bulletin 17C unregulated flow frequencies along the river ranging from -9% to +6% at the 1% AEP. Nearly identical flows were computed for the 1% and 0.2% AEP flows for both periods at Kansas City, with mean increasing, standard deviation decreasing, and skew increasing for the shorter systematic period. For the early spring season at Omaha, flows were about 6% higher at the 1% AEP, with mean and standard deviation both slightly higher, and skew being decreased from 0.363 to 0.302 for the shorter period. At Hermann, flow frequencies for the 1941 to 2019 period were about 9% lower than for the 1930 to 2019 period, and almost identical to the final adopted results, which used a historic period back to 1844 and a systematic period of 1930 to 2019. At Hermann, mean and skew increased, whereas standard deviation decreased for the shorter period of 1941 to 2019 compared to 1930 to 2019. Given the drought of the 1930's, a lower mean for the longer period was as expected throughout the river. However, impacts on standard deviation were either less pronounced as at Omaha, or decreased in the downstream gages, if eliminating a period of low flows from the record drought, which can decrease Bulletin 17C flows. Impacts to skew were variable.

- Bulletin 17C unregulated flow frequency analysis was also computed for a shorter systematic period of 1967 to 2019, given other change points before and after this date at some gages. This period includes recent major floods of 1993, 2011, and 2019, but drops the 1951 and 1952 floods, the wet 1940's period, and the 1960 flood. Flows for the 1967 to 2019 period decreased at Kansas City by 1-2% and 4-5% at the 1% and 0.2% AEP, respectively, compared to the other two longer periods. At Omaha in the early spring and at Hermann, flows for the 1967 to 2019 period increased compared to the longer periods. Increases were about 6% and 18% at the 1% and 0.2% AEP at Omaha, respectively, and 11% and 16% for the same frequencies at Hermann compared to the 1930 to 2019 period.

Shortening the record to remove the most common change point in 1941 did not conclusively or consistently impact the Bulletin 17C unregulated flow frequencies throughout the lower Missouri River. This is a result of the shortened period eliminating the record drought from the analysis, which can decrease standard deviation and decrease flows, generally offsetting the increased mean from the wetter period. Effects of shortening the record also eliminate the ability to consider historical flood records which help define the frequency of large floods. However, information from the qualitative climate assessment suggests that runoff may change in the future or may already be changing at some locations. Scoping for the in-depth climate analysis centered around updating the timeseries flow data to reflect future conditions flows for input into HEC-WAT, which may involve multiple estimates from different climate models and projections. Estimates in this report are considered "existing conditions" information, as expanded upon in the following section, which addresses concerns with other factors, such as development or land-use changes on flows. For the existing conditions analysis, the NRNI flow dataset is assumed to be stationary. While statistically significant trends were found, the streamflows used in the flow frequency analysis are assumed within the range of the hydrologic uncertainty analysis.

2.7 Basin Development and Impact on Stationarity

During the 2003 UMRSFFS, of particular concern with historic peak flows prior to 1898 were the reliability and potential for non-homogenous records due to land use changes. Sensitivity analysis using pre-1898 historic peak flows showed only minor differences in the Bulletin 17B flow frequencies if accounting for historic peaks. Given these factors, the pre-1898 historic peak data was not used in the 2003 study (USACE 2003). With the advent of Bulletin 17C procedures, historic peaks are an important piece of flow frequency procedures, with new revised methods to better account for uncertainty of such estimates. Consideration of land-use change and other factors possibly impacting the homogeneity of the systematic and historic peak data are discussed in this section of the report with an emphasis on the

Missouri and Kansas Rivers. Emphasis on the Kansas River was deemed important since it drives the transition between mixed and single population gages in the analysis as further described in Section 3.3. Land-use changes considered include clearing of floodplain forests primarily for agriculture and communities, channelization, conversion of prairie or forested uplands to cropland and urban areas, installing drainage tiles, and the advent of soil conservation measures such as terraces, small dams, and reserve programs. Figure 2-6 presents the current land cover in the Missouri River Basin (USACE 2018, Master Manual).

Figure 2-6. Current Landcover in the Missouri River Basin (from 2018 Master Manual)

Throughout the 2003 UMRSFFS, a case was made to use the record only back to 1898 due to concerns with the quality of historic peak flood estimates and also concerns that basin runoff is not homogenous due to land use changes. Generally, 1898 was an accepted date that most land that is currently in agricultural production was in production. Urbanization, though it can have localized impacts, affects a small percentage of the basin compared to conversion of pasture and forest lands to row crop production. Figure 2-7 presents a plot showing historic land cover for the United States between 1630 to 2020, which confirms most row crop production had been in place by 1898 based on the average for the country (Li, 2022). However, within the Missouri River Basin, some of this development lagged. While basin specific studies were not located at this time, visually from the figure approximately 25% of the stage of South Dakota was converted from grassland to cropland between 1900 and 1950. As summarized in Section 2.7.2, conversion of grassland to cropland in western portions of the Kansas River Basin began around 1860, increased steadily until 1930, then began to decrease somewhat. This indicates significant changes may have been occurring in the basin during the 1898 to 1929 pre-systematic period.

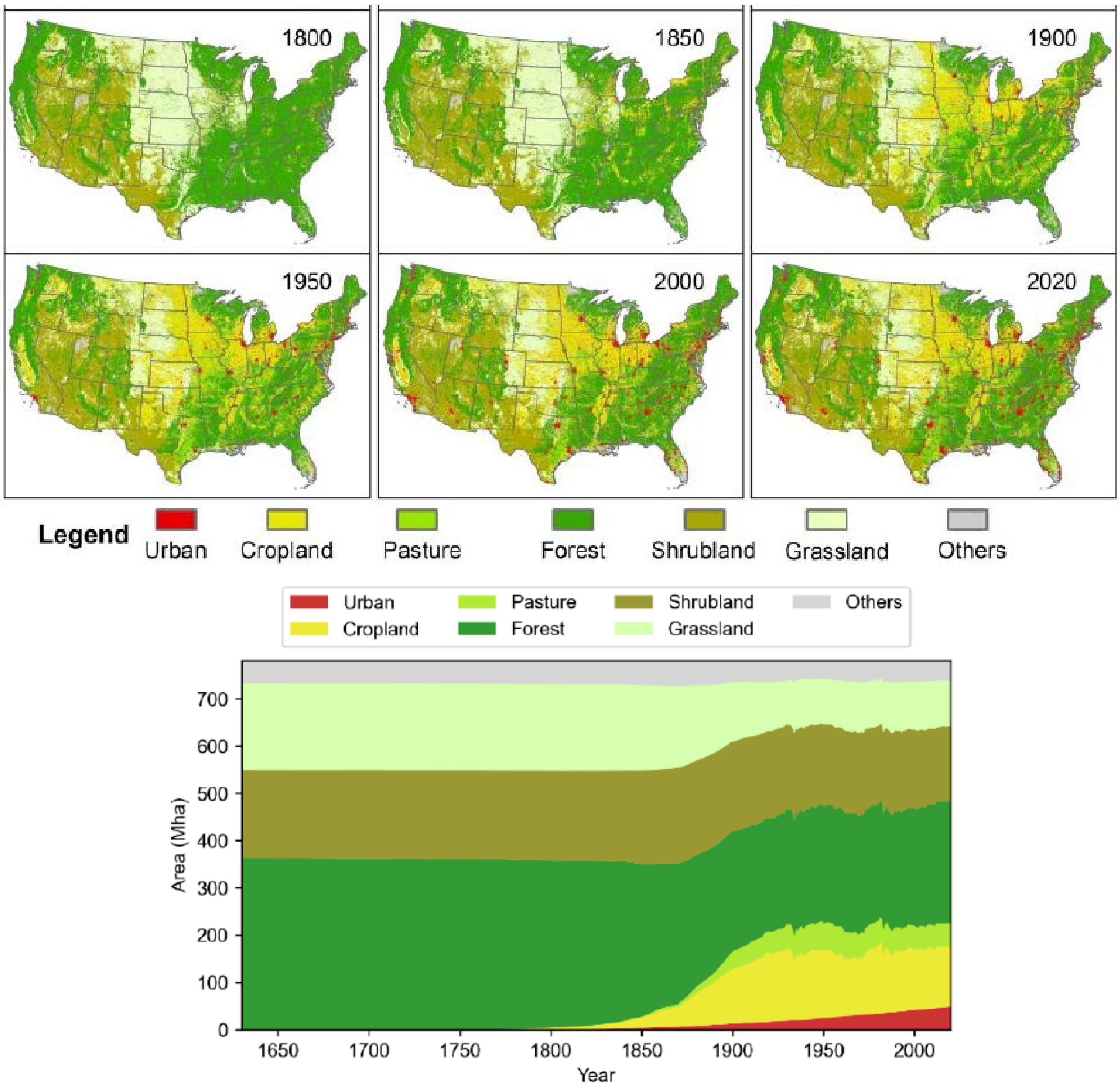


Figure 2-7. Changes in Land Use in the United States, 1630–2020 (adapted from Li 2022)

To reduce concerns with the quality of historic peak flood estimates, extensive flood history research was conducted and uncertainty with previously established estimates was considered as detailed in Section 2.4 and Section 3 of this report. Still, concerns regarding how consistent the runoff may have been compared to modern conditions must be considered. While agricultural production acres have been relatively stable since 1898, other watershed changes have also occurred over time. These include the installation of small dams, NRCS terraces which are often sized for 5yr or 10yr runoff by the NRCS in western portions of the basin, such as in Kansas, farming practices have changed, and in some eastern area, drainage tiles have been installed to minimize crop losses due to saturated soils. Generally western portions of the basin, which have less annual rainfall, have seen actions to keep water on site, whereas eastern portions have seen a mix of actions to reduce crop damages by removing water from the site combined with conservation measures. Though modeling these types of changes on the scale of the Missouri River and their impact on rainfall and runoff has been deemed impractical at this time, several smaller scale studies have been conducted which may provide useful context on the impact on peak streamflows of the Missouri River. The following sub-sections present examples of the types of development which could impact runoff and information to help inform the significance.

2.7.1 Impacts of Channel and Levee Changes on Flow Routings

One concern from the 1962 Hydrology Study was accounting for channel changes and levee construction over time (see Section 2.5) in the flow routings. Curves were made to convert observed peak flows to potential future flows for varying levels of levee construction in the 1962 study as reproduced in Appendix A. For the current study, and the 2003 UMRSFFS, gaged flow inputs were routed downstream through models calibrated to current conditions, and the ungaged flows were back calculated from observed records at each gage. These ungaged flows were then also used to compute unregulated flows and regulated flows. This method of routing the gaged flows downstream significantly reduces the uncertainty for how flows of the systematic record would respond to the current configuration of levees on the river since it accounts for most of the flow volume. However, the calculated ungaged flows could also be impacted by routings during older floods which occurred before the navigation channel or adjacent levees were completed. The 2003 UMRSFFS also performed additional routings using UNET, an unsteady flow hydraulic model which is now incorporated into HEC-RAS, during the stage frequency portion of the scope. In 2003 UMRSFFS, Appendix E, multiple geometries reflecting different periods of time were created in UNET to better calculate ungaged inflows, and ultimately, the results of the hydrologic routing were verified. Sensitivity analysis by Omaha District for no ungaged flow concluded that "it does not appear that the ungaged inflow data set skews results" in computed stage frequencies. A comparison of the current study to the 2003 UMRSFFS unregulated annual peak flows is provided in Section 3.2.1. Given limited differences, and sensitivity analysis which showed minimal impacts to frequencies, these potential impacts from levee and channel changes over the 90-year period of record to ungaged flows are assumed negligible.

For historical peak flows, it is possible that the historic floodplain, with its wider river meandering channel and mostly wooded valley, could cause additional attenuation and lower flows compared to the current conditions. Limited analysis of flow routings of the natural valley with moderate floods shows a minor impact on timing, and a smaller impact on peak flows. For example, the May 2007 flood hydrograph was routed from Boonville, MO to Jefferson City, a distance of over 50 miles, through an unsteady flow HEC-RAS model geometry reflecting the 1992 conditions, which had levees on both banks, and a scenario with no levees and a fully forested floodplain (Jacobson et. al, 2015). The USGS lists the May 2007 annual peak at 302,000 cfs, however, in the study provisional instantaneous data was used indicating a hydrograph peak of 338,000 cfs at Boonville, MO. The model showed 0.1% lower flows at Jefferson City than at Boonville for the "confined by levees" scenario. For the no-levees and fully forested floodplain, peak flows at Jefferson City were 0.2% lower than at Boonville, and the arrival of the peak was delayed by several hours compared to the "confined by levees" model results. These impacts could be larger in wider floodplain areas, such as Waverly, MO, or the river upstream of St. Joseph, MO. Combined curves of the 1962 levee study in Appendix A reflecting change as of 1960 and as projected if all levees were built showed adjustment of flows up to 12,000 cfs when routing from Sioux City to St. Joseph or Kansas City for floods of approximately 250,000 cfs, approximately 5%, with no difference for flows larger than 350,000 cfs. Given also limited attenuation of the historic 1881 flood peak as it traveled from upstream to downstream, these routing impacts are assumed to also be minor for the largest historic peak flows.

2.7.2 Kansas River Basin Example Impacts of Conversion of Cropland and Subsequent Terraces, Small Dams, and Conservation Programs on Streamflow

The conversion of rangeland to crop production after Kansas was opened for development in 1854 contributed to increased runoff in the early to mid 1900's (see Koellicker, 1998). Since major Kansas River floods of the early to mid-1900's floods occurred, farming practices have improved, and many Natural Resource Conservation Service (NRCS) and Farm Service Agency (FSA) programs, such as installing terraces and the construction of small dams, have decreased runoff over time. Change in the hydrologic risk, for example, annual precipitation rates, appears to indicate an increasing trend in Kansas, but could be masked by other factors, primarily in agricultural practices which make up over 90% of the land use (Koellicker, 1998). Data from the Farm Service Agency (FSA) indicates a net of over 3,400 square miles was converted from cropland into more natural landcover in Kansas between 1982 and 1997, including nearly 4,400 square miles (2.8 million acres) into the conservation reserve program (CRP) lands as established in 1985. In Kansas, CRP acres averaged approximately 2.8 million acres between 1990 and 2007 and decreased to less than 2.1 million acres by 2017. Similar trends have occurred in Nebraska. Additionally, FSA data indicates over 450 million miles of terraces have been built in Kansas (NRCS, 2003 fact sheet). Example studies of changing hydrologic conditions conducted in the Kansas River Basin are summarized in the following paragraphs, although not all watersheds have had the same level of impact as these examples. Figure 2-8 presents a map adapted from Koellicker 1998 that provides the "current" percent of runoff compared to the 1930–1950 period across the State of Kansas overlain with Farm Service Agency (FSA) terraced land data in relation to the examples and reference points in the basin. The figure also includes a water yield analysis and changes, 1850 to 2000 for Webster Dam from Koellicker, 1998.

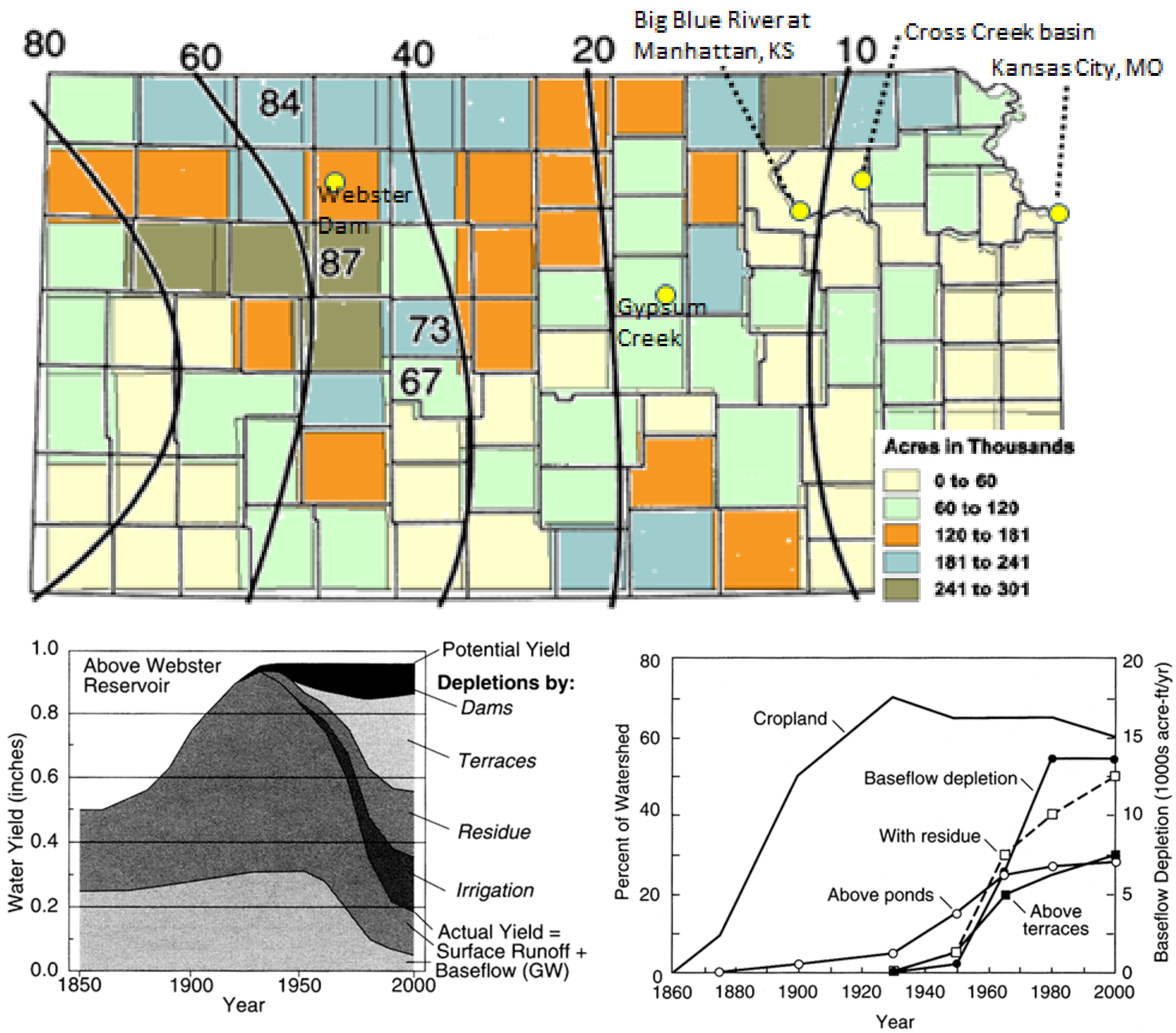


Figure 2-8. Percent of Streamflow Reduction Below the 1930–1950 Period in Kansas

Note: Due to various factors; overlain with Terraced Land Data (adapted from Koelliker, 1998, and NRCS, 2003)

A study of the Gypsum Creek watershed, a 193 square mile right-bank Smoky Hill River tributary in Saline County, Kansas, concluded that over 50% of the watershed was covered with NRCS terraces, which are typically designed to capture the runoff of a 10% AEP event (USACE 2018, Gypsum, Kansas FPMS study). This, and other land-use practices were attributed to decreased flows for a corresponding frequency when comparing peak flows estimated with the same precipitation from the original Federal levee design runoff model, calibrated to events in the 1950's, to updated models calibrated to the 2009 flood. Peak flow estimates of a 1% AEP were calculated at 36,000 cfs and 23,100 cfs, for the 1950's model and 2000's model, respectively, a decrease of 35%. Since the calibration events were on the order of a 10% AEP, it is possible that this difference could decrease during more extreme events. However, flood history of Gypsum, Kansas, provided similar information, with four major overflows occurring 1903–1951, and the largest event since being 1993 at only about half the peak flow of these four events.

Another study of Cross Creek, a drainage area of 178 square miles northwest of Topeka, Kansas, investigated the change in runoff from the largest 33 dams built in the watershed from 1973 to 2008. These include 15 dams built by the NRCS with flood control as part of their purpose on watersheds of 0.3 to 10.9 square miles, with all 33 dams totaling 79.5 square miles, or 45% of the watershed. The study concluded the dams reduced 0.2% AEP flows from approximately 61,000 cfs to 51,000 cfs, a 17% reduction (USACE 2018, draft Cross Creek HEC-HMS report). However, several of these dams begin overtopping between a 1% AEP and 0.1% AEP event, indicating a decreased effectiveness during extreme events.

After noticing that wet conditions in the early 1970's did not produce runoff expected for water supply in Webster Reservoir, which has a contributing drainage area of 1,150 square miles of the South Fork of the Solomon River, the U.S. Bureau of Reclamation (Reclamation) initiated studies to determine contributing factors. The 1984 report concluded that while ground water withdrawal was a factor, the largest effect by far upon declining streamflow was that of soil and water-conservation practices (Koelliker, 1998). Prior to development, the watershed above Webster was in rangeland. Agriculture was started around 1860 and by 1930, about 70% was in agriculture. Drought and erosion caused some crop land to go back to grass since 1930 (Koelliker, 1998). Webster Reservoir information shows how water yield increased since the 1850's, peaked in roughly 1940, and has since reduced to a new yield over 50% lower than the natural conditions. However, this amount of change is mostly present in western portions of the basin, and less impacted in the east (Koelliker, 1998).

This information indicates that the great flood of 1951, and to a lesser degree 1903, may be reduced if repeated on modern watershed conditions in the Kansas River Basin. Several climate change and non-stationarity analysis have been conducted on the Kansas River which were cross referenced to help determine the potential significance on Missouri River flows. The most recent study is the post-ATR DRAFT Climate Appendix of the Kansas River Basin Watershed Study dated July 2021, which analyzed five mainstem gages and 8 dams, including the lower seven dams and Harlan County. The period of record varied by location but covered up to 1919–2019 at the most downstream mainstem gage at De Soto, Kansas. The analysis concluded that the 1941–2019 period can be considered stationary at all locations except Harlan County, which had a significant downward trend in inflows. Consistent change points around 1940 at multiple locations were attributed to the transition out of the 12-year drought of the 1930's, which is indicative of the cyclical weather patterns this region faces. Trend analysis of the 1941 to 2019 period showed slight downward trends in streamflows at the Fort Riley, Wamego, and Topeka gages, and slight upward trends at Lecompton and DeSoto, with none of these trends being statistically significant (USACE 2023, post-ATR Draft, Kansas Basin Study). Unfortunately, the systematic record stops short of major floods of the early 1900's, namely 1903, the largest flood known on the Kansas River between 1844 and 1951, 1908, the largest event between 1903 and 1951, and a smaller overflow of 1904. Sensitivity analysis showed that the shortened 79 year record of 1941 to 2019 produced 9% and 16% lower flows for the 1% and 0.2% AEP events, respectively, than the full flood history back to 1844 at DeSoto, Kansas, with similar or greater differences at upstream gages (USACE 2023, post-ATR Draft, Kansas Basin Study).

Compared to 1930–1950 conditions, eastern portions of the Kansas River Basin which produce the most runoff are less impacted than western portions of the basin, and change has been occurring over time, and may be less impacted during large events based on these examples. Additionally, the initial conversion of rangeland to farmland may be largely mitigated by other factors in portions of the basin. For example, terraces and residue left on fields through improved farming practices could essentially mitigate the impact on water yield of converting rangeland to farmland in the Webster Dam example in western Kansas. Efforts to homogenize the 60,500 square mile basin for these changes were deemed impractical. However, there is no reason to believe that estimates of historic peaks for floods derived largely from the Kansas River, including 1844 and 1903, do not provide useful flood information. Nor is there sufficient evidence to decrease the peak of 1951 and other floods of that period given results of trend analysis.

2.7.3 Grand River Basin Example of a Basin Impacted by Channelization, Drainage Tiles, and Other Factors

Flows of the Grand River at Sumner Missouri, which has a drainage area of 6,880 square miles, were used as flow inputs to this study. The Grand River Basin drains portions of north-central Missouri and south-central Iowa. As part of the 2020 Grand River Basin Feasibility Study, a climate resilience and non-stationarily detection analysis was performed (USACE, 2020, Grand River). Historic discharge data at three of the long term USGS gages in the Grand River Basin indicated statistically significant trends of increasing average annual discharge, annual peak streamflow, and identifications of non-stationarities for the period of available data (1922 to 2016 and 1928 to 2016). Further analysis and a reduction of the period of record to 1942 to 2016 resulted in no detection of statistically significant trends or non-stationarities, and generally higher flows than if using the full record back to the 1920's. However, also noted in the study is that other factors beyond increased precipitation may be at play in the Grand River watershed. Specifically, significant channel straightening was completed widespread throughout the Grand River and its major tributaries throughout the early 1900's as documented in the Grand River Basin "308 Report". Additionally, significant land area was converted from prairie or woodlands to agricultural production. In recent years, although soil conservation efforts have helped, many areas in this region have seen rapid installation of drainage tiles to improve field runoff and maximize crop production. As a result of these changes, many portions of the basin may be seeing an increased runoff compared to historical conditions due to land-use changes in addition to climate change.

Efforts to homogenize the basin for these changes through modeling were deemed impractical. Sensitivity analysis using Bulletin 17C was conducted for the 6880 sq mile drainage area for the Grand River at Sumner, MO and found that periods of 1942 to 2019 and 1930 to 2019 result in flows approximately 3% and 4% higher than the full 1909, 1922 to 2019 record at the 1% AEP, respectfully. The differences are within 2% at the 10% AEP and increase to 7% and 11%, respectively at the 0.2% AEP for the 1941–2019 and 1930–2019 periods, respectfully. The 0.2% AEP was determined to have a similar value at approximately 210,000 cfs for the 1930–2019 and the 1970–2019 time periods. This analysis used only station skews with no smoothing. No earlier data was readily available for sensitivity analysis for historical peak events. While the use of more recent data does result in higher flows for events larger than 10% AEP after channelization and landcover changes were more fully completed within the basin, the impact of the changes may be minor in terms of peak streamflows. Generally, while drainage tile may increase flow volumes, the impact on peak flows is likely diminished during large storms which overwhelm the systems. Therefore, the systematic flow data for the Grand River, and other similar streams in the region are assumed reasonable for the existing conditions flow analysis.

2.7.4 Impacts of Urban Watersheds

Major metropolitan areas pertinent to peak flows on the Missouri River are primarily the Omaha, NE and Kansas City, MO metropolitan areas, along with a few smaller cities. An example of an urban watershed is the Big Blue River in Kansas City, Missouri, which has its headwaters in Johnson County, Kansas. As part of a feasibly report prepared in the 1990's, impacts of urbanization for the 188 sq. mile watershed of the Blue River at Bannister Road were made using a rain-runoff model. After calibrating a rain-runoff model to a flow frequency analysis using data from 1956 to 1888 and 1990 land cover, the projected fully urbanized land use was analyzed to estimate future without project flows. The analysis showed a projected increase of 10% AEP flows of approximately 7%, with 0.2% AEP flows increasing by approximately 2%. On Sep 14, 1961 from the remnants of Hurricane Carly a flood peak of 41,000 cfs broke the previous record estimated of 35,000 cfs of November 1928, the largest flow at least back to 1894 on the Blue River. Modeling from the 1960's indicates that had the basin been fully developed, the 1961 peak would have been nearly identical to the current record peak of August 22, 2017 of 43,900 cfs, None of these events correlate with major floods of the Missouri River. The Blue River reflects the largest urban watershed in the Kansas City, MO metropolitan area, and urban areas make up a small percentage of the overall Missouri River Basin landcover. Many communities also have stormwater ordinances, which may help reduce future impacts. Therefore, urban areas are anticipated to significantly increase flood risk on the Missouri River.

2.7.5 Conclusion on Development on Flow Records and Historic Peaks

An overall impact of increased runoff can be seen on some tributary gages and some mainstem gages through a mix of climatic and land use factors. While there is evidence of the impact of changing land use on runoff throughout the basin, these changes did not fully cease in the year 1898 and may still be evolving somewhat as areas are developed or as agricultural policies are revised. Still, the year 1898 represents the approximate accepted period after which many of the land cover changes, aside from navigation project and most levee construction in the floodplain, had already occurred. Routings, rating curve development, and sensitivity analysis completed in the 2003 UMRFFS help minimize risk of flows derived from stage records from 1898 to 1929 being non-homogenous with the current systematic period of 1930 to 2019. However, there are still differences between routing methods, data quality, and differences in depletion estimates between the two studies. Regarding concerns with the homogeneity of the data prior to 1898, the following assumptions are made:

1. Historic peaks prior to 1898, if repeated, may see altered runoff than from the basin of the early 1900's, which may be different than runoff from today's Missouri River Basin. In western portions of the basin, this could result in more runoff initially due to landcover change of prairie to croplands sometimes with little vegetative cover, to decreased runoff due to improved farming practices, terraces, and small dams. In some eastern portions of the basin, which typically produce the greatest amounts of runoff during major rain events, overall runoff may occur faster and possibly at a greater rate in the modern conditions than in the historic peaks. Much of the Ozarks region of Missouri remains little changed from historic conditions.
2. Based on the example studies of smaller watersheds in the basin, land use changes may have the most impact during frequent flood events, with less impact at extreme events. In most cases checked, land-use change impacts are captured within ranges of 10–20% on estimated flows, except in one case of a nearly 200 square mile basin in the unregulated portion of the Kansas River Basin where 1% flows could have decreased up to 35% since the 1950's.
3. Given the scale of the basin, constant change over time, and detail needed to fully account for all land use changes, efforts to fully homogenize the flow records for land use change are considered impractical at this time. Actions in the basin have

included items that both increase or decrease streamflows, some in the same watersheds.

Therefore, historical flood peak values in this report can be reasonably included in the Bulletin 17C analysis as discussed for each individual gage. Additionally, older peaks are also useful for sensitivity analysis. Based on this information, several sensitivity analysis were recommended and conducted. First, Bulletin 17C unregulated flow frequency analysis was conducted using best estimates of historical peak floods, then repeated using a bias towards higher estimates of historic peak flows. This was conducted to help determine the potential impact associated with uncertainties with historic peak estimates and how the river could respond to the same event in the current basin conditions. Sensitivity analysis to check for changes throughout the systematic period of 1930–2019 was also conducted at representative gages as informed by the climate assessment summarized in Section 2.6, and documented in Sections 3.7.3 for Omaha, 3.8.3 for Kansas City, and 3.8.6 for Hermann. Additionally, as detailed in Appendix D, analysis was performed to consider whether the 2003 UMRSFFS annual peak data from 1898 to 1929 was homogenous with systematic data from 1930 to 2019. Ultimately the 1898 to 1929 data was used to inform historical peak flows for use in Bulletin 17C, and for sensitivity analysis, but was not treated as systematic data. With these considerations and sensitivity analysis conducted, the time series data and historic peak data presented in Section 3.2 and 3.6, respectively, are considered sufficient for an existing conditions hydrology analysis.

3. Unregulated Flow-Frequency

3.1 Introduction

Unregulated flow frequency analyses were conducted according to the methodology advanced in United States Geographical Survey (USGS) Guidelines for Determining Flood Flow Frequency: Bulletin 17C published in May 2019. This procedure does not cover watersheds where flood flows are appreciably altered by reservoir regulation, watershed changes, or hydrologic non-stationarities, or where the possibility of unusual events, such as dam failures, must be considered. For that reason, the flow frequency analyses were performed on the unregulated (no regulation, no irrigation) annual peak flows from the time series summarized in Section 3.2. The peak flows used were maximum daily flows computed using the Missouri River mainstem HEC-ResSim model (USACE 2018 ManPlan) (USACE, 2018), and were converted to peak flows using instantaneous peak to daily average flow ratios. The Missouri River stations analyzed include Yankton, SD – just below Gavins Point; Sioux City, IA; Omaha, NE; Nebraska City, NE; Rulo, NE; St. Joseph, MO; Kansas City, MO; Waverly, MO; Boonville, MO; and Hermann, MO. The location of these stations is illustrated in Figure 3-1. Summary information for the river miles, drainage areas in total, the unregulated and regulated portions of the drainage areas, the 1947 MRLS Agricultural Design flows, and record post-dam flows are presented in Table 3-1. Based on the immediate needs for the flow frequency information, this analysis focused on expected probability flows when developing the unregulated flow frequency estimates. If a full risk analysis in a program such as HEC-FDA is required, the computed probability curves and correspondingly adjusted regulated frequency curves will also be required.

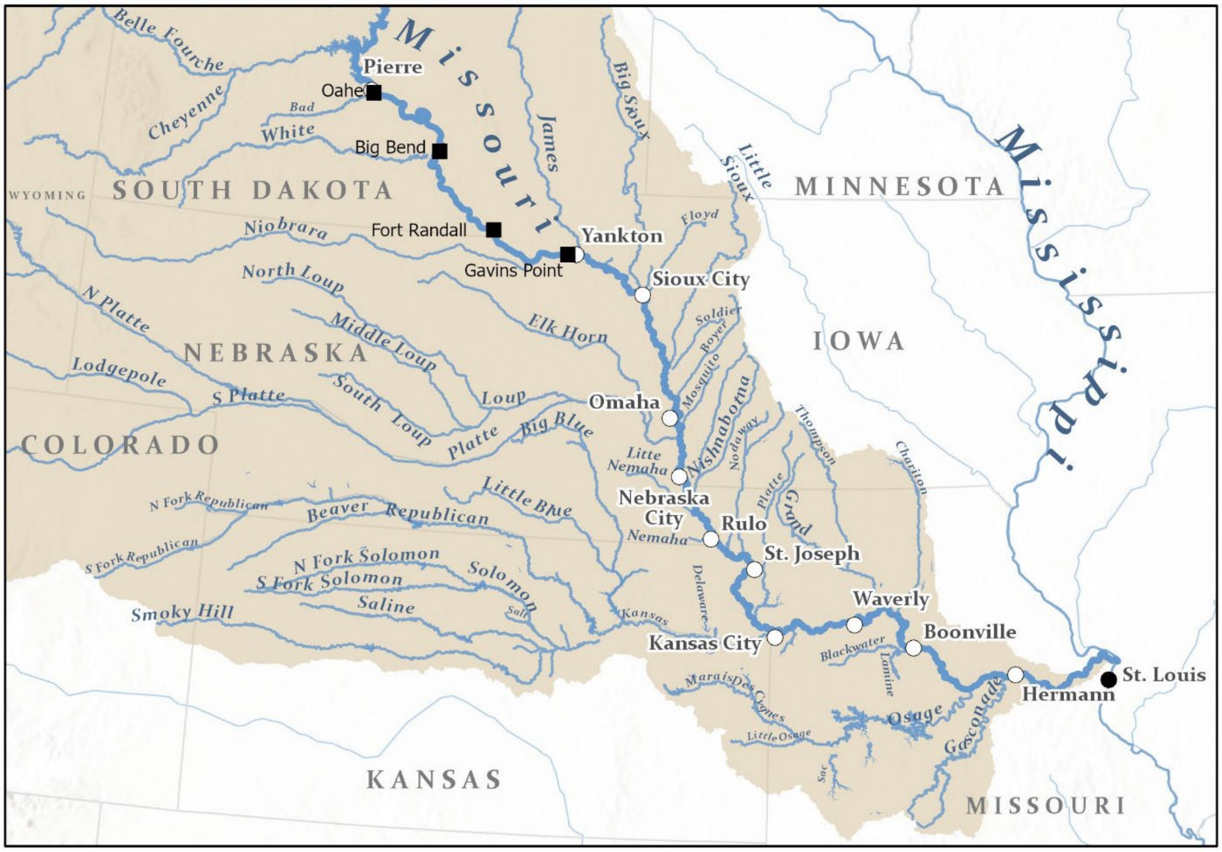


Figure 3-1. Stream Gages Used in the Lower Missouri River Frequency Analysis

Table 3-1. Missouri River Gage Locations, Drainage Areas, and Pertinent Discharges

Station / Location	Area Square Miles				Cubic Feet per Second (cfs)	
	River Mile	Total Drainage Area*	Drainage Area		1947 Ag Design Discharge	USGS flow Max of 1993[1], 2011[2], 2019[3]
			Regulated**	Unregulated		
Gavins Point	811.1	279,480	279,480	0		160,700[2]*
Sioux City	732.3	314,617	281,808[a]	32,809	150,000	192,000[2]
Decatur	691.0	316,140	281,808	34,332	167,000	191,000[2]
Omaha	615.9	322,820	281,808	41,012	250,000	217,000[2]
Nebraska City	562.6	414,420	318,216[b]	96,204	295,000	342,000[3]
Rulo	498.0	418,905	318,216	100,689	310,000	339,000[3]
St. Joseph	448.2	424,340	318,216	106,124	325,000	335,000[1]
Kansas City	336.2	489,162	369,276[c]	119,886	431,000	541,000[1]
Waverly	293.4	491,230	369,359 [d]	121,871	437,000	633,000[1]
Boonville	197.1	505,710	370,017[e]	135,693	475,000	755,000[1]
Hermann	97.9	528,200	381,517[f]	146,683	529,000	750,000[1]
Mouth	0.0	529,350	381,517	147,833	529,000	

*Value from USACE, 2018 Missouri River Master Manual; Note: there is 16,000 square miles of drainage area between Fort Randall Dam and Gavins Point Dam (minimal flood storage in Gavins); Yankton, SD is located at mile 805.8 with minimal drainage area between Yankton and Gavins Point Dam. Maximum flow column number superscripts denote which year has the highest flow at each gage, where 1993 is "1", 2011 is "2", and 2019 is "3".

**Cumulative tributary reservoir drainage areas from USACE Water Control Manuals or from USGS for Kingsley Dam were summed upstream to downstream, adding to the full drainage area upstream of Gavins Point Dam. Dams on tributaries entering the Missouri River above each gage are indicated in the superscripts as follows: a) James River Basin: Jamestown 1300 sq miles and Pipestem 1028 sq miles, b) four Papio Dams totaling 53 sq miles, Platte River Basin: ten Salt Creek Dams totaling 215 sq miles, North Platte: state-owned Kingsley Dam 32,500 sq miles (federal dams upstream included in this area), South Platte: Cherry Creek 386 sq miles, Chatfield 3,018 sq miles, and Bear Creek 236 sq miles, c) Platte River (MO/IA): Smithville 213 sq miles, Kansas River Basin lower 7 dams of Milford, Kanopolis, Wilson, Waconda, Tuttle Creek, Perry and Clinton totaling 50,847 sq miles (includes 11 upstream dams), d) Little Blue River basin: Longview 50 sq miles, Blue Springs 33 sq miles, e) Little Chariton Basin: Long Branch 109 sq miles, Chariton Basin: Rathbun 549 sq miles, and f) Osage Basin: Truman Dam 11,500 sq miles (area includes five upstream dams, does not include the privately owned Bagnell Dam, generally a pass-through hydropower facility, with 2,500 sq miles of incremental drainage area between Truman to Bagnell).

3.2 Times Series Flow Development

A HEC-ResSim (ResSim) model for the Mainstem Missouri River Dams, Kansas River Basin Dams, Osage Basin Dams, and Rathbun Dam in the Chariton River Basin was completed as part of the 2018 ManPlan EIS. The ResSim model was developed and validated against a flow record of 1930 to 2012 and is the primary basis for the model used to develop time series data for the unregulated flows and regulated flows. A copy of the 2018 report for the time series flow development may be viewed at https://www.nwo.usace.army.mil/mrrp/mgmt-plan/. A few minor updates to the 2018 ResSim model were required for this study. First, the ResSim model for the mainstem dams, a recently updated ResSim model for the lower seven Kansas River Basin Dams, and a recently updated ResSim model for the Osage Basin, including six USACE dams and the privately owned Bagnell Dam, were combined into one ResSim model. Previously, these were stand-alone models for each basin. Second, the period of record was extended seven years to incorporate the 2019 flood and the updated estimates of depletions from the U.S. Bureau of Reclamation as summarized in Section 2.5 were also incorporated. Sensitivity analysis was conducted to test the model routing parameters, but ultimately these were retained as is from the 2018 report. In general, for the Missouri, Kansas, and Osage Basin Dams, the only updates to rule curves were to improve the routing of large hypothetical floods exceeding those of the historical record, primarily relating to surcharge operations, or to update pertinent data such as elevation-storage information with later surveys.

Other remaining tributary dams were deemed too small with distances too great from the Missouri River to significantly alter flows to where they needed modeled in detail (see also Section 2.2). For this study, detailed modeling of Rathbun Dam on the Chariton River was conducted as detailed in Appendix I and holdouts routed to the Missouri in order to determine the regulated and unregulated flows of the POR. However, the analysis concluded the Missouri River peak flows were not sensitive to the reservoir holdouts and therefore Rathbun Dam on the Chariton River was not included in the ResSim model used for the scaled floods discussed in Section 5 and the WAT Monte Carlo Analysis. Estimates of Reclamation tributary reservoir holdouts not in the ResSim model were estimated by Reclamation and included in the depletions datasets used within the ResSim model. For the unregulated dataset, historical incremental flows based on historical gage data were routed downstream from Landusky, MT to Hermann, MO via the combined Missouri River, Kansas Basin, and Osage Basin ResSim Model, which removed regulation effects of only the modeled reservoirs within the ResSim model. The tributary reservoir effects were removed when depletions and tributary reservoir holdouts were added back to the model at each gage location. The regulated dataset was developed by simulating reservoir operations based on the 2018 Missouri River Master Manual, which only required removal of the small spring pulse from the 2006 Master Manual used in the 2018 study. The unregulated and regulated datasets were also routed from Gavins Point downstream to Hermann, MO via HEC-RAS models as presented in Section 4.0, and table explaining flows used in Section 4.1. The HEC-RAS routing used the ResSim unregulated and regulated flows at Gavins Point as the upstream boundary condition. Final unregulated and regulated datasets 1930 to 2019 from ResSIM are summarized in Figure 3-2 which plots the middle 80% of the flows at four gages for each day of the year.

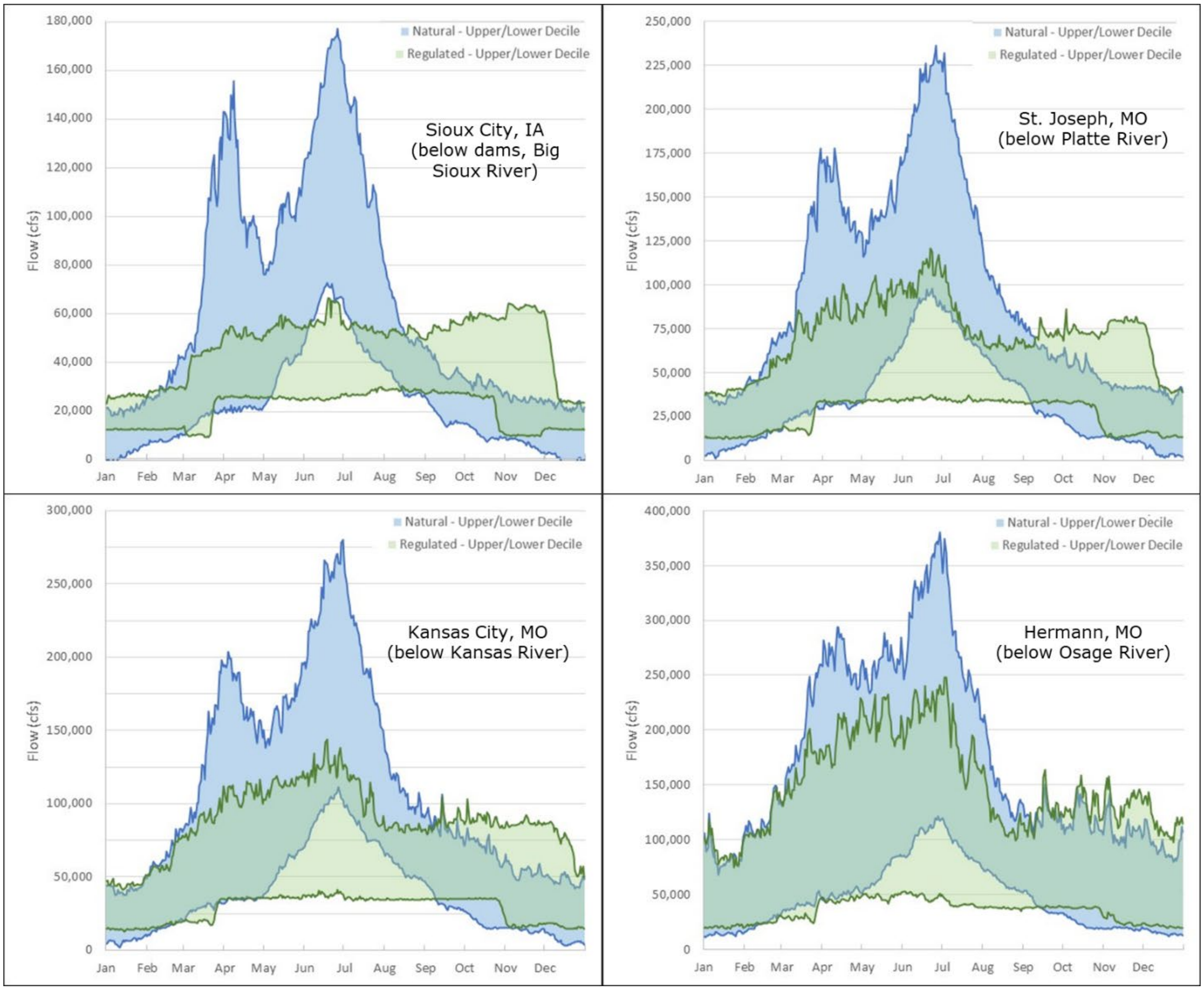


Figure 3-2. Final Unregulated (Natural) and Regulated Time Series Data, Upper and Lower Decile Flows for Each Day of the Year, Sioux City, IA, St. Joseph, MO, Kansas City, MO, and Hermann, MO

As seen in Figure 3-2, the natural flow pattern of the Missouri River consists of a dual peak flood season, one of early spring from plains snowmelt, and a second usually higher late spring and summer flood from mountain snowmelt, each as supplemented by rainfall. Normal effects of the reservoirs are also visible in Figure 3-2 in that they tend to reduce and smooth out the dual peak floods, and reduce the presence of low flow periods, generally creating higher flows in fall and winter than would naturally occur. Timeseries data also shows increasing flows from upstream to downstream with less ability to regulate flows as drainage area increases below the dams. Figure 3-3 presents the maximum and minimum flows for each time series each day of the year at St. Joseph as an example of how the daily time series data was used to develop maximum annual unregulated and regulated peak flows. Seven largest natural flows each day of the year are highlighted, three in 2019, and one each year in 1952, 1993, 2008, and 2011. For the summer floods 1993 and 2011, regulated and unregulated daily peak flows occurred on the same timing, with upstream dams providing a significant reduction in peak daily flows and with the regulated flows being very close to the observed USGS peaks, given all dams were operational. For early spring, two unregulated peaks occurred in 2019, the first in March, which corresponded to the observed USGS peak flow which was also very similar to annual peak regulated flow that year. However, in 2019 the largest unregulated peak occurred at St. Joseph in late May / early June. For the largest early spring flood of April 1952, Fort Peck Dam reduced the flows as indicated by the observed USGS peak, whereas had all dams been operational, the regulated peak would have been reduced to fourth highest on record later in the month. Examples from 1952 and 2019 show how the unregulated and regulated peaks may not occur at the same time of the year or from the same runoff event.

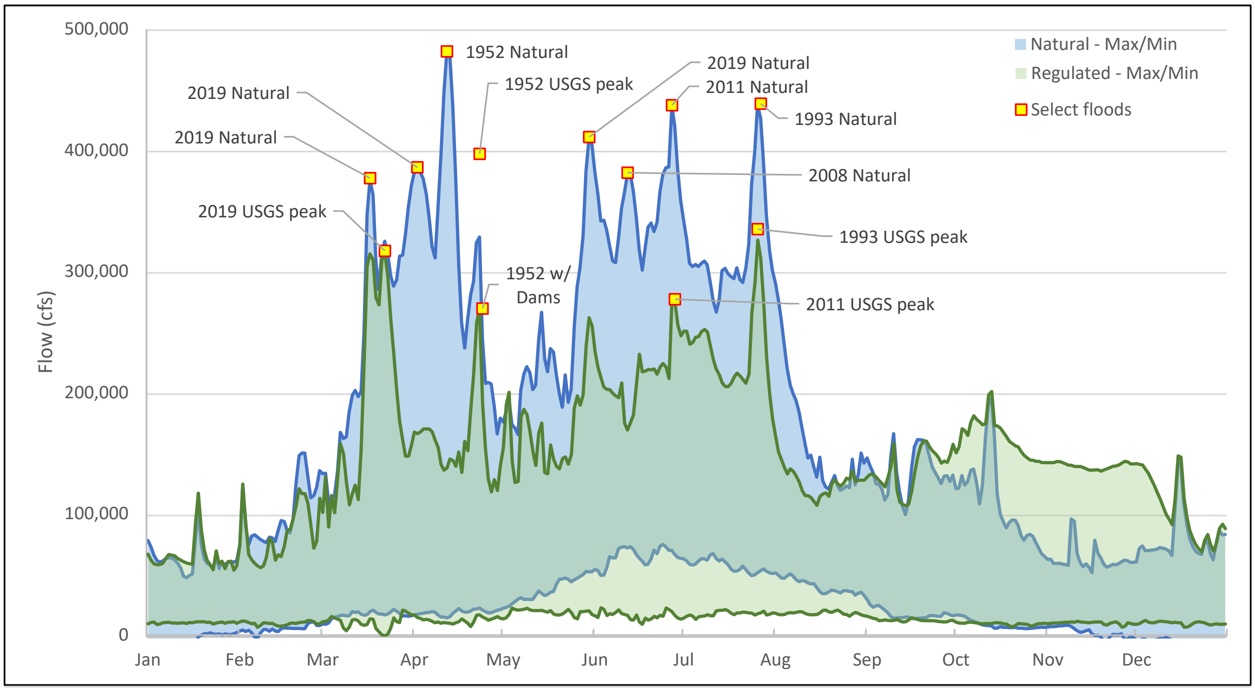


Figure 3-3. Unregulated (Natural) and Regulated Time Series Data, Maximum and Minimum Flows for Each Day of the Year at St. Joseph, MO

3.2.1 Current Study vs 2003 Unregulated Annual Peak Flows

A comparison of the current study unregulated peak flows was made with the 2003 UMRFFS to help further determine the impact of differences in channel routings in the unregulated data series. The routing method used in the 2003 study was regression routing between Gavins Point Dam and St. Joseph using a FORTRAN code Unregulated Flow Development Model developed by USACE, Missouri River Basin Water Management. The current study used routings from ResSim, and also tested routings using HEC-RAS. Depletion estimates have been updated between the two studies. Appendix D presents a comparison of the unregulated annual peak flows between 1930 and 1997 for the 2003 UMRSFFS Study and the current study, similar to Table A-36 from Appendix F of UMRSFFS to compare the 1962 study routings to the 2003 study. As seen in Appendix D, most gages have similar flows on average to the 2003 study, where Gavins Point / Yankton, Sioux City, Omaha, Kansas City, Boonville and Hermann are all within 2%. A more detailed comparison is also presented in Appendix D.

The maximum unregulated flow from the current study was also compared to the same year peak from the 2003 study. This flow was driven by 1952 upstream of Kansas City, and primarily 1993 downstream, except for Hermann which was the 1986 flood in the current study. Maximum flows in the unregulated record were 5% higher at Gavins Point, and 11% higher at Sioux City and Omaha than the 2003 study. For the three gages between the Platte and Kansas Rivers, the current study has slightly lower flows than the 2003 UMRSFFS on average, 6% at Nebraska City, and 3% at Rulo and St. Joseph, whereas the maximum flows are approximately 6–7% higher at Nebraska City and St. Joseph and 16% higher at Rulo than the 2003 study. At Waverly, MO, the current study produces higher flows than the 2003 study by 17% on average, and 12% for the largest event. For the 1993 flood, the current study matches the 2003 UMRSFFS study unregulated peak within 2% from Omaha to the mouth, except for Nebraska City, which is 6% lower in the current study, and Waverly as previously mentioned. For Hermann, MO, the highest peak in the current study was that of October 1986, which was estimated 20% higher than the 2003 study. The 1986 flood was derived from Osage Basin, and the increase reflects additional ResSim modeling that carefully estimated the impact of the six federal dams on the peak of the Missouri at Hermann. In comparison, the 2003 study utilized spreadsheet and MS Access programs to model reservoirs in the Osage River Basin.

Since depletion estimates were updated to current levels and are therefore different between the two studies and would be reflected in the unregulated data of both studies, the impacts of these estimates on flow frequencies must also be considered. As presented in the 2003 UMRSFFS, Appendix F, Table F-20, incorporation of depletions had a negligible impact in computed unregulated flow frequencies upstream of Rulo, gages, and less than 10% impact at St. Joseph at the 1% and 0.2% AEP flows. Even though depletions can account for as much as 25% of the annual unregulated flow, depletions generally have a small impact on larger floods (UMRSFFS 2003, Appendix F). The current study annual unregulated peak flows are considered reasonable in comparison to the 2003 UMRSFFS.

3.3 Seasonality and Mixed Population Analysis

The Missouri River exhibits a seasonal flood pattern with an early spring season usually dominated by shorter duration plains snowmelt floods, and a late spring and early summer flood season dominated by rainfall and augmented by mountain snowmelt (see Figure 3.2). As seen in the figure, seasonal flooding is usually the strongest at locations upstream of the

Platte River, as denoted by Sioux City, IA, where the March–April peak is not significantly lower than the later June peak. Downstream tributary flows begin to skew the higher peak to usually occur in June–July, with a less noticeable seasonal pattern at daily flows exceeded only 10% of the time at Hermann, MO. Of particular importance to major floods of the Missouri River Basin, the early spring flood mechanism tends to be different than the late spring or summer in that rainfall on snowmelt, sometimes with the ground impacted by frost thus limiting infiltration, tends to drive the largest floods upstream of the Kansas River. In late spring or summer, the flood mechanism is driven by rainfall supplemented by mountain snowpack runoff.

According to EM 1110-2-1415: "Hydrologic factors and relationships during a general winter rain flood are usually quite different from those during a spring snowmelt flood or during a local summer cloudburst flood. Where two or more types of floods are distinct and do not occur predominately in mutual combinations, they should not be combined into a single series for frequency analysis. It is usually more reliable in such cases to segregate the data in accordance with type and to combine only the final curves, if necessary." Therefore, as in the 2003 UMRSFFS, the seasons were delineated using calendar date as a proxy for hydrologic mechanism, which works well to date in the Missouri River upstream of Kansas City based on available flood history information (see 2018 Master Manual, 2003 UMRSFFS, and Section 2.4 for more detailed flood history information). The early spring season spans January through April, and the late spring and early summer season spans May through December. The late fall and early winter season tend to have low flows, although significant rainfall driven floods do occur in the autumn season. For example, the flood of October 1986 produced the maximum unregulated flood peak at Hermann, MO as calculated in this study.

In the Missouri River Basin, for very wet years, it is possible that earlier snow-based flooding could contribute to higher base flows when summer rainstorms enter the area. However, the mechanisms driving these seasonal floods are considered distinct as compared to guidance in EM 1110-2-1415. Seasonality tends to have a larger influence upstream that diminishes with drainage area. Working downstream from Yankton, SD towards Kansas City, MO, average annual rainfall increases and soil types tend to have a higher clay content, resulting in considerably higher runoff compared to plains areas upstream of Sioux City, IA and western portions of the Platte and Kansas River basins. Sensitivity analysis at St. Joseph, MO, shows that for the same data period, a mixed population analysis results in approximately 5–13% higher flows at the 1% annual chance exceedance probability (AEP) than for an annual series (see Section 3.5.8). Preliminary analysis for the Kansas City gage, and findings of the 2003 UMRSFFS, indicate this pattern does not extend below the Kansas River, which can produce major flooding on the Missouri River by itself without a significant contribution from the Missouri River. Early spring floods have not historically aligned with peaks of the Kansas River. The four largest floods at Kansas City of 1993, 1844, 1951, and 1903 were all rainfall events in June and July following 1–2 months of extended wet weather, each with a large flow from the Kansas River. Similarly, peak flooding in 2019 upstream of Kansas City was in March corresponding with plains snowmelt, whereas at and downstream of Kansas City, late spring rainfall-based flooding produced higher flows than in March. This pattern is shown visually in Figure 3.2 for St. Joseph and Kansas City, which shows the maximum flows each day of the year. Similar trends are seen at Boonville, MO, and at Hermann, MO, where large floods have occurred more distributed throughout the water year. Therefore, a mixed population analysis was performed, computing seasonal curves separately and combining them to create the final flow frequency curves at the following stations: Gavins Point (Yankton), Sioux City, Omaha, Nebraska City, Rulo, and St. Joseph. Meanwhile, the four downstream stations of Kansas City, Waverly, Boonville, and Hermann, were analyzed with all-seasons annual maximum series. To reinforce this decision, mixed population analysis was also conducted for the Kansas City gage, and single season analysis was conducted for the St. Joseph gage as documented in the sections for each gage.

3.4 Peak to Daily Flow Ratios

Peak to daily flow ratios were computed based on observed data from the United States Geological Survey (USGS) and the U.S. Army Corps of Engineers Water Management System (CWMS) database. Details about the peak to daily flow ratio analysis can be found in Appendix B. A table of the peak to daily flow ratios is shown in Table 3-2. All-seasons peak-to-daily flow ratios were used at Rulo and St. Joseph because there was little difference in the seasonal ratios.

Table 3-2. Conversion Percentages of Maximum Daily Means to Instantaneous Peak Flows

Station	Season, Percent (%)		
	All	**Jan–Apr**	**May–Dec**
Yankton, SD	3.6	3.9	2.9
Sioux City, IA	3.3	3.7	2.2
Omaha, NE	3.8	4.1	3.6
Nebraska City, NE	4.1	4.3	4.0
Rulo, NE	5.6	5.6	5.6
St. Joseph, MO	3.6	3.6	3.6
Kansas City, MO	3.4	N/A	N/A
Waverly, MO	3.2	N/A	N/A
Boonville, MO	2.1	N/A	N/A
Hermann, MO	2.3	N/A	N/A

3.5 Data Analysis Procedure and Smoothing Adjustments

Simulated data from the Missouri River Mainstem HEC-ResSim model (USACE, 2018) was used to derive daily unregulated flows, or the no regulation, no development flows of the 1930-2019 systematic period of record as summarized in Section 3.2. Annual peak flows or seasonal annual peak flows were pulled from the daily time series, converted to instantaneous peak flows using factors from Section 3.4, then were utilized for Bulletin 17C flow frequency analysis. Previous modeling for the 2003 UMRSFFS developed a similar dataset from 1898 to 1997. Stage data, approximate historic rating curves and model routings were used in the 2003 UMRSFFS to estimate flows of the pre-USGS period of 1898–1928, with USGS data becoming more widespread by 1929. Records of the largest floods of 1898–1929 from the 2003 UMRSFFS were used in this study as part of the historical period in conjunction with other estimates of these and earlier floods after conducting flow frequency sensitivity analysis. Results from this sensitivity analysis, including use of the 1898-1929 data as systematic records, are documented in several of the individual gage narratives and in Appendix D. Unregulated flow frequency analyses at Gavins Point, Sioux City, Omaha, and Nebraska City were performed by Omaha District staff, while the analyses at Rulo, St. Joseph, Kansas City, Waverly, Boonville, and Hermann were performed by Kansas City District staff.

Computations were performed using the Bulletin 17C methods within the Hydrologic Engineering Center – Statistical Software Package (HEC-SSP), version 2.3 beta 5, as updated on April 27, 2023, to output expected probability for smoothed statistics. Mixed population computations were carried out within the mixed population analysis tool in HEC-

SSP for six gages upstream of the Kansas River. While computed probabilities are also reported, expected probability adjustments were used for both the single season and mixed population Bulletin 17C analysis. The expected probability adjustment fits the flow frequency curve through the mean of each quantile rather than the median. The mixed population combined expected probability flow frequency curves were computed by means of the combined probability equation PI=P(A)+P(B)-P(A)*P(B) with confidence intervals computed by means of order statistics using 90 equivalent years of record within HEC-SSP. Unregulated flow frequency confidence limits using Bulletin 17C methods of the four single season gages and for each season of the mixed population gages are shown in the report, which were slightly wider than the ordered statistics. However, the unregulated flow confidence limits had limited application in the computation of regulated flow frequencies and confidence limits. Historical floods and perception thresholds to represent time periods between floods were used in accordance with Bulletin 17C guidance. After performing analysis for all gages, the skew, mean, and standard deviation of logs were plotted against river mile, mile zero being at St. Louis, with addition plots for skew by mean and drainage area to inform the reasonableness of the results throughout the lower Missouri River.

Often the statistics of mean, standard deviation, and skew can vary with several factors such as tributary inputs, river slope, valley storage, and backwater from major confluences. The largest drainage area increases occur as follows: Yankton to Sioux City due to the James and Big Sioux Rivers, Omaha to Nebraska City due to the Platte River, St. Joseph to Kansas City due to the Kansas River, Waverly to Boonville due to the Grand River, and Boonville to Hermann due to the Osage and Gasconade Rivers. Other smaller but still significant tributaries and local drainage areas enter the Missouri River throughout its length. Although local variations are present, average slopes tend to also be uniform, decreasing only slightly from about a foot per mile in the upstream end of the study reach to just above 0.8 feet per mile downstream. Backwater from the Mississippi River does not impact Hermann 97.9 miles above the mouth. Valley width decreases below St. Joseph except near Waverly and the mouth of the Grand and Chariton Rivers (see Section 2). Flood history information shows these wider floodplain areas can result in attenuation. As all gages except Yankton, which is just downstream of Gavins Point Dam, are located along the federal navigation channel, velocities tend to be uniform throughout the reach. Contrary to expectations, while low velocity areas have been reduced, maximum point velocities prior to the navigation project were higher than current velocities, whereas mean velocities are similar between periods, indicating more variability historically (Blevins, 2006).

The statistics were separated into the early and late spring season for the six gages from Gavins Point to St. Joseph but are annual or single season for the four gages from Kansas City to Hermann. Sensitivity to the pre-systematic or historical period was conducted at several gages. For the early spring period, a historic period back to the earliest flood with a previously documented historic peak flow at each gage, being the 1875 flood for Omaha, the 1881 flood for Sioux City and Nebraska City, and to the 1908 flood for Gavins Point was computed for the Omaha District gages. In contrast, for Kansas City District gages, the earliest documented flood was in June 1844, with more recent estimates of earlier floods of April 1826 and April 1843 from USACE 2021, Kansas City Levees. Next, effort was made to use a consistent historic period at all ten gages. Historic peaks for gages with less information, namely Gavins Point, Sioux City, Nebraska City, Rulo and Waverly, were estimated for known flood years by scaling flows from upstream and downstream gages by drainage area. A consistent historic period of 1843/1844 to 1929 was adopted for the early spring season and annual gages as it could reasonably be obtained for all ten gages. As 1844 was decreasing in discharge with drainage area, and no reliable information was located for its magnitude upstream of Rulo, upstream gages used a late spring or May-Dec historic period back to 1878 at Nebraska City, and 1872 for Omaha and upstream corresponding to the start of stage records. Longer early spring or annual historic periods were computed as sensitivity analysis back to earliest settlement of the five gages with the most detailed flood history between 1816-1820 at Omaha, St. Joseph, Kansas City, Boonville, and Hermann, with the latter two also computed for a period back to 1699. These results were used to inform the reasonableness of the statistics. Consideration of historical flood information was generally found to reduce computed flow frequencies as compared to the 1930 to 2019 systematic period as detailed in Section 3.

Trends with mean plotted as expected for all time periods considered, increasing with drainage area and river mile, with significantly lower mean values for the mixed population gages for early spring than in late spring and summer, which tends to have more consistent flooding due to runoff from mountain snowpack typically peaking in June. Trends for standard deviation show much greater variability in upstream reaches in the early spring period, gradually decreasing with river mile and drainage area, and plotting higher than the four downstream single season gages. For the late spring and summer period, standard deviation is relatively consistent at just under 0.15 upstream of the Kansas River, plotting lower than the four single season gages downstream. Downstream of the Kansas River, standard deviation increases with drainage area as expected for the much narrower floodplain coupled with a wetter region with lower infiltration rates. As an example, as discussed in Section 2.1, the Osage River has a comparable average annual flow to the Yellowstone River but has much lower mean annual volumes in dry years, and much higher mean annual volume in wet years.

While the standard deviation and mean were deemed reasonable, the skews were smoothed along the streamline using the general frequency editor in HEC-SSP. Smoothing was done to help ensure gages with similar hydrology are producing reasonably consistent results that make physical sense when compared to the flood history. A skew value of 0.2 was adopted for the early spring season (Jan–Apr) of all six mixed population gages, and 0.2 for the late spring season (May–Dec) for the Gavins Point, Sioux City, Omaha, and Nebraska City gages. These were approximately the average or median skews of these stations, and due to the high uncertainty in skew, were rounded to one decimal place. As Kansas City has the most reliable historic peak information, its station skew was retained. For gages downstream of Kansas City, minor smoothing of skew was applied at Boonville to better follow the trend with river mile and drainage area, but within range of what was found for the extended historic period. Station skew was retained at Hermann, which has very good flood history information, especially when supplemented with Mississippi River history, with a value just above zero. Longer historic periods show the potential for negative skews at Hermann; however, for both historic periods back to 1844 and to early settlement in 1816, the skew is very close to neutral at 0.014 or -0.026. Therefore, the station skew of 0.014 was retained for the consistent historic period with upstream gages. No smoothing was applied for Waverly, as it followed the trend with river mile and drainage area.

The reach from Nebraska City to Waverly represents the transition between gages which exhibit a mixed population or single population curve. Below the Kansas River, the four largest events of 1844, 1903, 1951, and 1993 all peaked in June or July coincident with rainfall in the lower basin with large flows also from the Kansas River, adding also 1986 as an October flood of the Osage River. Station skew for Jan-Apr of Nebraska City and Rulo plotted similar to skew for Kansas City and Waverly, whereas St. Joseph exhibited a lower Jan-April skew, and a similar May-Dec skew as Kansas City and Waverly. Late spring skew at Rulo was identical to the smoothed skew applied for upstream locations. Generally, as distance downstream from the dams increased, and as drainage area increased, skew tended to decrease. This was more pronounced when plotting the early spring season.

Figure 3-4 presents the smoothing of skew by river mile, which was used to inform the smoothing. Figures 3-5 and 3-6 present the mean and standard deviation, which were not smoothed, against river mile. Figure 3-7 plots the skew versus mean, which was also used to inform the smoothing of skew as the mean informs the flow magnitude. Lastly, Figure 3-8 presents the plot of skew versus drainage area. As summarized in Section 3.6, the locations with the best or most reliable historic peak flows are considered Kansas City, followed by Omaha, St. Joseph, Boonville, and Hermann. Through work to use consistent historic peak flood information, overall the statistics plotted well and required minimal smoothing.

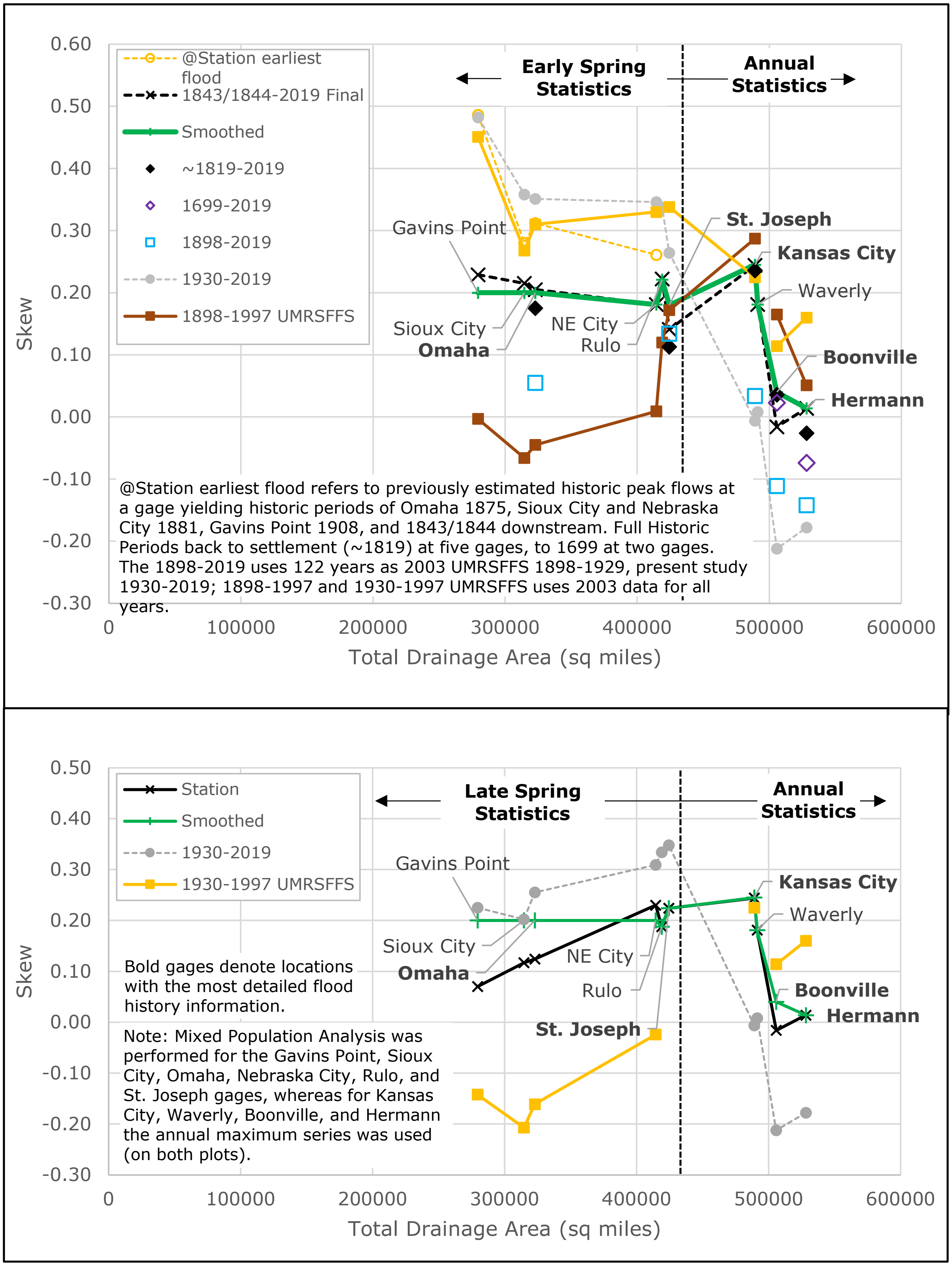


Figure 3-4. Trend for Unreguated Bulletin 17C Skew vs. Drainage Area

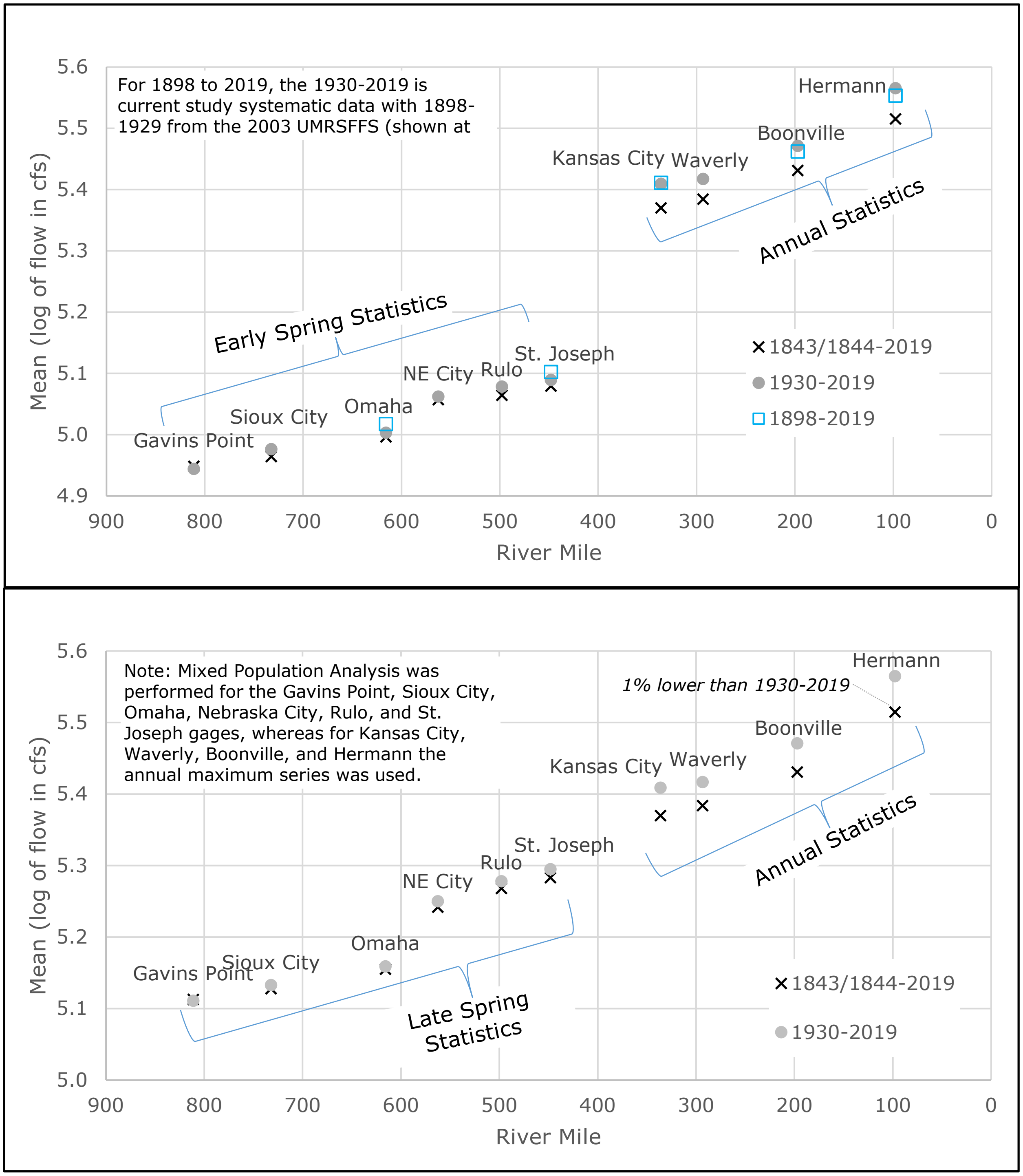


Figure 3-5. Trend for Unregulated Bulletin 17C Mean Log of Flow vs. River Mile

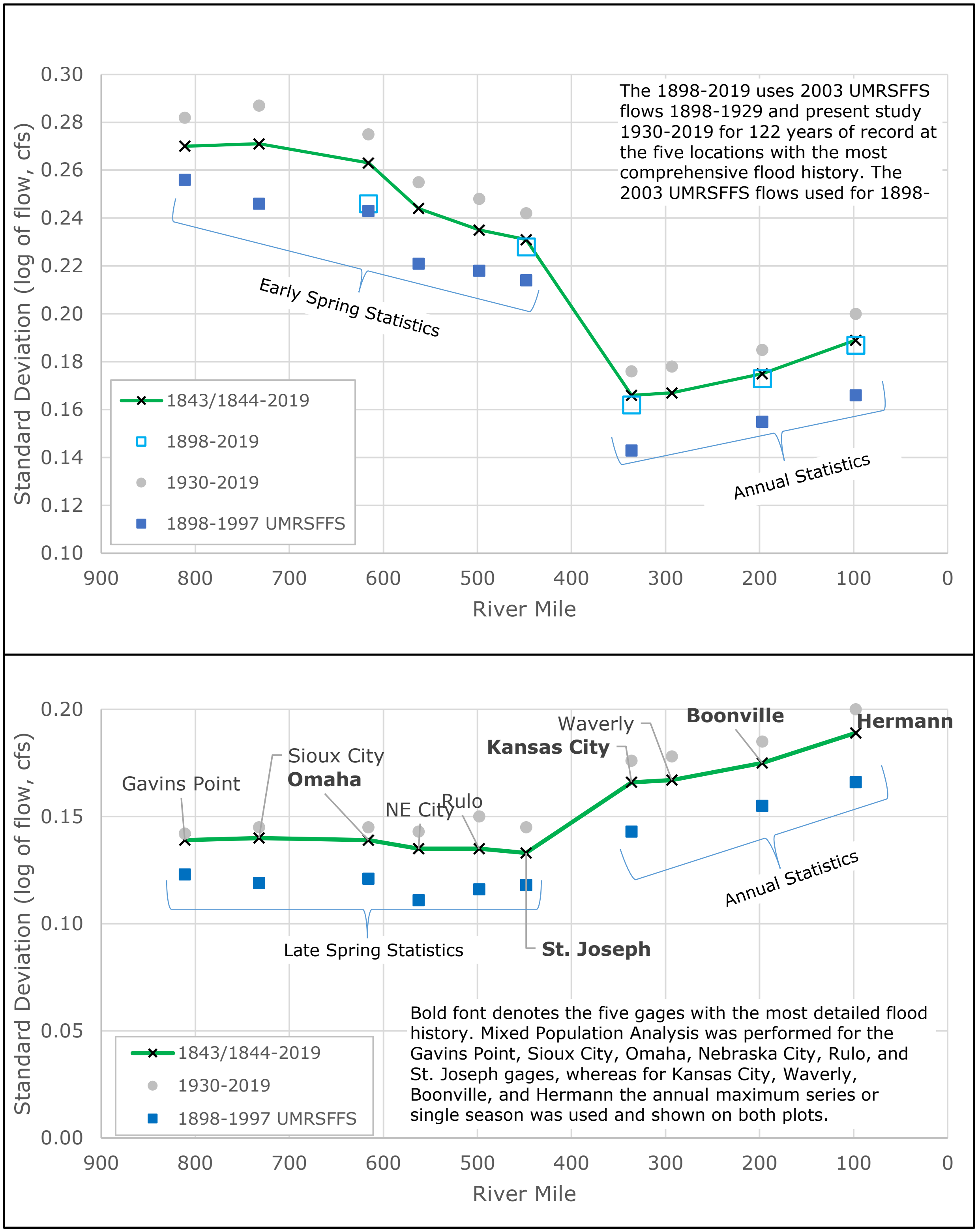


Figure 3-6. Trend for Unregulated Bulletin 17C Standard Deviation vs. River Mile

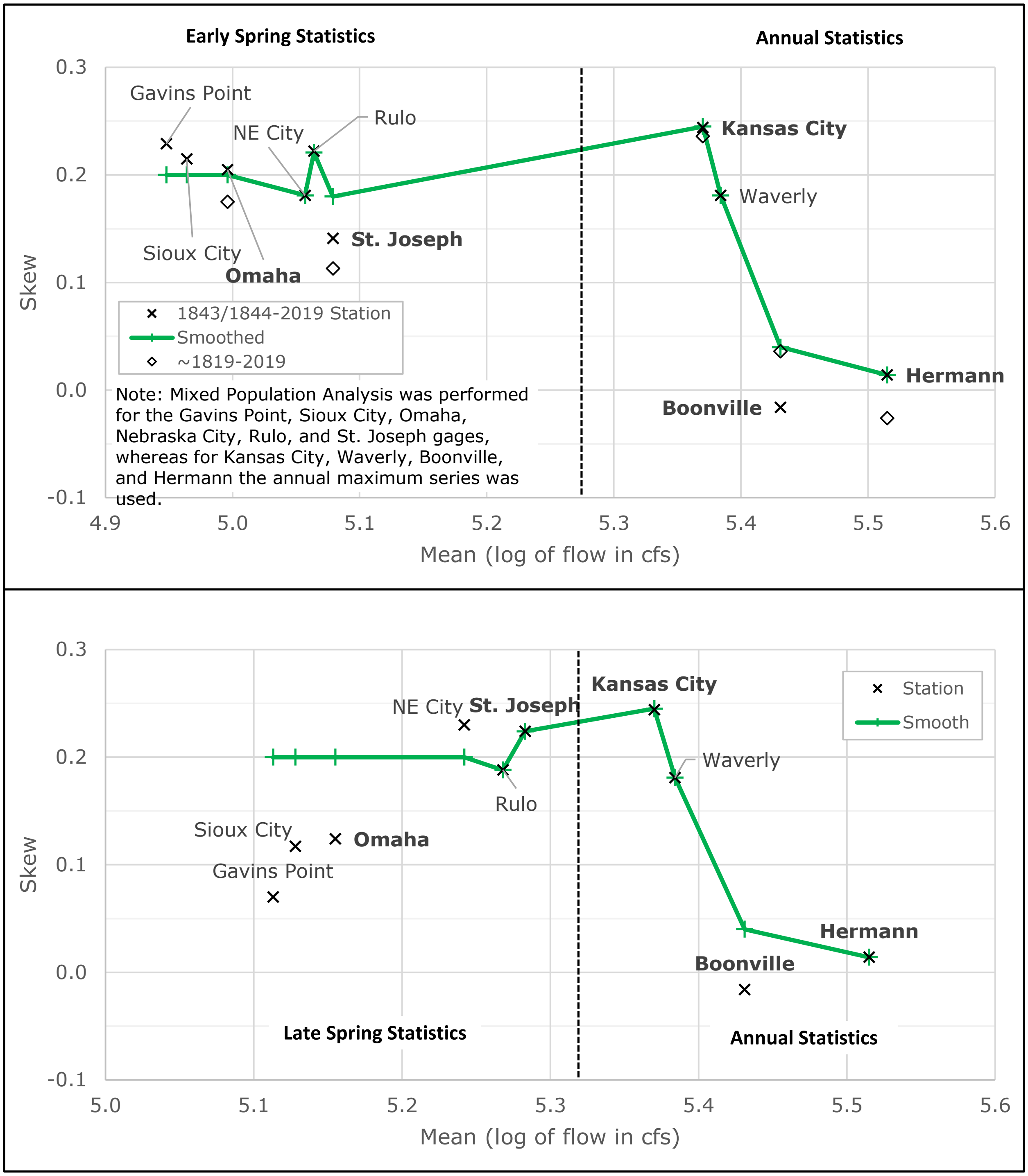


Figure 3-7. Trend for Unregulated Bulletin 17C Skew vs. Mean Log of Flow

Figure 3-8. Trend for Unregulated Bulletin 17C Skew vs. River Mile

Values from the expected probability unregulated Bulletin 17C analysis and mixed population analysis are presented in Table 3-3 for a consistent flood history back to 1843/1844 with minor smoothing of skew. After extending all gages to cover a consistent period as feasible at each location, crossing of frequencies was minimized through the 0.1% AEP. Routings account for flows which enter the wide floodplain below Sioux City to Omaha, which does not have major levees, and below the Platte River between Nebraska City and St Joseph, which has levees on both banks, many of which overtop during large floods such as 1993, 2011, and 2019. Historically, flows exceeding 300,000 cfs at Nebraska City and several of the largest flows at Rulo have peaked higher than at St. Joseph to include 1881, 1952, and 2019. Similarly, Yankton and Sioux City can produce higher unregulated peaks than Omaha during large floods such as 1952. At a 1% AEP, the analysis shows almost identical unregulated flows from Nebraska City to St. Joseph, where the Nishnabotna River is the largest tributary in the reach at approximately 2800 square miles. The frequency of large floods is driven by the early spring, Jan–April period for the mixed population gages upstream of Kansas City, which all share a record unregulated flood from 1952 which produced similar peaks throughout the reach.

Table 3-3. Summary of Unregulated Flow Frequencies and Bulletin 17C Statistics, 1843/1844-1929 Historic Period, 1930-2019 Systematic

	Final Unregulated Bulletin 17C flows expected - history back to 1843/1844 - smoothed skew statistics									
AEP (%)	Gavins	Sioux C.	Omaha	NE City	Rulo	St. Joseph	KC	Waverly	Boon	Hermann
0.1	836,000	876,000	881,000	868,000	846,000	828,000	947,000	957,000	1,030,000	1,380,000
0.2	686,000	719,000	727,000	730,000	715,000	707,000	835,000	848,000	924,000	1,230,000
0.4	565,000	591,000	602,000	617,000	608,000	607,000	738,000	751,000	827,000	1,090,000
0.5	531,000	555,000	567,000	584,000	578,000	578,000	709,000	723,000	798,000	1,050,000
1	438,000	458,000	471,000	497,000	497,000	500,000	624,000	639,000	711,000	928,000
2	362,000	378,000	391,000	424,000	429,000	435,000	547,000	562,000	630,000	816,000
4	301,000	313,000	327,000	364,000	372,000	379,000	476,000	490,000	553,000	710,000
5	283,000	295,000	309,000	346,000	356,000	362,000	454,000	468,000	528,000	676,000
10	236,000	246,000	258,000	296,000	307,000	314,000	387,000	401,000	454,000	575,000
20	196,000	203,000	215,000	251,000	262,000	268,000	322,000	334,000	379,000	473,000
50	144,000	150,000	159,000	189,000	198,000	205,000	231,000	239,000	269,000	327,000
80	110,000	114,000	121,000	147,000	154,000	160,000	169,000	174,000	191,000	226,000
90	96,200	99,500	106,000	129,000	136,000	141,000	145,000	148,000	160,000	186,000
95	86,400	89,300	95,500	117,000	123,000	128,000	128,000	130,000	138,000	158,000
99	70,900	73,200	78,600	96,600	101,000	107,000	100,000	101,000	103,000	114,600
Mean (Jan-Apr; Annual)	4.948	4.964	4.996	5.057	5.064	5.079	5.37	5.384	5.431	5.515
St Dev (Jan-Apr; Annual)	0.27	0.271	0.263	0.244	0.235	0.231	0.166	0.167	0.175	0.189
Skew (Jan-Apr; Annual)	0.229	0.215	0.205	0.181	0.222	0.141	0.244	0.181	-0.016	0.014
Adop Skew (Jan-Apr/annual)	0.2	0.2	0.2			0.18			0.04	
Historic Period	176	176	177	177	177	177	176	176	176	176
Equiv yrs Record	114.759	114.596	115.363	116.132	115.229	115.466	119.761	118.766	121.191	121.477
Mean (May-Dec)	5.113	5.128	5.155	5.242	5.268	5.283				
St Dev (May-Dec)	0.139	0.14	0.139	0.135	0.135	0.133				
Skew (May-Dec)	0.07	0.117	0.124	0.23	0.188	0.224				
Skew adopt (May-Dec)	0.2	0.2	0.2	0.2						
Historic Period	148	148	148	142	176	176				
Equiv yrs Record	104.355	103.594	104.521	102.43	117.829	117.358				
Drainage area	279,480	314,617	322,820	414,420	418,905	424,340	489,162	491,230	505,710	528,200

Figure 3-9 presents a plot showing the computed probability unregulated flow frequency results for the annual series at Kanas City, Waverly, Boonville, and Hermann, MO, compared to the early spring and late spring curves for the unsmoothed analysis. For the late spring period, the computed curves remain parallel up and down the river using either a station skew or a smoothed skew, however, the smoothed result was viewed as an improvement regionally and was therefore adopted. For the unsmoothed analysis of the early spring period, computed curves begin to cross by more than 1,000 cfs near the 10% AEP in the Nebraska City to St. Joseph reach. However, the unsmoothed computed mixed population curves do not cross until a 1% AEP in the same reach, with almost identical flows from Nebraska City to St. Joseph. In the Kansas City to Boonville reach, computed curves at Kansas City begin crossing Waverly at the 0.02% (1/5,000) AEP, with 1% higher flows at Kansas City at a 0.01% (1/10,000) AEP. This result between Kansas City and Waverly considered reasonable based on the minor increases in drainage area and differences in floodplain geometry between the two sites. Additionally, a few upstream gages begin to cross Boonville near a 0.02% (1/5,000) AEP.

By smoothing Boonville to a skew of 0.04, similar to the skew determined for the period of 1816 to 2019 at Boonville, computed flow frequency at upstream gages no longer crosses Boonville through the 0.01% (1/10,000) AEP. In the upstream reach, crossing profiles of the early spring period are only minimally improved by smoothing the skew, initially investigated by using 0.2 for all gages from Yankton to St. Joseph. However, this made Nebraska City cross Rulo more often than with no smoothing. Crossing of the computed early spring flow frequencies was determined to be minimized by applying a skew of 0.2 for Gavins Point to Omaha, retaining the station skew of 0.181 for Nebraska City and 0.221 for Rulo, and smoothing St. Joseph up slightly to 0.141 to 0.18. A skew of 0.18 is viewed as reasonable for St. Joseph compared to analysis of other time periods and datasets. With this smoothing applied, Rulo crosses St. Joseph by about 2% at the 0.2% AEP, and Sioux City and Omaha cross their downstream gages by 1% at that frequency. At the 0.01% (1/10,000) AEP computed probabilities, Sioux City crosses Omaha by 2%, Omaha crosses Nebraska City by 5%, and Rulo crosses St. Joseph by 6%, with Rulo and Kansas City crossing the next gage downstream by 1%. Additionally, Sioux City would no longer cross Boonville, and does not cross Kansas City until a 0.01% AEP, now by only 3%. Figure 3-10 presents a plot showing the computed probability curves for the early spring period and late spring period along with the annual series gages downstream of the Kansas River for the smoothed results.

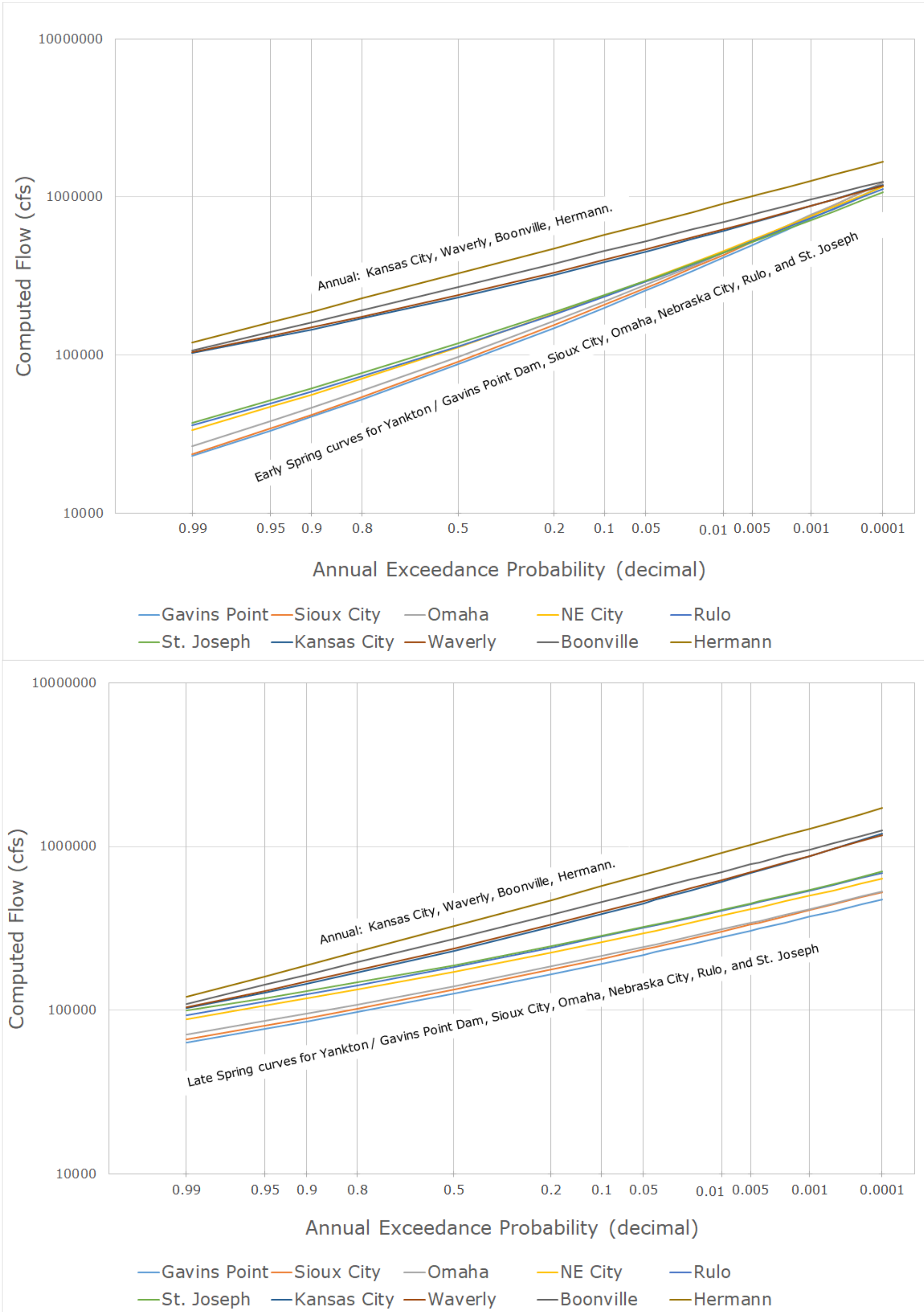


Figure 3-9. Computed Bulletin 17C Unregulated Flow Frequency Curves, Early Spring (Jan–Apr) and Late Spring (May–Dec), No Smoothing

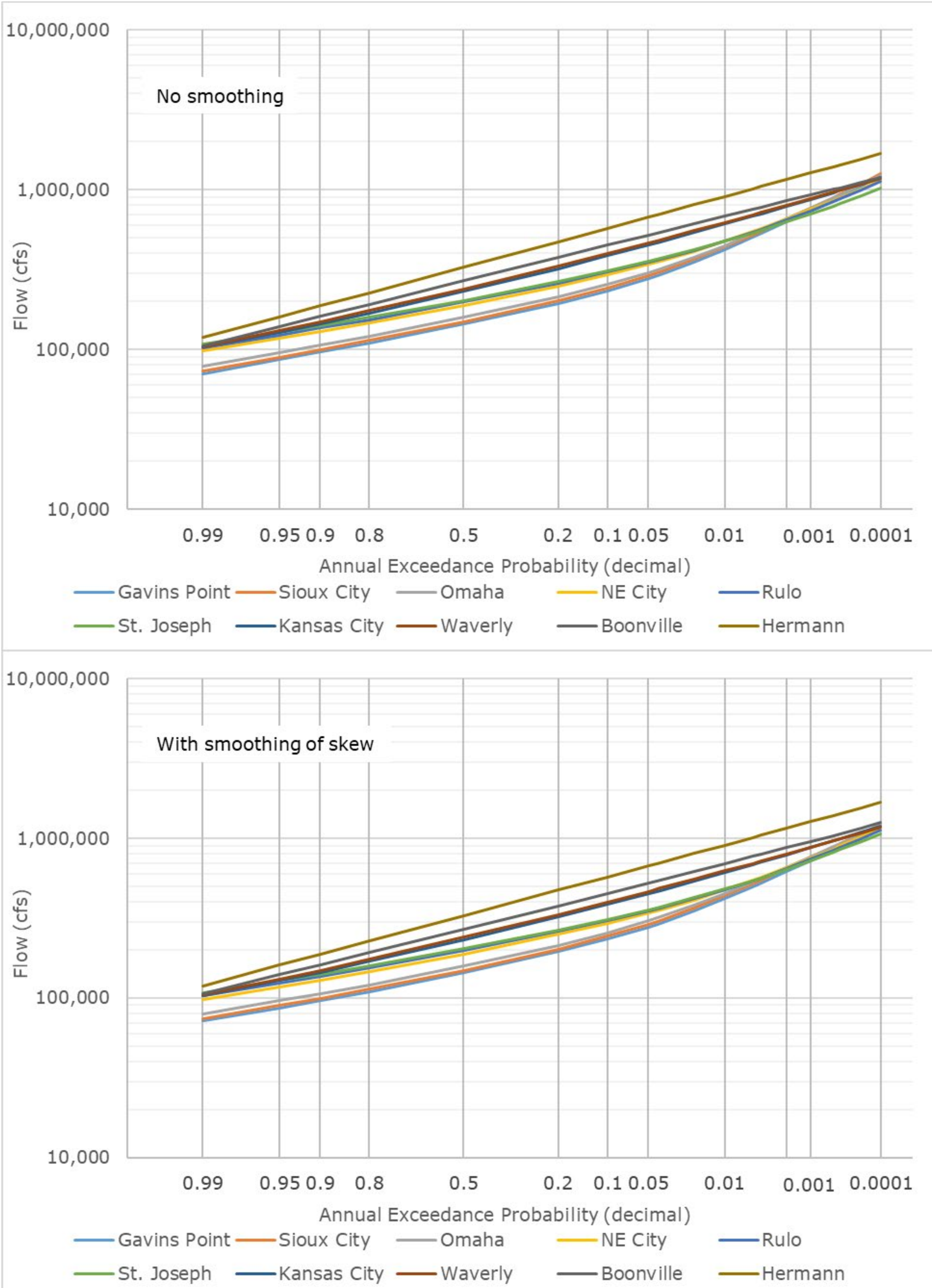


Figure 3-10. Unsmoothed and Smoothed Computed Bulletin 17C Unregulated Flow Frequency Curves, Combined Mixed and Annual

Figure 3-11 presents a plot showing the early spring period for the six upstream gages and annual period for the four downstream gages with the expected probability, with and without adjustment. The analysis shows flows converging to near identical values upstream of Kansas City, likely a function of drainage area for such a large basin. Therefore, considering some crossing is expected due to floodplain attenuation, the results were considered reasonable for application in determining the regulated flow frequencies. Should results be required beyond the 0.2% AEP, additional analysis of the expected probability adjustment may be warranted, such as considering other distributions, whereas computed probabilities are assumed reasonable.

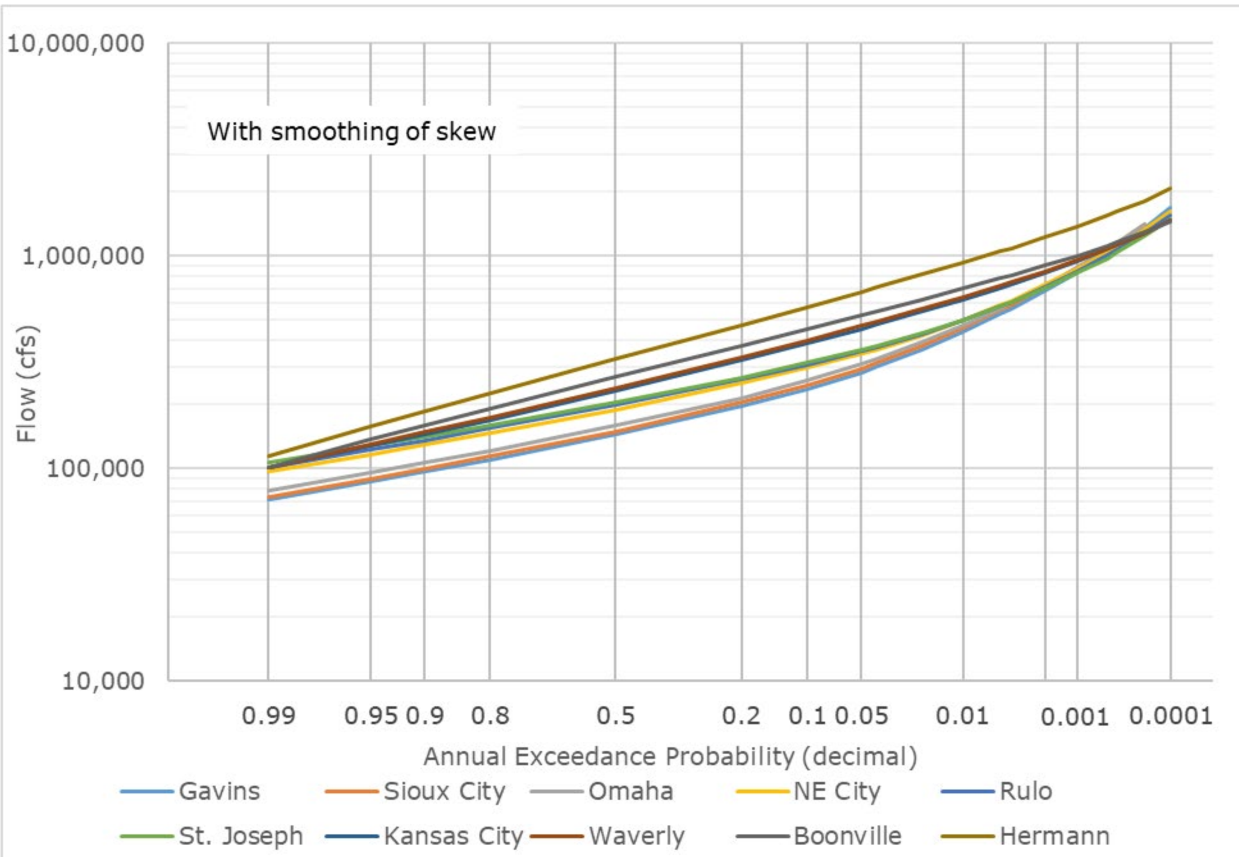


Figure 3-11. Final Expected Bulletin 17C Unregulated Flow Frequency Curves, Combined Mixed and Annual

3.5.1 Comparison of Regional Smoothing, Current vs 2003 Study

In the 2003 UMRFSS, smoothing was done regionally in three groups, gages upstream of the Platte River, between the Platte and Kansas Rivers, and downstream of the Kansas River. This was performed to obtain regionally consistent frequency curves at each gage, however, the study acknowledged that little guidance on how to regionalize statistics for mixed population analysis exists, which is still true for the current analysis. Upstream of the

Platte River, the 2003 UMRSFFS Jan–Apr station skews ranged from -0.085 at Sioux City to -0.003 at Yankton, adopting a regional average of -0.05. For the reach between the Platte and Kanas Rivers, Jan–Apr skew increased with drainage area from 0.008 at Nebraska City to 0.172 at St. Joseph, MO, adopting a smoothed skew of 0.077 in the 2003 UMRSFFS. Also for the 2003 UMRSFFS, for the May–Dec period, a smoothed skew of -0.427 and -0.09 was adopted for gages upstream of the Platte River and between the Platte and Kansas Rivers, which had ranges of -0.476 at Sioux City to -0.345 at Omaha, and -0.183 at Nebraska City to 0.032 at St. Joseph, respectively. Downstream of the Kansas River, a regional skew of 0.17 was adopted for all annual frequency gages in the 2003 UMRSFFS. While the station skews were not included in the 2003 UMRSFFS report, Appendix E, the annual peak data was used to recompute the analysis using Bulletin 17B, yielding a station skew of 0.287 at Kansas City, 0.165 at Boonville, and 0.04 at Hermann for the 1898 to 1997 period.

Current study results show significant increases in skew upstream of the Kansas River at all gages except St. Joseph, which had a skew of 0.172 for the 1898-1997 period in the 2003 UMRSFSS. Sensitivity analysis at St. Joseph showed that Jan–Apr station skews of 0.134 and 0.264 for the 1898 to 2019 and 1930 to 2019 periods, respectively, with a station skew of 0.136 for the final analysis which used a historic period back to 1843. Smoothing of skews was done minimally in this study, adopting an early spring value of 0.20 upstream of the Platte River, similar to the value obtained at Omaha using a historic period back to 1819 and also to 1843. Upstream of Rulo, late spring skew was smoothed to 0.2 for all four gages. In the reach between the Platte to Kansas Rivers, a minimum early spring skew of 0.18 was adopted, similar to the St. Joseph station skew of the 2003 UMRSFFS, and nearly identical to the station skew at Nebraska City, thus leaving Rulo at 0.222. Downstream of the Kansas River, the skew was allowed to decrease with drainage area as shown in the statistics of both studies, only smoothing up the skew of Boonville slightly to 0.04, which is closer to the value for a historic period back to 1816.

3.6 Historical Peak Flow Data Summary

Previously published historic peak flow values from historic reports and those published on the USGS website, often derived from past USACE studies, were compiled for use in Bulletin 17C flow frequency analysis. Key documents included the 1962 Agricultural Levee Restudy Report (USACE, 1962), the 1947 Missouri River Levee System Definite Project Report and associated 1946 hydrology appendices (USACE 1947), the Missouri River "308 Report (USACE 1932/1935), and the Kansas City Levees, Supplemental Hydrologic and Hydraulic Analysis and Levee Height Report (USACE 2021). However, this information had very limited information included for the Rulo and Waverly gages and presented uncertainties with historic peak estimates that varied over time. Additional investigation using the 2003 UMRSFSS information, additional flood history research adapted from the Kansas City Levees Report, and available high-water marks and stage data was conducted and incorporated to determine uncertainty with previous estimates and to recommend best estimates. While more detailed information was compiled for the Hermann, MO, Boonville, MO, Kansas City, MO, St. Joseph, MO, and Omaha, NE gages, the overall impact of expanding the flood history period, altering the values of historical flood estimates, or expressing the floods as point values as opposed to ranges was deemed very minor in changing the results.

A summary of efforts to verify the reasonableness of historic peak flows is provided in the following section, with more specific information on the inputs and sensitivity analysis for the five gages with more detailed flood history in the individual gage sections. As previously discussed in Section 3.5, the final statistics were plotted longitudinally along the river, and the results were carefully considered to verify consistency. As seen in Section 2.2, all major dams in the Missouri River Basin became operational after 1930. Smaller dams constructed earlier are assumed to have a negligible impact on the Missouri River peak flood flows. In terms of basin development and associated depletions, for the earliest floods there was very limited agriculture at that time, whereas the 2003 UMRSFSS data with and without depletions was reviewed for the period of 1898 to 1929. Additionally, as discussed in Section 2.7, no basis to adjust historical flood peaks due to land use changes was identified. Therefore, since the unregulated flows are no dams and no depletions, no adjustment of the historic peak flows was warranted. However, uncertainty of the estimates due to uncertainty with historic flood stages, ratings curves, or runoff under current conditions was incorporated into the analysis at select gages to determine the potential impact on the computations, which was minor. Appendix A presents all final perception thresholds and historic peak flows used in the analysis and the basis of the flow estimates.

3.6.1 Historic Peak Flow Data Summary

The most reliable historic peak records are derived from stage data prior to systematic USGS gaging that initiated in the 1920’s using estimated rating curves specific for that point in time. Rating curves have been dynamic over time due to the naturally dynamic nature of the Missouri, often shifting and changing course and length, floodplain sediment deposits during large floods, combined with human development. Examples of human induced changes impacting the rating curves include the clearing of the largely forested floodplain for development, construction of bridges, the navigation channel or BSNP, and federal and locally built levees, and bed dynamics in response to degradation below Gavins Point Dam and sand and gravel mining. Table 3-4 shows the available dates of stage and flow records, where the earliest records were collected by the Missouri River Commission (MRC), followed by the Weather Bureau (WB) now known as the National Weather Service (NWS). As the War Department (USACE) was often involved in construction of early bridges along the Missouri River, historical documents were reviewed and plates located that show daily stages that extend records back in time prior to the MRC data at two locations, Rulo, NE and Kansas City, MO. Data gaps in the early 1900’s at study gages of Waverly, Rulo, and

Nebraska City were filled in using routings derived from upstream and downstream stage records with and without depletions for periods of missing stage records in the 2003 UMRSFFS study, creating a continuous flow dataset from 1898 to 1997. The general method to fill in flow records in the 2003 UMRSFFS study involved routing flows from the Missouri River and gaged tributaries from the gage upstream to the gage downstream and apportioning incremental ungaged flows by drainage area. Prior to the 2003 study, the 1962 Missouri River Hydrology Study also used a period of record initiating in 1898. Generally, the quality of stage records increases with time as gages were standardized by the Missouri River Commission and future gage operators. Use of historic peak stage information from these gages requires extremely careful review of datum shifts as elevations of the St. Louis Directrix were updated over time, as gages moved locations, or were upgraded. For MRC gages, the water year in which records began is listed.

Table 3-4. Missouri River Main Stem Gaging Stations, Data Sources and Periods of Record

Gage	River Mile (1960)	Drainage Area (sq miles)	MRC Stages	NWS Stages	USGS Flows	2003 UMRSFFS Routing Fill
Yankton	805.8	279,480		1921–date	1930–1995*	1898-1920
Sioux City	732.3	314,620	1878–1899	1900–1928	1929–date*	
Omaha	615.9	322,820	1872–1899	1900–1928	1929–date	
Nebraska City	562.6	414,420	1878–1899		1929–date	1900–1928
Rulo*	498.0	418,910	1886–1899	1929–1949*	1949–date	1900–1928
St. Joseph*	448.2	424,340	1872–1899	1900–1929	1929–date	
Kansas City*	366.1	489,160	1873–1899	1900–1929	1929–date	
Waverly	293.4	491,230	1883–1899	1915–1928	1928–date*	1900–1914
Boonville	197.1	505,710	1874–1899	1900–1925	1925–date	
Hermann	97.9	528,200	1873–1899	1900–1928	1928–date	
St. Charles	28.2	529,350	1878–1899	1917–date	2000–date	1900–1916

*Additional stage records are available from plates in bridge documents as in Chanute 1870 for Kansas City (2.5 years from 1867 to June 1869), and Rulo 1890 Report (1884–1887 stages) which contain references to earlier flood elevations of 1844 and 1858 for Kanas City and 1881 for Rulo. The Rulo stage records from 1929–1949 were by USACE rather than by the NWS; Gavins Point Dam outflows are available from USACE water management databases for Yankton. USACE 1946, Levee DPR states "Records prior to 1893 are unreliable" at St. Joseph, however both this document and USACE 1962 provide estimates of some floods from this period. Data gaps for Sioux City of 30 Sep 1931 to 01 Oct 1938, and Waverly from 01 Apr 1977 to 01 Apr 1978 were filled by routing. Waverly has one additional year of MRC stage records available, August 1878 to August 1879.

Other gages referenced for historical records had MRC stage data starting in the following water years: Vermillion, SD in 1879, Plattsmouth, NE in 1873, White Cloud, KS in 1881, Fort Leavenworth, KS in 1872, Lexington, MO in 1873, Glasgow, MO in 1878, and Jefferson City, MO in 1878.

Additional historic peak flow estimates are available in historic documents, the results of many of these estimates are published on the USGS website. However, the literature review revealed many of the historic peak flow estimates were revised over time usually with limited documentation on the reason for revision. Reasonableness of historic peak estimates were checked in this study against the 2003 UMRSFFS flow data paired with the historic stages and available flow measurement data, placing emphasis on measurement prior to BSNP construction at each location. Available flood history information for the Missouri River, major tributaries below Yankton, SD, and the Mississippi River in the reach between the Missouri and Ohio Rivers with emphasis on the St. Louis, Missouri gage location was also investigated as feasible at this time. As historic newspapers are digitized, additional flood history information could become available over time. A summary of the pertinent flood history is provided below in the context of the ability to detect floods, with additional details for the major floods included in Section 2.5.

From Kansas City to the mouth permanent settlements with flood history records were located back to approximately 1816 when the population in the floodplain began to increase especially with the establishment of Franklin, MO, adjacent to the Boonville gage. Additionally, more limited information is available dating back to the 1700's. The first permanent European settlement on the Missouri River is considered St. Charles, Missouri, which has been continuously occupied since 1769. However, development in St. Charles was found to be "above the overflow of the Missouri", creating limited records detecting large floods at that location prior to the 1844 flood. Upstream of Kansas City development lagged, however the Omaha area provides some flood history information dating back to 1810 or 1812, with better information starting in 1819 tied to US Military facilities. Flood history information in the Middle Mississippi River was considered back to 1699 when Cahokia was established, followed by Kaskaskia in 1703 and St. Genevieve, MO around 1735, which was relocated after the 1785 flood. The first documented flood damages were at Kaskaskia in 1724 when an overflow forced residents to the bluffs. However, the French Fort Orleans was present in the floodplain between the Waverly gage and Grand River at the time and major flooding was not documented in Bourgmont's journal. The relative magnitude of the 1785 flood compared to 1844 in the Mississippi River between the Missouri and Ohio Rivers is debated in literature. Best information indicates that a large flood was documented in April 1785, with a height ranging from nearly one foot above to a few feet below 1844 in the vicinity of St. Louis. It was also believed to be a few feet below 1844 in St. Genevieve, MO.

The first flood with documented damages on the Missouri River is a moderate flood in the vicinity of Omaha in 1820, which damaged US Army facilities at Fort Atkinson and motivated relocation to higher ground. Widespread flooding was documented again in late April 1826 as documented in Section 2.5.4 including flooding of some US Army facilities at Fort Atkinson, the Chouteau trading post in Kansas City, and damage at St. Louis, with Franklin, MO escaping with little damage near Boonville. From this information, reasonably reliable estimates of the height of 1826 have been made at Kansas City, Boonville, and St. Louis. The 1785 flood was communicated to early settlers in the Missouri River floodplain as being bigger than 1826 by the French and Native Americans. Between 1785 to 1826, the largest known flood is in 1811, which was believed similar to 1826 in St. Louis, and was documented as an overflow upstream of the Kansas River by Bradbury and Brackenridge in July, with no major overflow documented in Boonslick, vicinity of Boonville, as of July 1811. However, no information could be located to reasonably estimate its height in relation to other floods. Table 3-5 presents a summary of historical flood detection information.

Table 3-5. Summary of Locations with Historical Flood Information Prior to Stage Records

Omaha / Council Bluffs (Big Sioux to Platte River)	St. Joseph (Platte to Kansas River)	Kansas City (Kansas to Grand River)	Boonville (Grand to Osage River)	Hermann (Osage River to the mouth)
▪ 1810–1812 Fort Manuel Lisa #1 (or Fort Mandan; upstream near Bismarck, ND); Bradberry, Brackenridge 1811 Journals ▪ 1812–1823 Fort Lisa #2 by Omaha	▪ 1744–1764 Fort de Cavagnial (France, in bluffs, for trade with Kansa Tribe, also on bluffs), possible rise in 1750's (Chappell 1908), no estimates located	▪ 1723–1726 or 1728 Fort Orleans (France); floodplain near Missouria Tribe (bluffs), Bourgmont journal ▪ ~1792**–1844 or 1846** Kansa Tribe live on Kansas River floodplain terraces	▪ ~1803 or 1808 Boonslick and Cote Sans Dessein begin settlement	▪ **<u>1699</u>** – first settlement below Missouri River mouth in Caholkia, IL; 1703 Kaskaskia (1724 flood damages) ▪ 1735–1785*, 1785–present St. Genevieve MO
▪ **<u>1819</u>**–1820*, 1820–1827** Fort Atkinson (USA) ▪ 1822 Bellevue NE ▪ 1824 F. Guittar settlement at Council Bluffs ▪ 1837 Potawatomi Tribe arrival, mission 1838 ▪ 1842–1843 Fort Croghan (USA)* ▪ 1846–1852 Morman settlement ▪ 1854 Omaha NE established	▪ 1826 Black Snake Hills (Joseph Robidoux), later became St. Joseph (bluffs) ▪ 1827 Fort Leavenworth KS in bluffs (USA) ▪ 1828 Platte County, MO est. ▪ 1841 Holt County, MO est. ▪ 1843 St. Joseph MO established ▪ 1847 Fremont County, IA est. ▪ 1856 Elwood, KS est.	▪ 1808–1827 Fort Osage (USA, bluffs), Sibley journals ▪ **<u>1819</u>**–1826, Chouteau #1* ▪ 1822 Lexington MO ▪ 1827 Independence ▪ 1828–1844, Chouteau #2* ▪ 1831 Westport MO and Westport steamboat landing (Town of Kansas 1838, became Kansas City MO) ▪ 1831–1844 Grinter Ferry original on Kansas River*	▪ **<u>1816</u>**–1827 Franklin, MO* ▪ 1827–present New Franklin ▪ 1817 Boonville established ▪ 1836 Glasgow established ▪ ~1827–1844*, 1844–1855 Jotham Meeker at Ottawa Mission, upper Osage River	▪ 1769 St. Charles, MO first European settlement on Missouri R (bluffs) ▪ Floodplain settlement (farmers, misc. communities) in early 1800's; Osage by Warsaw MO ~1820's (1844 USGS hist peaks at Warsaw and Bagnell MO) ▪ Ottawa (Meeker) Mission on Marais des Cygnes in KS 1837–1844* ▪ 1837 Hermann established

*Locations that were relocated or abandoned due to flood damages (or bank erosion damages as at Franklin); **<u>BOLD</u>** denotes dates after which detection of large floods is possible.

**Possibly relocated due to flooding damages in whole or in part, but other factors were also at play; previous floods (e.g. 1785) may have informed the Kansa Tribe on selecting infrequently flooded village sites along the Kansas River.

After conducting a literature review, detailed investigation of the reasonableness of various historic peak flow estimates was conducted for select representative gages of Hermann, Boonville, Kansas City, St. Joseph, MO, and Omaha NE. Rating curves at each gage were established with a "best estimate" historic curve developed largely using previous best estimates of historic peak flows coupled with the earliest USGS flow measurement or peak flow information, targeting data prior to initiating major construction of the Missouri River Bank Stabilization and Navigation Project (BSNP) where feasible. Stage trend reports were used to inform BSNP construction dates along with potamology investigations (see USACE June 2021 and USACE 1980). Dates of levee construction from the National Levee Database were summarized on each graph for the historic peak rating curves along with most recent rating curves and flow measurements. Historic peak flow ranges were also used for the 2003 UMRSFFS data between 1898 and 1929 using published ranges of flows estimated from stage records and routings with and without depletions to estimate ranges as available for Kansas City District gages from 2003 UMRSFFS, Appendix E. Flow ranges were established using ranges of flow measurements for the same event in historic documents, such as 1844 for Hermann.

While less detailed data is available at the Rulo, Waverly, and Gavins Point or Yankton gages than the other gages, effort was made to generate estimates of major historic events such as April 1881 and June 1844 as feasible to make computations at those locations as consistent as possible. This was also done at a lesser extent at Sioux City and Nebraska City to use a consistent historic period as could be generated at the other five study gages. Table 3-6 presents a summary of estimates of historic peak stages, flows and flow ranges used in the flow frequency analysis with emphasis on the Kansas City District gages and Omaha, NE. Additional historic peak estimates for Omaha District gages is summarized in Section 3.7, and for all gages in Appendix A. The information reflects a summary of research efforts to verify data in previously published reports, which often were updated over time, or new estimates developed for older floods with reasonably reliable stage information. Additional information on the incorporation of historic peak floods is included in the individual stream gage sections. When values were needed for historic floods for gages with less record, flows were scaled from upstream and / or downstream gages by drainage area and rounded due to uncertainty. At Rulo and Waverly, these estimates were plotted against available stage records to visually check for reasonableness, whereas Yankton was impacted by a major ice dam in 1881 and was not plotted, as in the sections for each gage.

Table 3-6. Summary of Missouri River Historic Peak Information, 1826–1903

Year	1826	1843	1844	1851	1858	1867	1881	1883	1892	1903
Month	Apr	Apr	Jun	Jun	Jun/Jul		Apr	Jun	May	May/Jun
	Depth below 1844 (feet)									
St. Louis	7.6	unkn	0	4.8	4.3		7.7	6.5	5.3	3.3
Hermann	7-9	>10	0	6-8	6-8		11.6	10.8	10.5	5.8
Boonville	~8	~6-8	0	6-8	8-10		9.4	9.4	9.5	2.2
Waverly			0				6.1	8.5	11.6	5.1
Kansas City	10	6	0	<1858	12.3	15.0	10.2	13.5	13.0	3.0
St. Joseph		~1844/81	0	<1858	~1883	~2.2	-2.7	1.4	5.8	4.0
	Depth below 1881 (feet)									
St. Joseph		~1844/81	*2.7*	<1858	~1883	~4.9	0.0	4.1	8.5	6.7
Rulo		~1844/81	3.2	<1858	~1883		0.0	unkn	4.6	unkn
Omaha	~1843	~0.5-4?	<<1881	unkn	unkn	4	0.0			in bank
	Best estimates of flows (cfs)									
St. Louis	784000	<784000	*1350000*	931000	959000	568000	822000	863000	926000	1020000
Hermann	*550000*	*450000*	800000	595000	595000		390000	420000	430000	676000
Boonville	390000	*428000*	710000	*428000*	*353000*		363000	338000	334000	591000
Waverly			640000				370000	280000		550000
Kansas City	362000	476000	625000	<301000	301000	237000	373000	271000	283000	548000
St. Joseph	*340000*	*360000*	350000	*>200000*	*289000*	290000	370000	306000	232000	268000
Rulo		*360000*	300000		<300000		375000	<300000		
Omaha	*330000*	*360000*	300000		<270000	275000	370000			
	Percent of the flow at location compared to St. Louis, MO (Mississippi River)									
Herm max	*74%*	*64%*	67%	70%	68%	66%	52%	54%	54%	71%
Hermann	*70%*	*57%*	59%	64%	62%		47%	49%	46%	66%
Boonville	50%	*55%*	53%	46%	37%		44%	39%	36%	58%
Kansas City	46%	*61%*	46%	<31%	31%	42%	45%	31%	31%	54%
St. Joseph	43%	*46%*	26%		30%	51%	45%	35%	25%	26%
	Ranges of flows for Bulletin 17C, single value = maximum for location (kcfs)									
Hermann	*500-580*	*400-500*	700-900	550-650	550-650	250-375	320-425	350-470	365-500	573-720
Boonville	340-440	*400-500*	625-795	390-520	315-520		320-400	320-400	320-400	612
Waverly			600-700				340-400			554-600
Kansas City	319-405	*400-500*	575-700		280-350	220-300	320-400	250-300	250-300	548
St. Joseph	*250-370*	*300-450*	*300-380*	*n/a*	*250-300*	240-320	350-425	275-325	n/a	252-348
Rulo		*300-450*	*250-350*				350-400			
Omaha	*250-370*	*300-450*				240-300				
Herm max	580000	500000	900000	650000	650000	375000	425000	470000	500000	720000

Note: Italics denote more uncertainty with a particular estimate compared to other data.

3.6.2 St. Louis, MO (Mississippi River)

While not a study gage, the Mississippi River at St. Louis provides up to a 92% correlation to Missouri River gages as summarized later in this section, coupled with a more extensive flood history. Therefore, some consideration of flows at St. Louis was deemed pertinent to the flood history research as a cap and indication of the reasonableness of historic peak flow estimates. Published peak flow estimates at St. Louis, MO date back to 1862 and follow a generally stable rating curve for flood flows compared to many of the Missouri River sites.

According to USGS Scientific Investigations Report (SIR) 2009-5232, the primary shift in the rating curve correlates to construction of the Alton-Gale Levee System on the Illinois side of the river as completed in the 1960's (Huizinga 2009). Average streamflow increases significantly below Kansas City, adding the Grand, Chariton, and Lamine Rivers above Jefferson City, and the Osage and Gasconade Rivers above Hermann and St. Charles, with the Missouri River contributing an average of approximately 43% of the streamflow of the Mississippi River at St. Louis, Missouri. However, the Missouri River typically produces larger flows than the Upper Mississippi River during extreme floods, despite the relatively drier climate upstream of Kansas City (USACE 2003, UMRSFFS Appendix G).

Drainage area at Kansas City compares to 95% and 70% of the area at Jefferson City and St. Louis, Missouri, respectively, representing much of the flood risk at those locations. Using the 2003 UMRSFFS unregulated peak flows, correlation of the Missouri River sites data to St. Louis from 1898 to 1997 is 92% for Hermann, 84% for Boonville, 72% for Kansas City and 58% for St. Joseph. Therefore, the comparisons of Missouri River flows to Mississippi flows at St. Louis are assumed the most useful for the Missouri River below the Osage River as indicated at Hermann, and to a lesser degree to those flows upstream of the Kansas River. Three historic Mississippi River peaks found pertinent to Missouri River flood history were determined from available high water mark documentation in St. Louis using a historic rating curve developed for this study as presented in Table 3-7.

Table 3-7. Pre-1862 Historic Peak Estimates, Mississippi River at St. Louis, MO

Year	Depth Below 1844	Stage (feet)	Flow* Estimate (cfs)	Stage estimate Source
1826	7.58	33.74	784000	Scharf 1883, St. Louis Directrix (benchmark K3); or gage 0' at Market Street 33.76' below the directrix, Mississippi River Commission 1903. Likely on May 16-17 according to William Clark.
1851	4.75	36.57	931000	Humphries 1867; TP 23 (1954) says 36.6 feet on June 10, 1851.
1858	4.3	37.02	959000	Humphries 1867; TP 23 (1954) says 37.2 feet on June 15, 1858 from high water mark.

*The historic rating curve assumed for these flows is shown in Figure 3-12. TP 23 (1954) also shows 1828 at 36.4', and 1855 at 37.1', unknown dates, and not correlating to major Missouri River floods

Same year peak flows were also compared using the 2003 UMRSFFS data as presented as ratios and correlations to several Missouri River gages in Table 3-7 to indicate how the Missouri River typically compares to Mississippi River flows at St. Louis. These ranges were compared to historic peak flow estimates in Table 3-6 in the preceding section as a check on the reasonableness of the historic peak flow estimates. For example, most Missouri River floods at Hermann, MO are expected to compare to approximately 60–80% of the magnitude for the same year flood at St. Louis, whereas minimum and maximum values should be above 40% and below 90%, respectively, based on the 2003 UMRSFFS data. Values for Hermann peak flow estimates in Table 3-6 compared to 52–74% of the flow at St. Louis, MO, which is within the expected range from Table 3-8.

Table 3-8. Ratio of 2003 UMRSFFS Unregulated Peak Flows and Gage Correlations, 1898–1997, Missouri River Gages vs. Mississippi River at St. Louis

	Hermann	Boonville	Kansas City	St. Joseph
Max	0.94	0.80	0.80	0.70
Min	0.36	0.32	0.29	0.18
90%	0.79	0.68	0.67	0.57
Median	0.65	0.55	0.51	0.42
Mean	0.65	0.55	0.50	0.42
Correlation	92%	84%	72%	57%

Note: Numbers expressed as a decimal reflect the Missouri River flows divided by the St. Louis flows.

According to USGS SIR 2009-5232, the flood of 1844 had a peak stage of 41.32 ft at the St. Louis gage, and before 1998 was published by USGS as having a peak discharge of 1,300,000 cubic feet per second (cfs), which was estimated by the USACE from the 1903 flood at the Chester and Thebes gages. In the Missouri River Basin 308 Report, the 1844 flood was estimated at 1,350,000 cfs also by comparisons to the 1903 flood. The actual discharge of the 1844 event is unknown, but the published value officially was revised in 1998 in the USGS record to 1,000,000 cfs based on the results of physical and analytical model tests of this flood and further review by USACE (Huizinga 2009). For the purpose of this report, comparisons were made using the 1,350,000 cfs estimate for 1844 since this estimate appeared to plot closer to the older historical annual peak flood data. However, it is highly possible that changes to the floodplain since 1844 could have resulted in higher stages for a lower discharge at that time. Figure 3-12 presents the rating curve at St. Louis, MO, to include the historic peak information. The figure supports the conclusion from SIR 2009-5232 that the rating curve shift correlates to construction of the Alton-Gale Levee System. No evidence can be seen in the records that suggests other major factors, such as dike construction, have altered the rating curve at St. Louis, MO. The historic peak estimates of 1826, 1851, and 1858 are also included on the figure, along with highlights of floods documented at Hermann to include 1881, 1883, and 1892. While multiple USGS rating curves are available (see Huizinga 2009), a historic rating curve based on a period of the oldest annual peaks 1862 to 1903 was assumed to be representative of uncertain historic peak flow estimates, where 1903 exceeded the 1858 estimate.

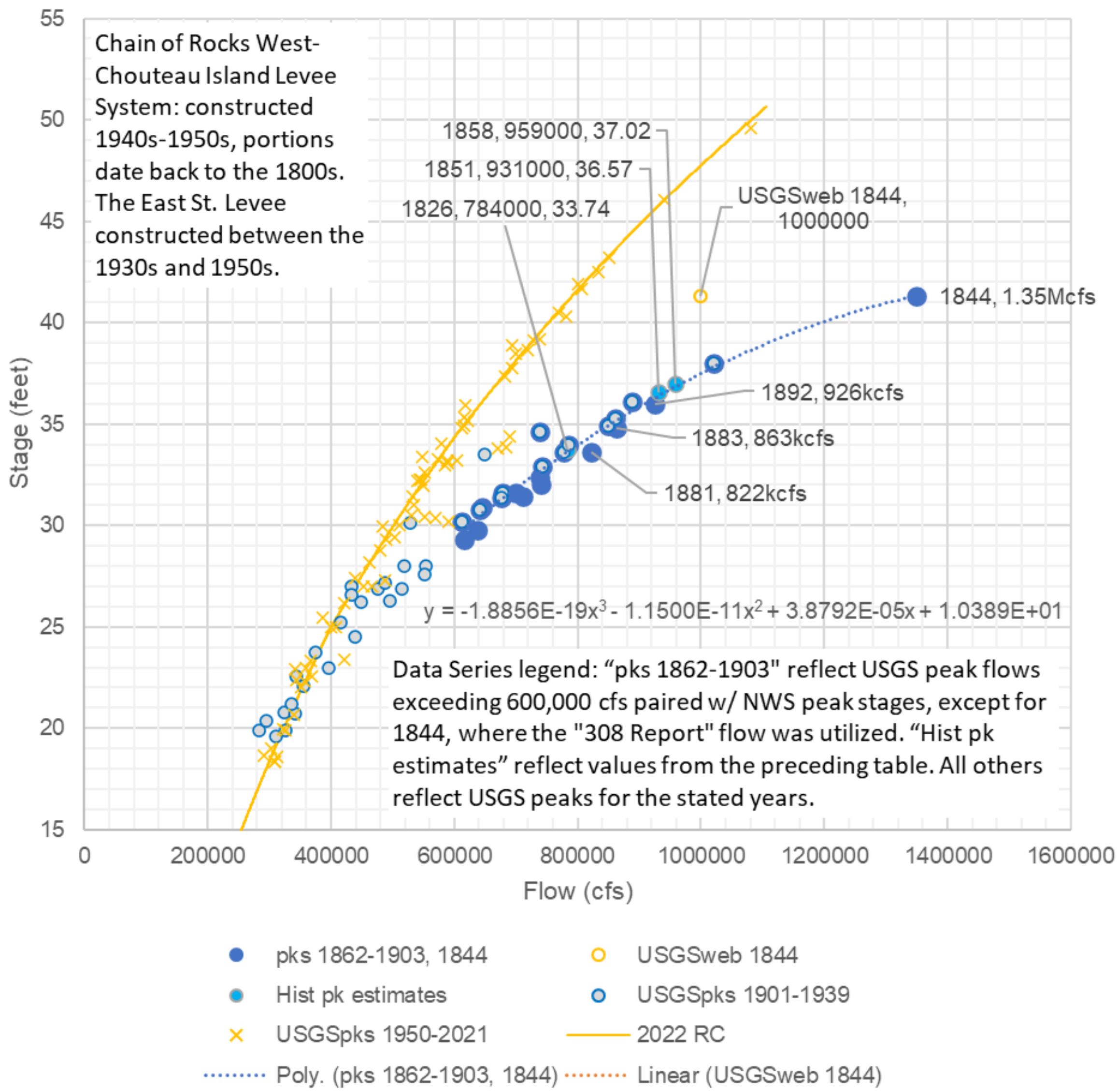


Figure 3-12. Historic Rating Curve, Mississippi River at St. Louis, MO

3.7 Omaha District Unregulated Flow Frequencies

Procedures discussed in Section 3.5 were applied at the Omaha District gages. Estimates of historic peak flows were available from the USGS, the 1962 Agricultural Levee Restudy Report, and the 2018 Missouri River Mainstem Master Manual. Earlier documents also had historic peak flow estimates, especially for 1881 as summarized in Appendix A. Historic peak flow estimates are shown in Table 3-9 and Table 3-10 for the early spring and late spring seasons, respectively, including 2003 UMRSFFS data for overlapping pre-USGS years and the years with the highest flow estimate for each gage from 1898 to 1929. Overall, the 2003 UMRSFFS estimates compare within -12% to +14% to earlier estimates, except for 1915, 1916, and 1917 where UMRSFFS is 20%, 23% and 33% lower than the 1962 study at

Nebraska City, respectively. Data tables of the systematic peak flows, perception thresholds, and historic peaks used are shown in Appendix A. All unregulated flow frequencies and statistics are summarized in Section 3.9, with plots for each gage documented in Sections 3.7.1 to 3.7.4. Additional sensitivity analysis to various time periods is presented in Appendix D.

Table 3-9. Missouri River Historic Flows- Early Spring (cfs)

Month	Year	Yankton	Sioux City	Omaha	NE City	Source
April	1826			~330,000		Sections 2.4.4, 3.5, 3.7.3
April	1843			~360,000		Sections 2.4.5, 3.5, 3.7.3
April	1867			275,000		Sections 2.4.9, 3.5, 3.7.3
April	1875			238,000		1962 Levee Restudy Report
April	1881		360,000	370,000	400,000	1962 Levee Restudy Report
April	1881		362,000	370,000	380,000	2018 Master Manual
April	1884				256,000	1962 Levee Restudy Report
March	1887			230,000		Assumed flow**
April	1899	252,600	254,000	241,700	273,000	2003 UMRSFFS Unregulated
April	1899*		258,300	224,700	274,300	1962 Levee Restudy Report
April	1912				256,400	1962 Levee Restudy Report
April	1912	194,000	194,500	204,100	225,900	2003 UMRSFFS Unregulated
	1913	209,600	200,700	208,000	205,600	2003 UMRSFFS Unregulated
April	1917		229,000		315,200	1962 Levee Restudy Report
April	1917	199,700	201,400	206,800	211,100	2003 UMRSFFS Unregulated
April	1929		190,000			USGS, first year
Non-1881 Max 1872-1929		252,600	258,300	241,700	315,200	Gavins Point to Platte River 1899

*Missouri River Commission Records at Omaha show the early spring peak stage of April 25, 1899, as 4.1 feet higher than the maximum late spring stage of July 2, 1899 (see Appendix A); whereas the 1962 report shows the peak at Sioux City on July 15, 1899 and on July 20, 1899 at Omaha and Nebraska City. The 2003 UMRSFFS also places 1899 in early spring.

**The March 1887 stage was comparable to April 1875, June 1878, and April 1899 as shown in Section 3.7.3 and Appendix A, flow assumed consistent with 1962 Levee Restudy Report estimates.

Table 3-10. Missouri River Historic Flows- Late Spring (cfs)

Month	Year	Yankton	Sioux City	Omaha	NE. City	Source
June	1878			233,000		1962 Levee Restudy Report
July	1905	251,500	239,000	175,300	244,500	2003 UMRSFFS Unregulated
July	1905		252,000			1962 Levee Restudy Report
July	1908	187,000				2018 Master Manual
June	1908	173,000	188,000	232,000	260,200	2003 UMRSFFS Unregulated
June	1915				263,600	1962 Levee Restudy Report
July	1915	189,700	181,100	178,200	210,200	2003 UMRSFFS Unregulated
July	1916				276,700	1962 Levee Restudy Report
July	1916	188,000	186,900	176,600	212,300	2003 UMRSFFS Unregulated
	1921	188,700	180,200	215,500	296,600	2003 UMRSFFS Unregulated
	1927	211,300	209,200	233,900	250,300	2003 UMRSFFS Unregulated
July	1929			198,000		USGS
Max		251,500	252,000	233,900	296,600	

3.7.1 Gavins Point Unregulated Flow Frequency

Mixed population analysis was conducted at Gavins Point / Yankton using the systematic period of 1930 to 2019 and historical flood information. Initial results were computed using a historic period back to the 1908 flood at Yankton, the earliest flood described at that location in the 2018 Missouri River Master Manual, using its estimate of 187,000 cfs as the perception threshold prior to systematic data. These results were expanded after ATR and TRG review to include the early spring historic period back to 1844, the year after a known April flood at Omaha, and to 1872 in May-December corresponding with Omaha gage records to make the analysis consistent with downstream gages. Estimates of the 1881 flood, the record of the historic period, are available upstream at the Fort Randall Dam site at 325,000 cfs, and downstream at Sioux City at 360,000 cfs. Given an increase in drainage area of 16,000 square miles between Fort Randall and Gavins Point, and a just over 51,000 square miles from Gavins Point to Sioux City, a flow of approximately 335,000 cfs at Gavins Point can be assumed for the late April 1881 peak. The large ice jam of the early April flood, which produced by over 15 feet the record stage at Yankton, had 24% and 13% lower flows than the late April peaks at Sioux City and Omaha, respectively (USACE 1946). Given uncertainties with ice jam routings which are reduced with current dam operations but could either increase or decrease downstream flows (2003 UMRSFFS, Appendix F), and the lower flow of the early April event, the late April flow estimate is assumed reasonable for use as a historic peak estimate.

Between 1844 and 1871 a perception threshold of 280,000 cfs was assumed after considering best estimates of the 1867 flood at Omaha and St. Joseph, the largest flood since June 1844 in St. Joseph, and likely largest since April 1843 in Omaha in that period. This threshold was slightly reduced as compared to Sioux City and Omaha to account for flows of the James and Big Sioux Rivers. Between 1872 and 1897, stage records are available at gages between Yankton and the Platte River beginning in 1872 at Omaha and 1878 at Sioux City. Given this, a perception threshold of 238,000 cfs was selected for the period 1872-1897 based on the 1875 historic peak estimate at Omaha from the 1962 Levee Restudy Report. While drainage area is higher at Omaha, the possibility of attenuation from upstream to downstream exists, therefore the use of the Omaha 1875 flow is assumed reasonable. For the period 1898 to 2019, the 2003 UMRSFFS data is the best available information at Yankton aside from the 1908 flood estimate and corresponding perception threshold of 187,000 cfs. According to the 2003 UMRSFFS, this threshold was exceeded in twelve years between 1898 and 1929, the largest estimated at 252,600 cfs in April of 1899. Of these 20 years exceeding 187,000 cfs, 8 events occurred in Jan–Apr, including 1899, 1904, 1910, 1912, 1913, 1917, 1920, and 1929. These events exceeding 187,000 cfs based on the 2003 UMRSFFS data were included in the historic period of 1898 to 1929 for both seasons. Figures 3-13 to 3-14 present the chronology and unregulated flow frequency for the initial historic period back to 1908. Figure 3-15 present the chronology plot for the Jan-

Apr historic period back to 1844. Figure 3-16 presents the resultant unregulated flow frequency curve, showing both the result for station skew of 0.226, standard deviation of 0.271, and mean log of flow in cfs of 4.949, and as smoothed to a skew of 0.2 as discussed in Section 3.5. The extended period increased the historic period considered from 112 to 177 years, and effective record length from 90.7 to 115.0 years for the Jan–Apr period.

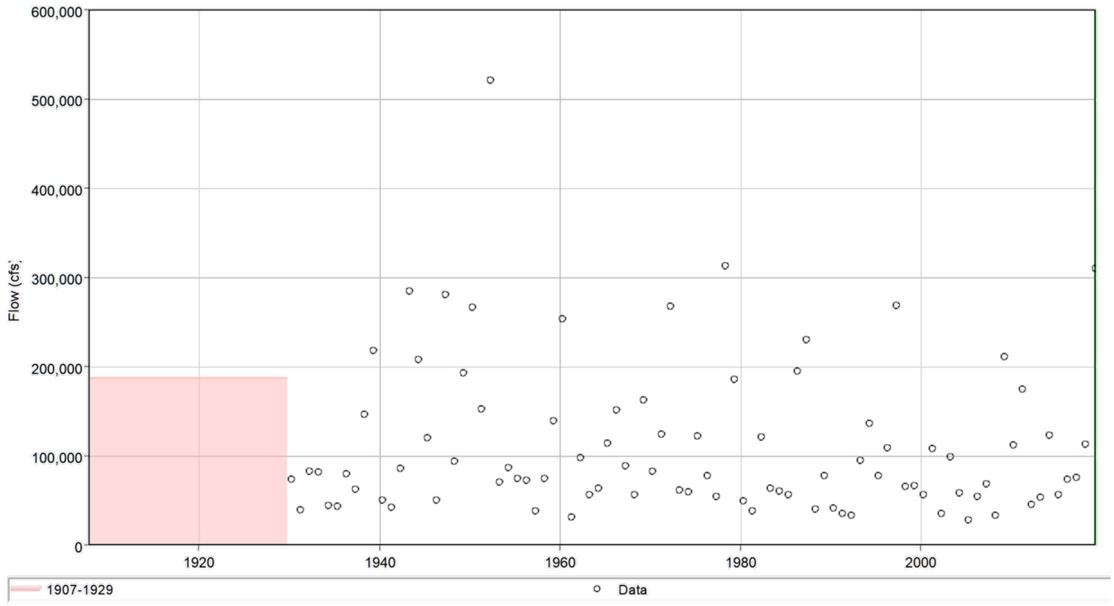


Figure 3-13. Gavins Point Jan–Apr Chronology Plot For EMA Input, 1908-2019

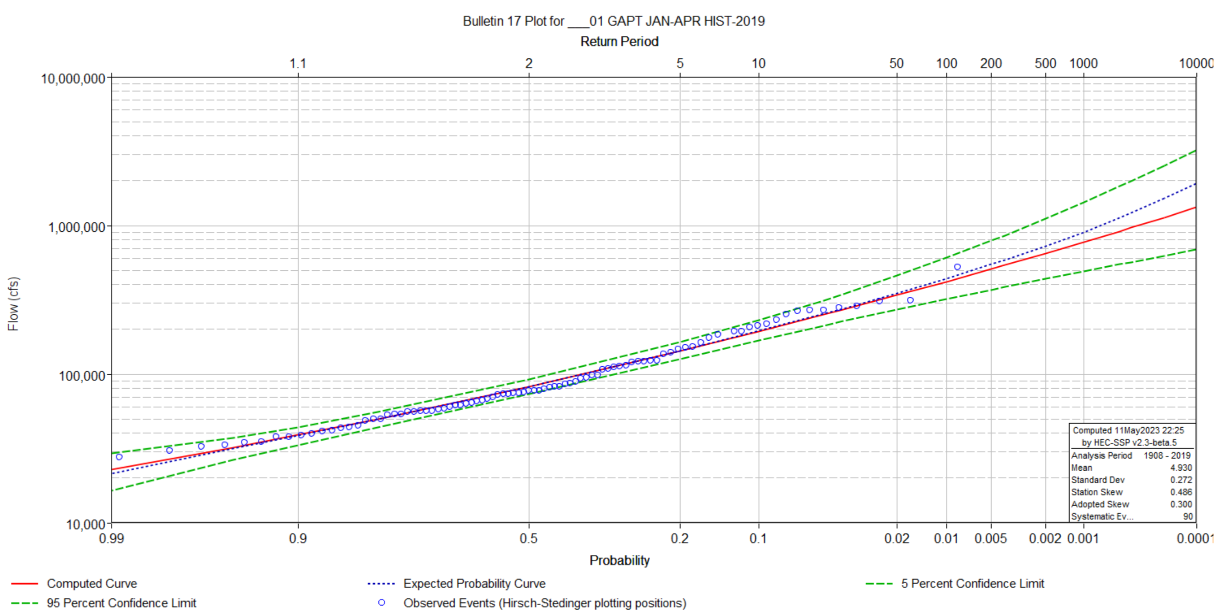


Figure 3-14. Gavins Point Jan–Apr Unregulated Flow Frequency Curve, 1908-2019

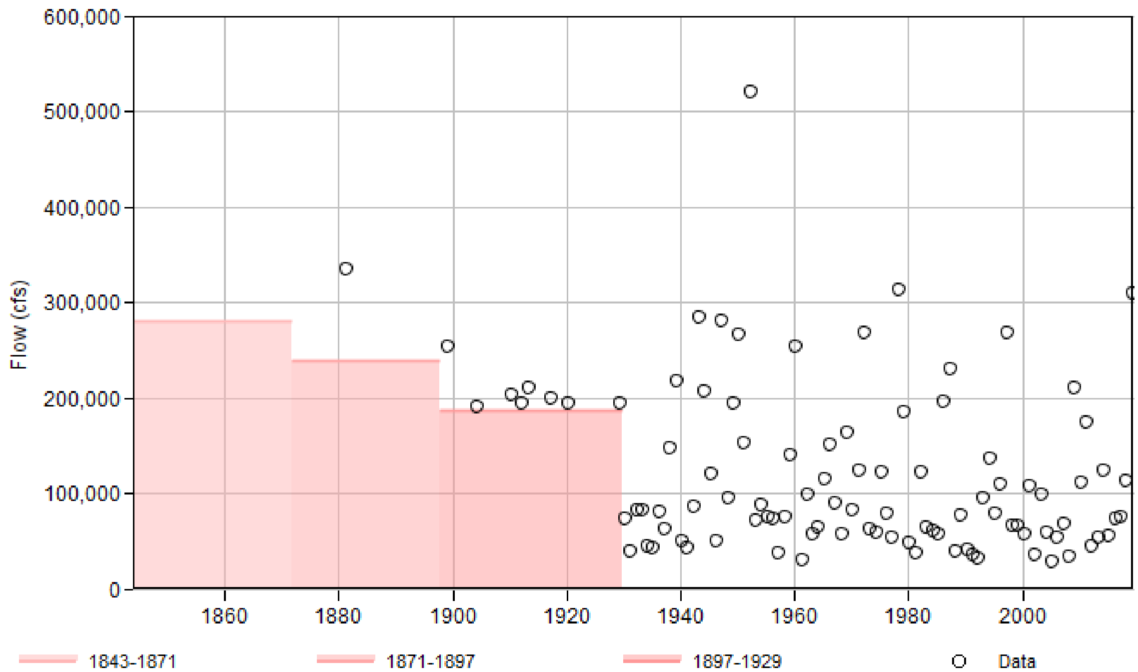


Figure 3-15. Gavins Point, JAN–APR Chronology Plot for EMA Input, 1844-2019 (Adopted)

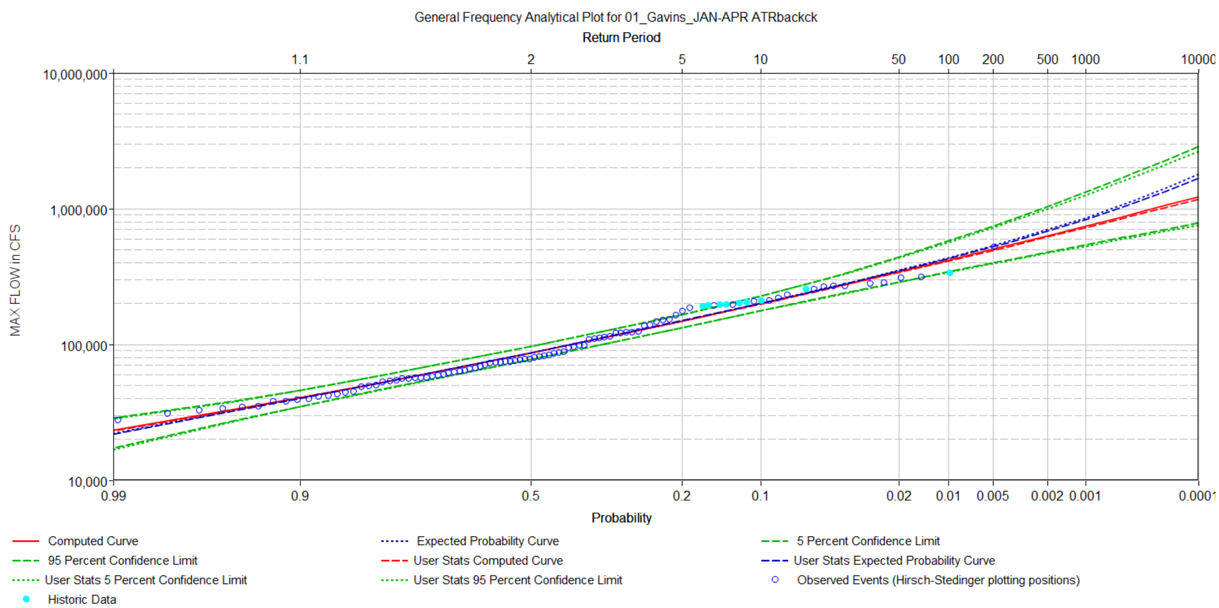


Figure 3-16. Gavins Point Jan–Apr Unregulated Flow Frequency Curve with and without Smoothing of Skew

Figures 3-17 and 3-18 present the May-Dec flood chronology as previously described and unregulated flow frequency for a historic period back to 1872, respectively, including both the station skew and smoothed skew of 0.2 as discussed in Section 3.5. Figure 3-19 presents the resultant mixed population unregulated flow frequency curve, which shows the early spring period produces higher flows for events more extreme than 10% AEP. Confidence limits shown on the mixed population frequency are from the ordered statistics as discussed further in Section 3.5 and Section 3.8.2.

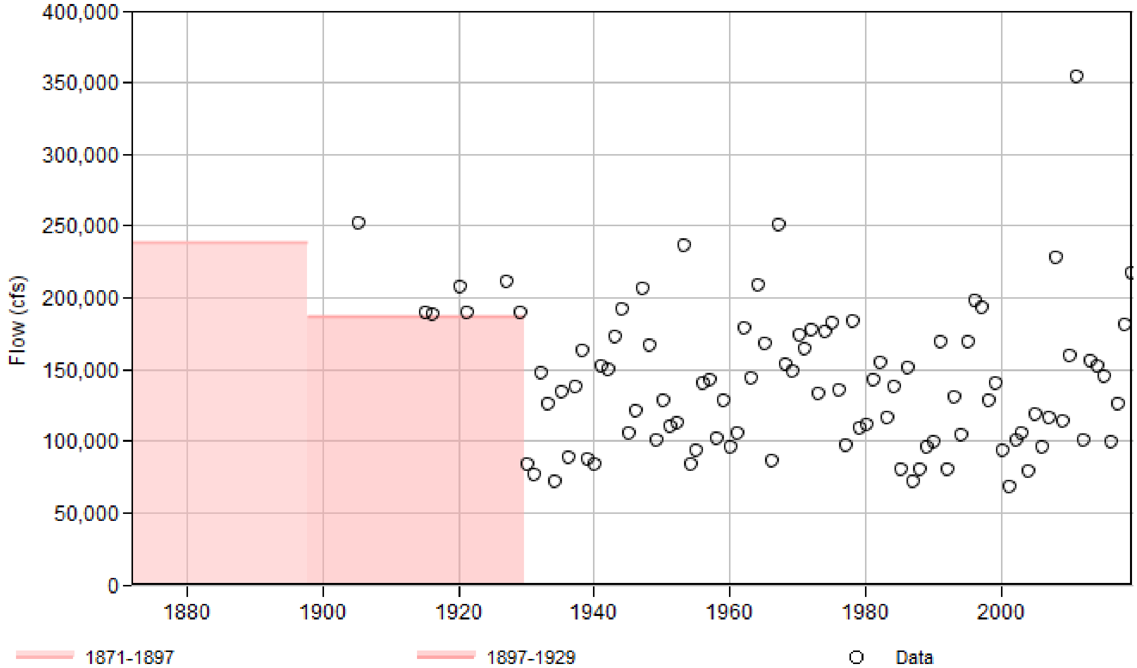


Figure 3-17. Gavins Point May–Dec Chronology Plot For EMA Input, 1872-2019

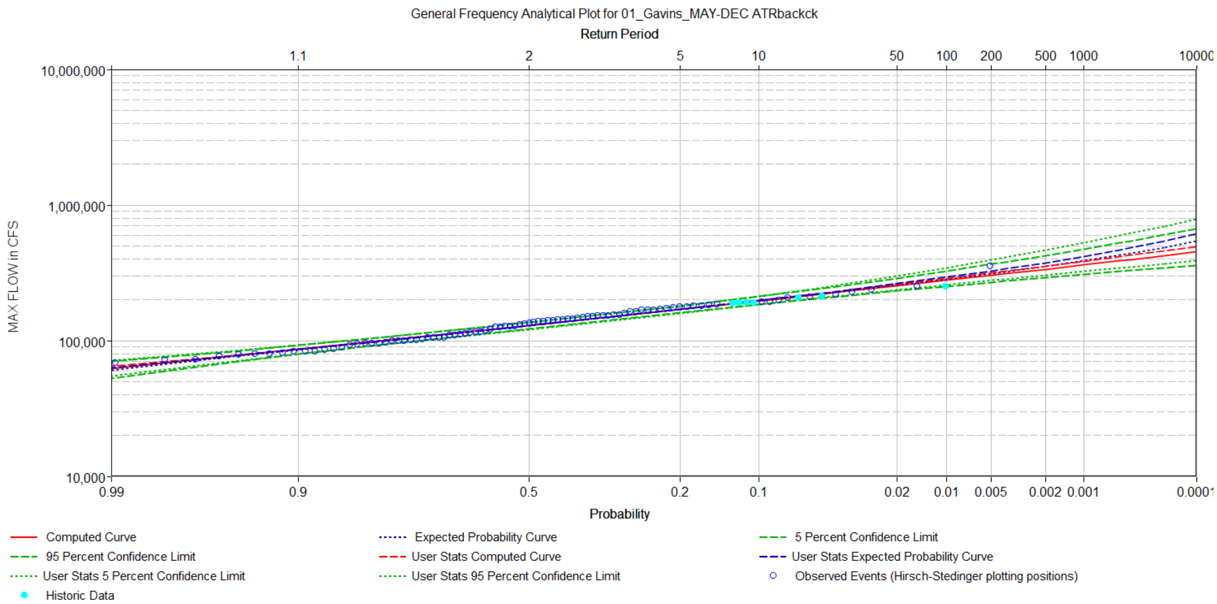


Figure 3-18. Gavins Point May–Dec Unregulated Flow Frequency Curve, 1872-2019 with and without Smoothing of Skew

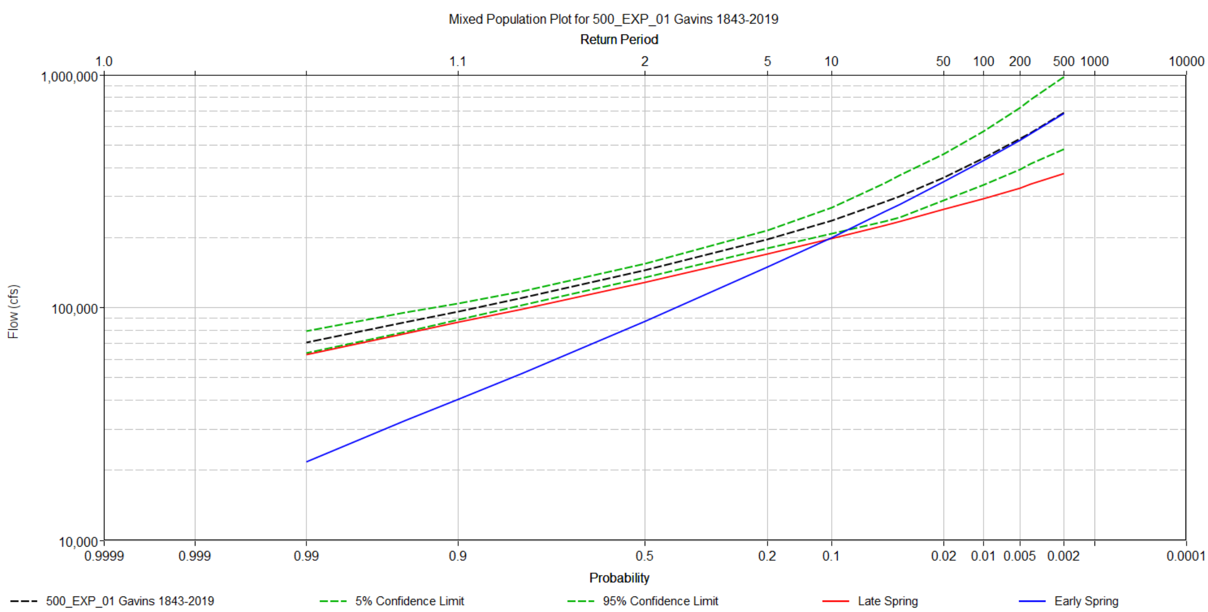


Figure 3-19. Gavins Point Mixed Population Unregulated Flow Frequency Curve

3.7.2 Sioux City, IA, Unregulated Flow Frequency

Mixed population analysis was conducted at Sioux City using the systematic period of 1930 to 2019 and historical flood information. Initial results were computed using a historic period back to the 1881 flood at Sioux City, the earliest detected flood at Sioux City with a documented historic peak flow. These results were expanded after ATR and TRG review to include the early spring or Jan-Apr historic period back to 1844, the year after a known April flood at Omaha to yield more similar statistics as downstream gages with more detailed flood history information. Additionally, the late spring or May-Dec historic period was expanded to 1872 to coincide with stage records downstream at Omaha, with stage records also becoming available in Sioux City in 1878. As no large floods prior to 1872 in May-Dec were determined from the flood history research, and the frequencies of large floods are not sensitive to this season, no further extension of the late spring historic period was conducted. Initially a perception threshold of 229,000 cfs was used between 1881 and 1929 based on the April 1917 flood estimate from the 1962 Levee Reevaluation Report. This threshold was retailed for the 1898 to 1929 period of both seasons where 2003 UMRSFFS data is available.

April 1899 was the largest early spring event aside from 1881 between 1872 and 1929 based on stage records and historic rating curves at Omaha and Sioux City, estimated at 258,300 cfs in the 1962 Levee Restudy Report, slightly higher than the 2003 UMRSFFS unregulated estimate of 254,000 cfs. Stage records at Omaha, NE, as discussed in Section 3.7.3, showed April 1875 was the largest early spring flow and June 1878 the largest late spring between 1872 and 1878 when stage records initiated at Sioux City. Both the April 1875 and June 1878 floods were estimated between 230,000 to 240,000 cfs, and assuming some attenuation was possible from Sioux City to Omaha, a perception threshold of 250,000 cfs, slightly smaller than April 1899, was selected for the 1872 to 1897 period prior to 2003 UMRSFFS data. Prior to 1872, a perception threshold of 300,000 cfs was assumed at Sioux City as informed by estimates of April 1867 at Omaha.

For the early spring historic period back to 1881, a mean of 4.966, standard deviation of 0.276, and skew of 0.28 were determined. For the expanded early spring historic period back to 1844, statistical values were slightly reduced to a mean of 4.964, standard deviation of 0.271, and station skew to 0.215. As discussed in Section 3.5, skew was smoothed both for the early spring and late spring to 0.2, in line with other gages in the reach between Gavins Point and the Platte River. This expanded period with smoothing lowered the 0.2% and 1% unregulated flow AEP flood by approximately 11% and 6%, respectively, making it less likely for flow frequency curves of Sioux City to exceed downstream gages that do not make physical sense. For example, the mixed population results using a historic period back to 1881 were exceeding Kansas City at a 0.1% AEP, which has eight unregulated events exceeding 500,000 cfs, three exceeding 600,000 cfs, and one exceeding 700,000 cfs compared to one exceeding 500,000 cfs at Sioux City.

Figures 3-20 and Figure 3-21 present the chronology plots for input into the Bulletin 17C flow frequency analysis for the at station historic period back to the earlies documented flood peak of 1881, and back to 1844, the year after the 1843 flood as adopted. Figure 3-22 presents the unregulated flow frequency for the early spring period of the adopted analysis.

Figures 3-23 and 3-24 present the chronology plot and flow frequency curve for the late spring, or May-Dec season. Each Chronology Plot shows the perception thresholds and historic peak flows as previously described and as tabulated in Appendix A, whereas the computed flow frequencies are shown on the flow frequency plots. Figure 3-25 presents the mixed population frequency computed as described in Section 3.5, which shows the early spring period produces higher flows for event more extreme than a 10% AEP. While flooding in the late spring produces larger floods on average, the early spring flooding is more variable with potential for increased runoff during frozen ground conditions across a very large upstream watershed. Confidence limits shown on the mixed population frequency are from the ordered statistics as discussed further in Section 3.5 and Section 3.8.2.

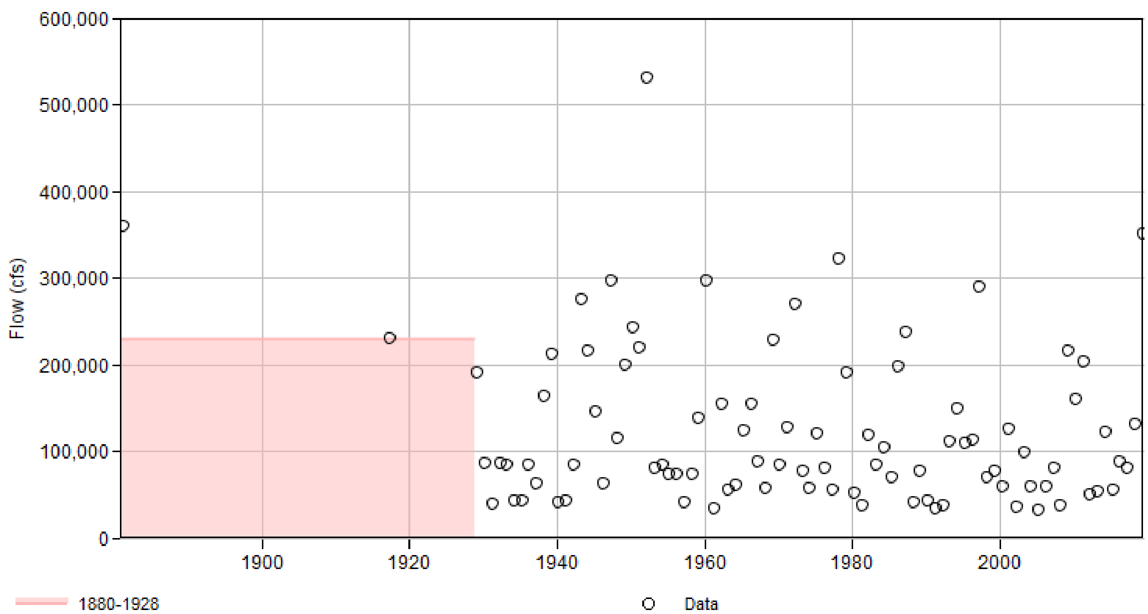


Figure 3-20. Sioux City, IA Jan–Apr Chronology Plot For EMA Input, 1881-2019

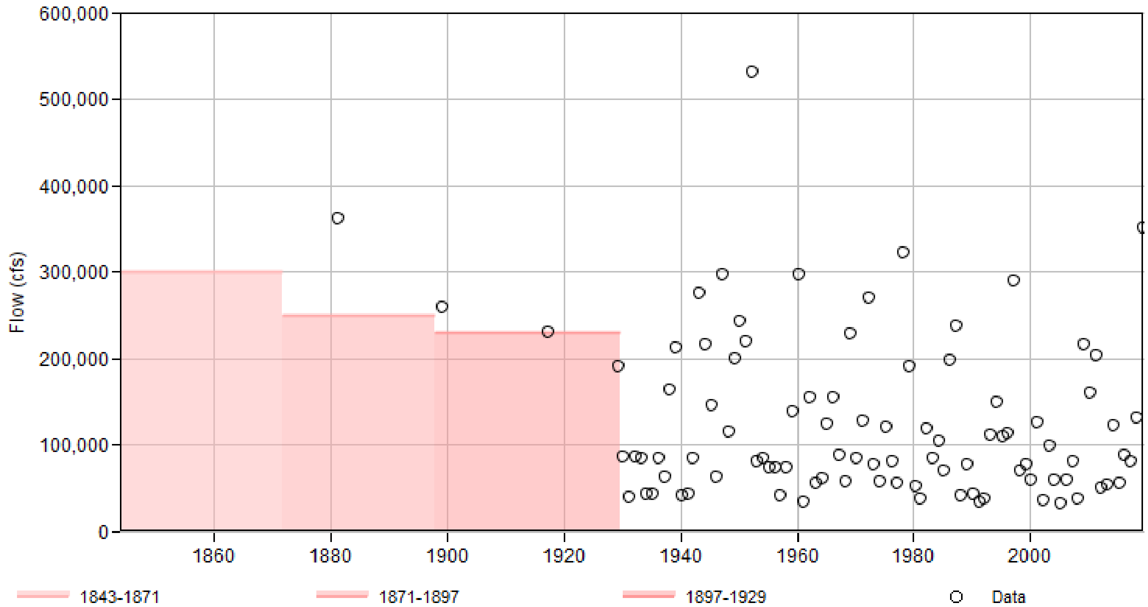


Figure 3-21. Sioux City, IA JAN–APR Chronology Plot for EMA Input, 1844-2019 (Adopted)

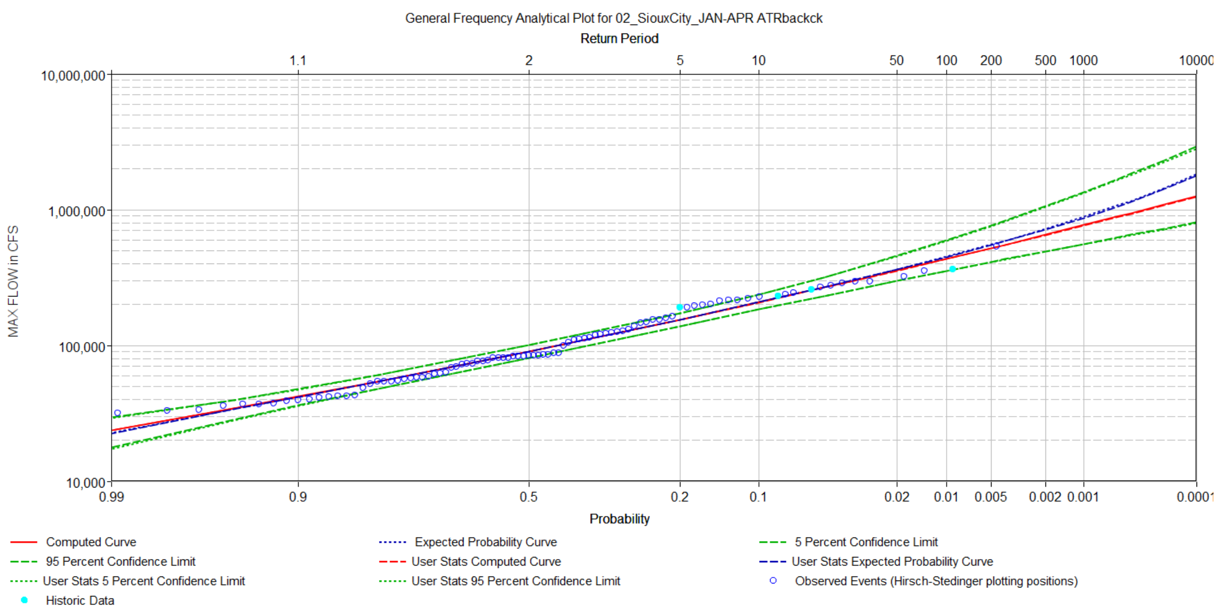


Figure 3-22. Sioux City, IA Jan–Apr Unregulated Flow Frequency Curve, 1844-2019 with and without Smoothing of Skew

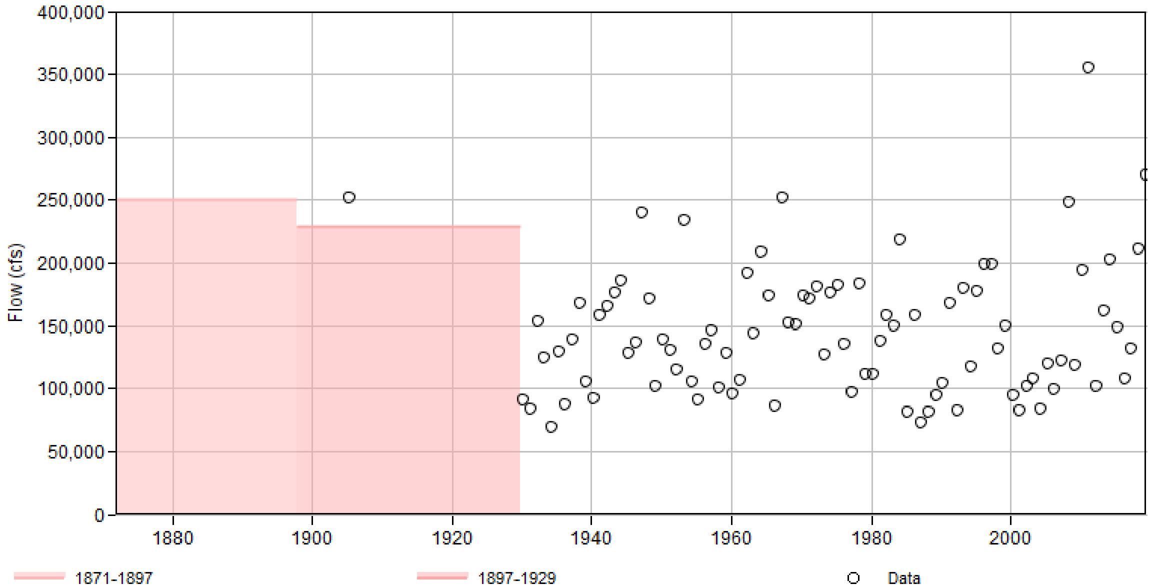


Figure 3-23. Sioux City, IA May–Dec Chronology Plot For EMA Input

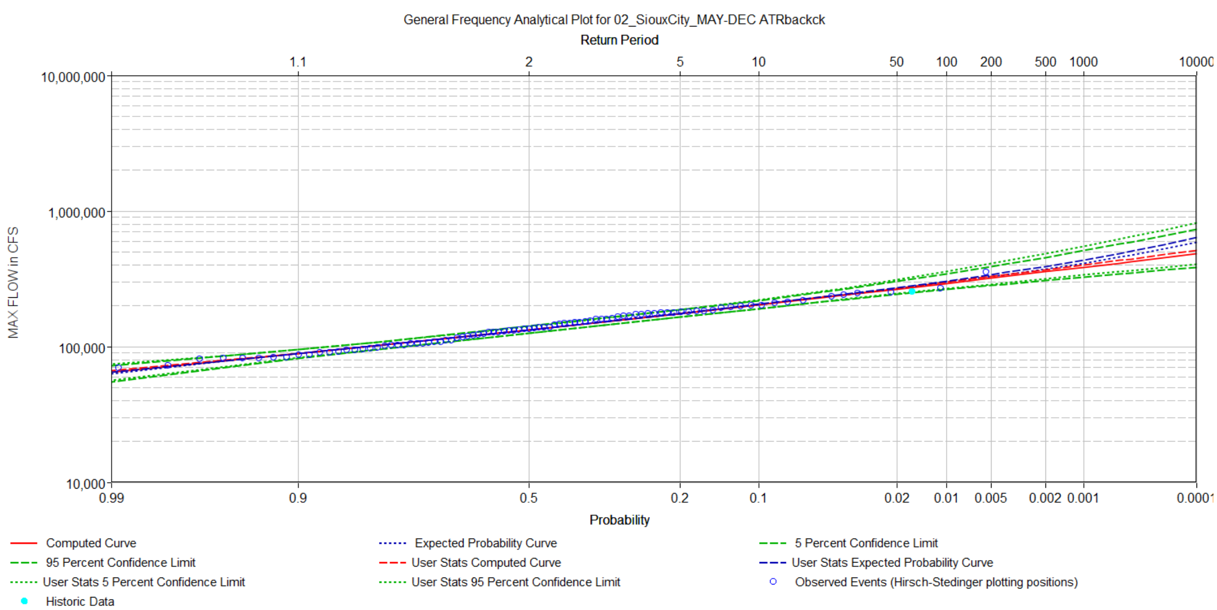


Figure 3-24. Sioux City, IA May–Dec Unregulated Flow Frequency Curve with and without Smoothing of Skew

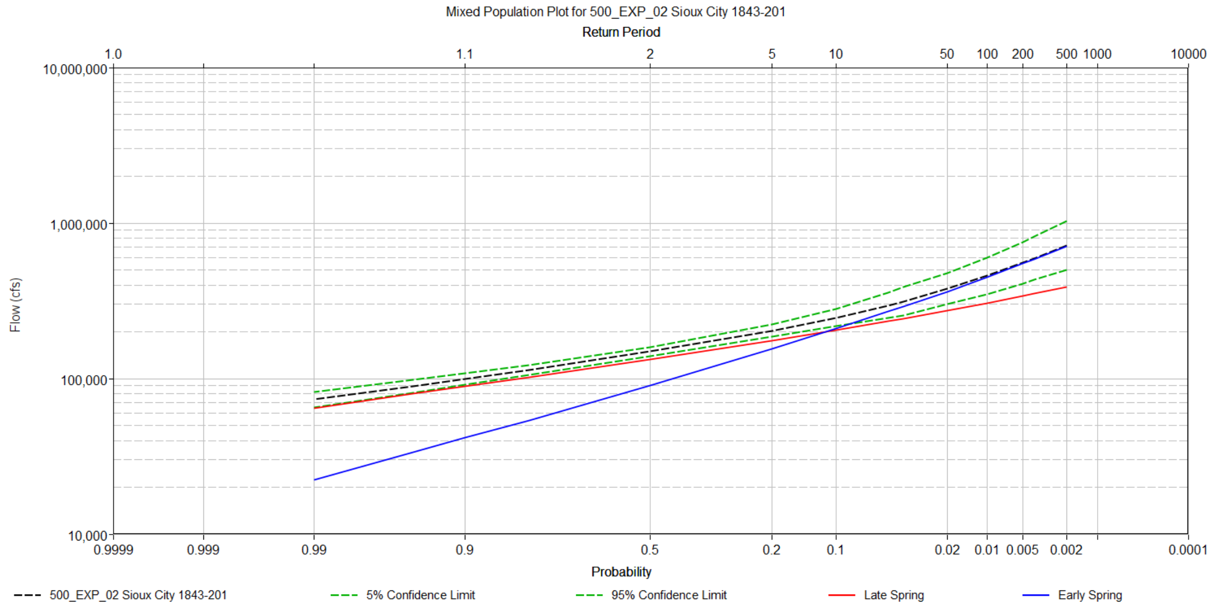


Figure 3-25. Sioux City, IA Mixed Population Unregulated Flow Frequency Curve

3.7.3 Omaha, NE, Unregulated Flow Frequency

Mixed population analysis was conducted at Omaha using the systematic period of 1930 to 2019 and historical flood information. Initial results were computed using flood history information back to the April 1875 flood at Omaha, NE. These results were then expanded after ATR and TRG review to include early spring period back to 1843, a known flood at Omaha, and to 1819, the earliest date of development that can be tied to historical flood information near Omaha. Figure 3-26 presents a historic rating curve adopted for this study using the pre-BSNP 1929–1934 USGS peak flows and the 1881 flood, along with the current USGS rating curve and USGS peak flows from various time periods to help reflect channel and levee changes. Historical stage trend documentation shows an approximate 4-feet upward shift at 100,000 cfs between 1934 and 1935 that steadily declined until the early 1950's, then steadily increased until the early 1980's, corresponding to BSNP and private levee construction (see USACE 2021, MRBWM stage trends, Plate 11). Higher flows were also impacted by Federal Levees completed in 1950 and 1951 at Council Bluffs and Omaha, respectively, just in time to pass the 1952 flood which loaded the levees to the top.

Best estimates for 1826 and 1843 assumed a minimum of four feet above flood stage based on depths reported in the US Army Barracks at Fort Croghan in 1843, whereas six feet was reported in 1826 in barracks at Fort Atkinson, up to the height of the 1881 flood. Magnitude of the floods of 1826 and 1843 at Omaha was also informed by flow estimates downstream at Kansas City which has more reliable stage information for these events. The adopted historic rating curve from the 2003 UMRSFFS and available 1880-1882 Missouri River Commission (MRC) flow measurements greater than 50,000 cfs are included on the figure.

At Omaha, the largest measurement was on July 11, 1882 when the river was 1.8 feet below the June peak. These discharge measurements, and those at other Missouri River gages by the MRC, are documented in the Mississippi River Commission (MsRC) 1895. Current stage data was plotted as tabulated in 2003 UMRSFFS, Appendix F after confirming stage was reasonably converted to the USGS gage as documented in MRC data tables for Omaha in Appendix A.

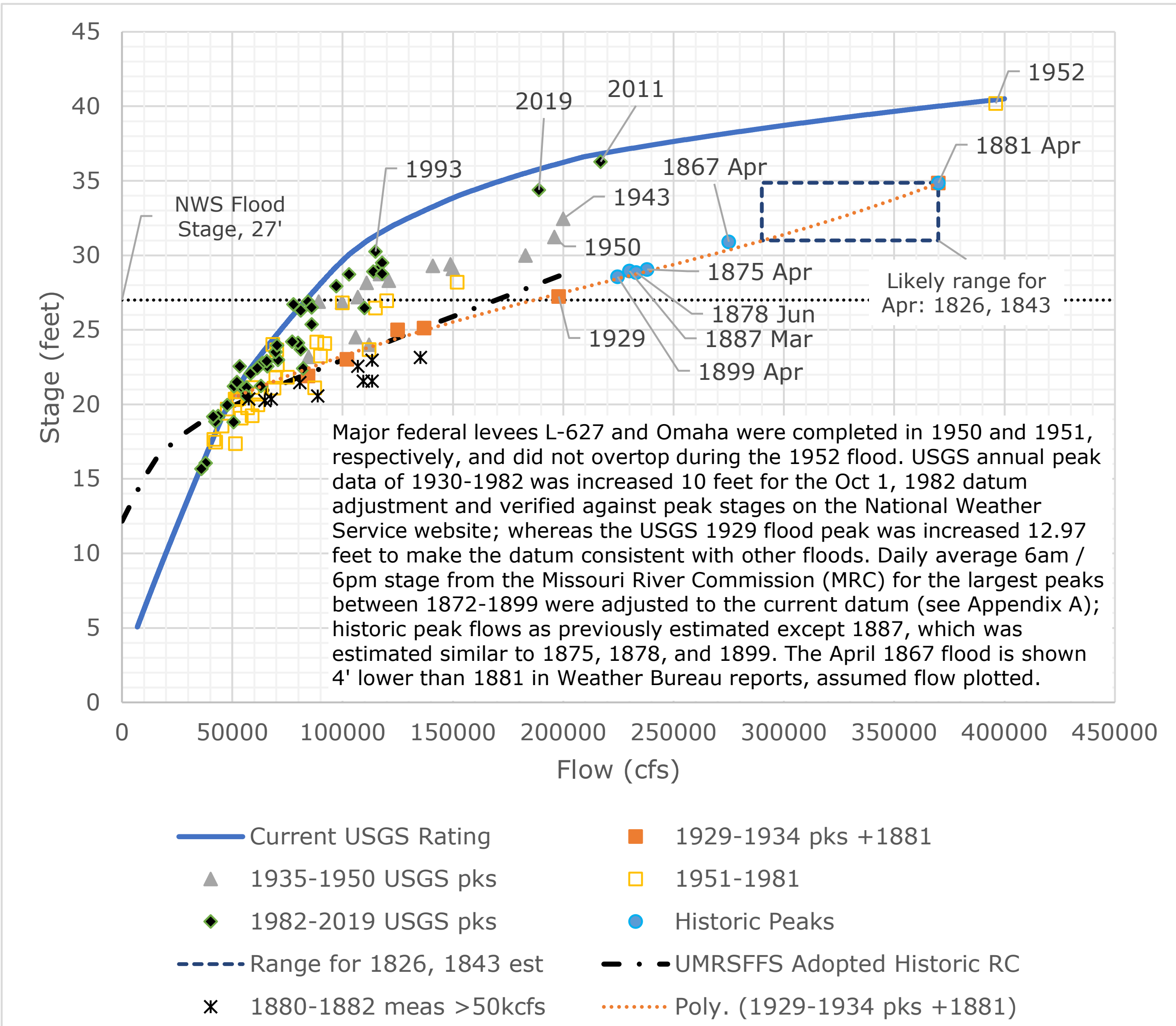


Figure 3-26. Current and Historic Rating Curve Information, Omaha, NE

As seen in Figure 3-26, the minimum assumed stage for the 1826 and 1843 floods is approximately three feet higher than the next four highest floods between 1872 and 1899, with the maximum stage at or below the record 1881 flood of 370,000 cfs. The floods of 1875, 1878, 1887, and 1899 all peaked about 1.5-2 feet above flood stage from Missouri River Commission stage records and were plotted using flows from Section 3.7, except

March 1887 which was assumed at 230,000 cfs. Likely comparable to these four floods, the 1820 flood, which wasn't detected downstream at Kansas City or Franklin, MO, reportedly caused all or portions of the original Fort Atkinson to be relocated higher after incurring damages. While some attenuation is possible if the floods originated upstream of Omaha, flows in 1826 or 1843 larger than 1881 are mostly unlikely given Kansas City, MO estimates of 1826 at 362,000 cfs and 1843 at 476,000 cfs, coupled with best estimates of coincident Kansas River flows. However, depending on the exact contribution of the Kansas River, which is uncertain, 1843 potentially could have been higher than or comparable to 1881 at Omaha. Several accounts of high water on the Kansas River at ferries for Oregon trail travelers were located, indicating a high, but in-bank flow on the Kansas River was likely to have accompanied the rise on the upper Missouri River that year, up to the channel capacity of approximately 100,000 cfs (USACE 2021, KC Levees). However, as in other years such as 1858, those flows may not have aligned.

Fort Croghan was established by the US Army in 1842 near present Council Bluffs, IA, with knowledge of the flood of 1826, leaving it unwise to have it situated lower than the 1826 flood, but likely given the location information summarized in Appendix A. Reference to 1843 as the largest flood since 1826 at Fort Croghan was located, but the wording indicated it was made in preparation for the crest to reach the US Army facilities rather than describing the peak (See Section 2.4.5). At Omaha, NE, there were notations in some of the early-stage record books that indicated that the 1844 flood at Omaha was 10 feet higher than the 1881 flood. However, further study found no credible evidence to support this, and a considerable amount of evidence to refute it (USACE 2003, UMRSFFS Appendix F). As documented in Section 2.4, the 1844 flood was most significant downstream of the Platte River, increasing in magnitude with drainage area, and 1843 was often overshadowed by 1844 given the short time between events. In USACE 1946, Agricultural Levees DPR, it was stated that "A prior report indicates that the June 1844 flood reached a stage at Omaha only 0.5 foot lower than the maximum which occurred in April 1881. However, it has been impossible to substantiate this statement". This statement was from the 308 Report (USACE 1935, 1932), Part II of a Report on Mainstem of Missouri River and Minor Tributaries, page 22, paragraph 52 on the flood of 1881, which refers the reader to Appendix IV, which states 1844 was within 0.4 feet of 1881, but provides no detail of the source.

For the Bulletin 17C analysis, flow ranges were assumed as 250,000 cfs to 370,000 cfs for 1826 and 300,000 cfs to 450,000 cfs for 1843, with best values for April 1826 assumed in the mid-point of the reasonable range, approximately 330,000 cfs or six feet above flood stage. For April 1843, a best estimate of 360,000 cfs was assumed, in line with an event slightly lower than 1881, and as documented with 1843 comparable to 1844 and 1881 downstream in northwestern Missouri. Given available gage records to cover the usual flood season of 1872 at Omaha, the 224,700 cfs perception threshold based on April 1899 from the 1962 Levee Restudy Report used for the historic period prior to 1929 was revised to

230,000 cfs based on the 1887 flood estimate between 1872 to 1897. Historic peaks above the 224,700 cfs threshold between 1898-1929 from previous studies or USGS flows were added as documented in Appendix A.

Consideration was also made to include the 1898-1929 data from the 2003 UMRSFFS as systematic peak flows. However, differences in the statistics, especially the significantly lower standard deviation and skew, even if the much higher mean is reasonable as defended in the 2003 UMRSFFS, led to the decision to use the 1898-1929 records as informing the perception thresholds and larger historic peak flows, rather than as systematic data. Additional discussion of these differences in included in Appendix D. Figures 3-27 to 3-28 present the chronology plots for the early spring period for historic periods back to 1875 and 1843 as adopted. Figure 3-29 presents the Bulletin 17C unregulated flow frequency for the 1843 to 2019 historic period as adopted, including the smoothing of skew to 0.2 which minimally impacted results at Omaha. Figure 3-30 presents expanded chronology to 1819 and corresponding Bulletin 17C unregulated flow frequency curve for the early spring, including sensitivity to perception thresholds of 1855-1871, the year after Omaha was established until the year before stage records initiated. Results for the 1819-2019 period were not sensitive to whether the perception threshold 1855-1871 was set using the 1867 flood best estimate or if the threshold was set above the flood, with similar statistics and flows within 1% across all frequencies. For the late spring period, Figure 3-31 presents the chronology plot back to 1872, coinciding with the start of stage records at Omaha, with the flow frequency curve presented in Figure 3-32. Figure 3-33 presents the final mixed population results based on a historic period of 1843-2019. Confidence limits shown on the mixed population frequency are from the ordered statistics as discussed further in Section 3.5 and Section 3.8.2.

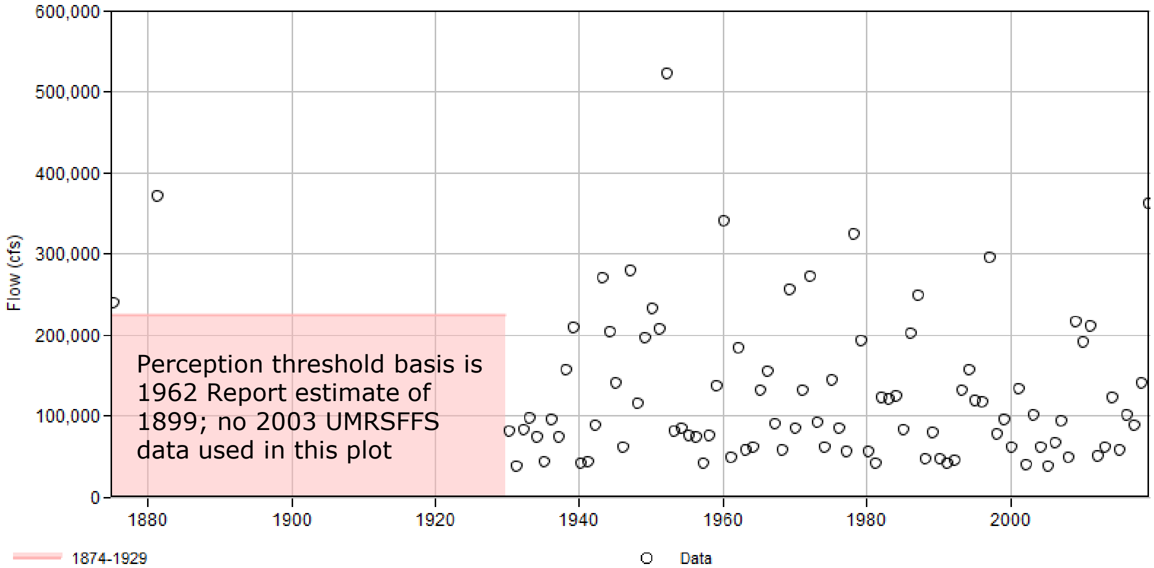


Figure 3-27. Omaha, NE Jan–Apr Chronology Plot For EMA Input, 1875-2019 Historic Period

Note: Perception threshold set to 1899 flood estimate.

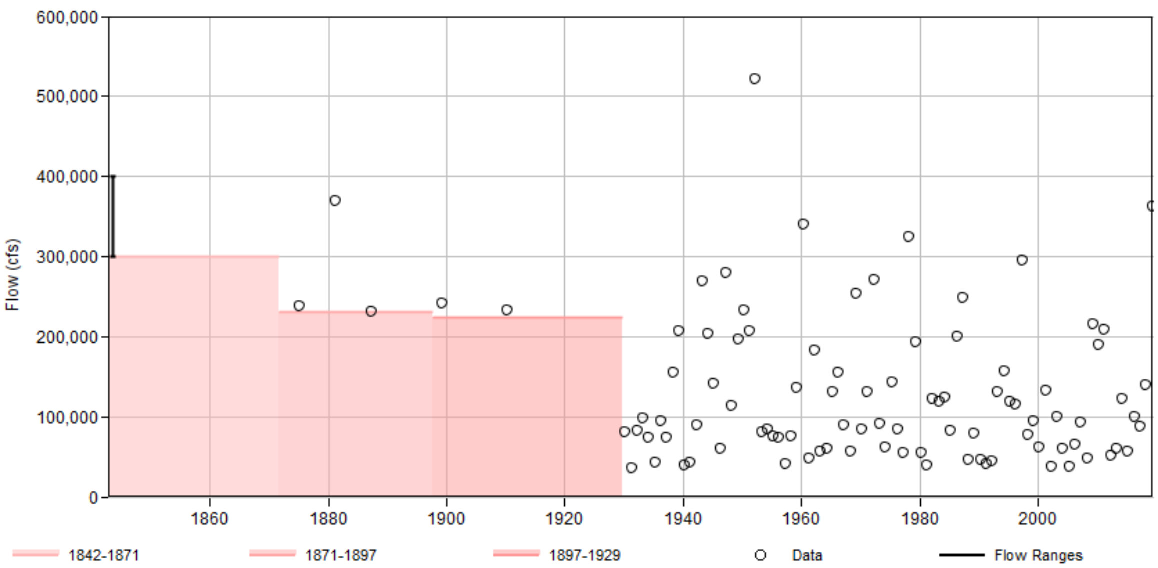


Figure 3-28. Omaha, NE Jan–Apr Expanded Chronology Plot for EMA Input, Historical Period of 1843-2019 (Adopted)

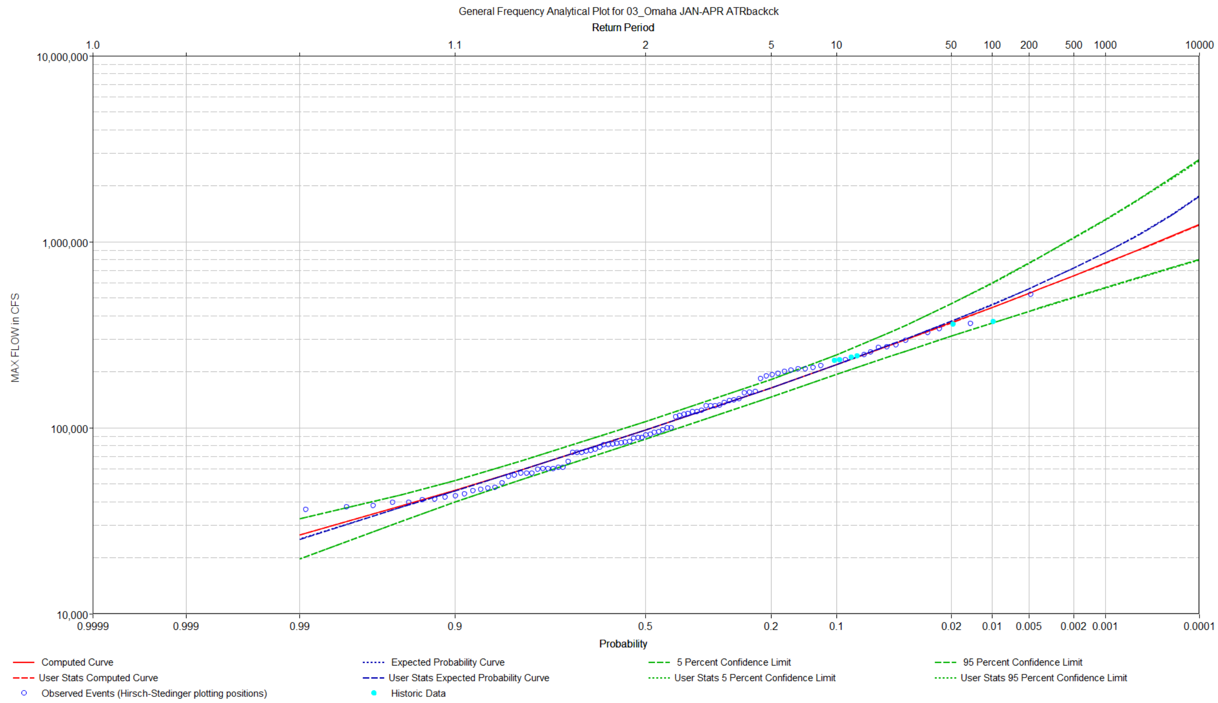
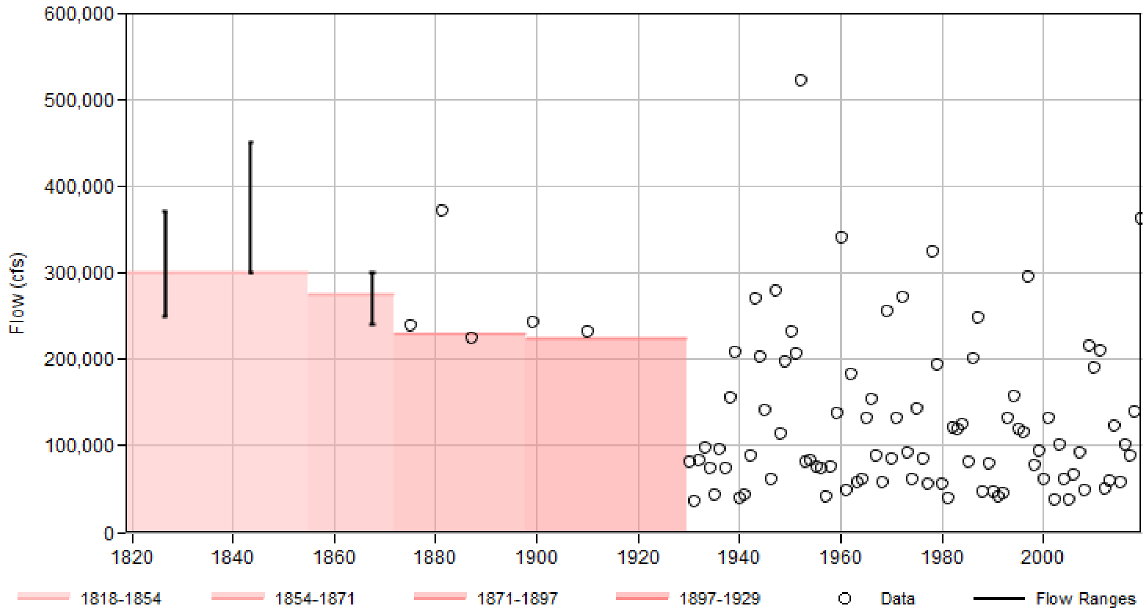


Figure 3-29. Omaha, NE Jan–Apr Unregulated Flow Frequency Curve, 1843-2019 (Adopted)



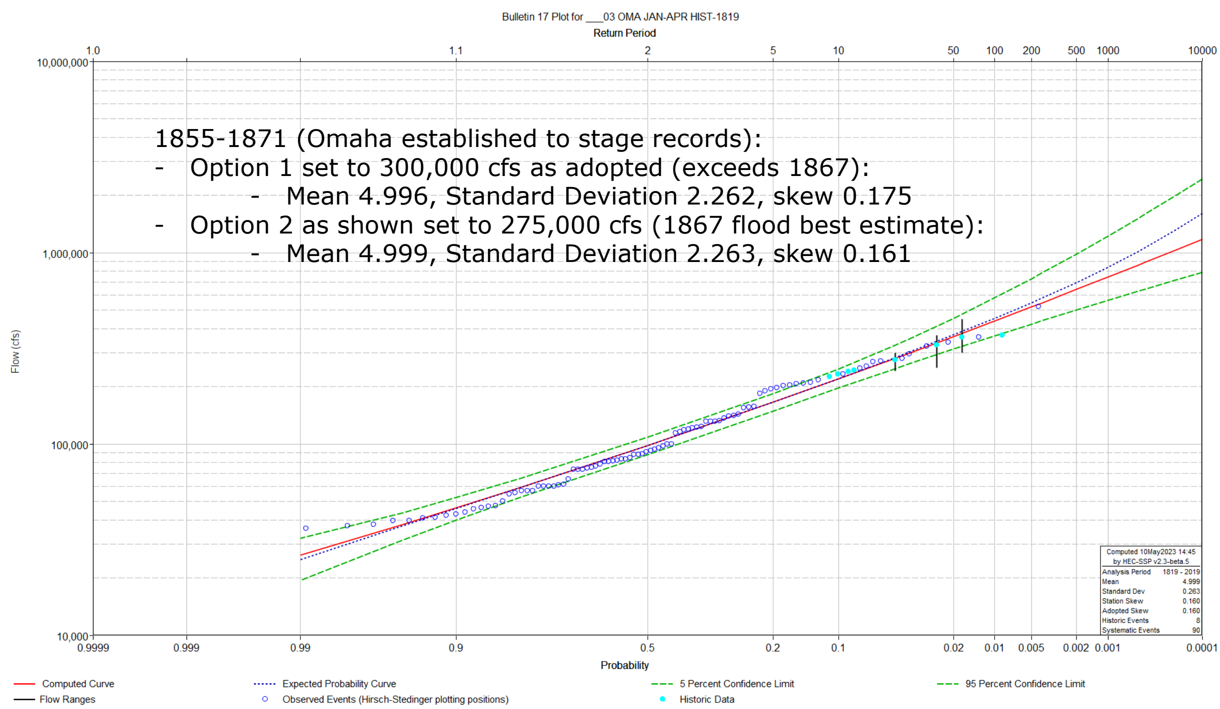


Figure 3-30. Omaha, NE Jan–Apr Expanded 1819–2019 Chronology and Bulletin 17C Unregulated Flow Frequency Plot, Historical Period Sensitivity

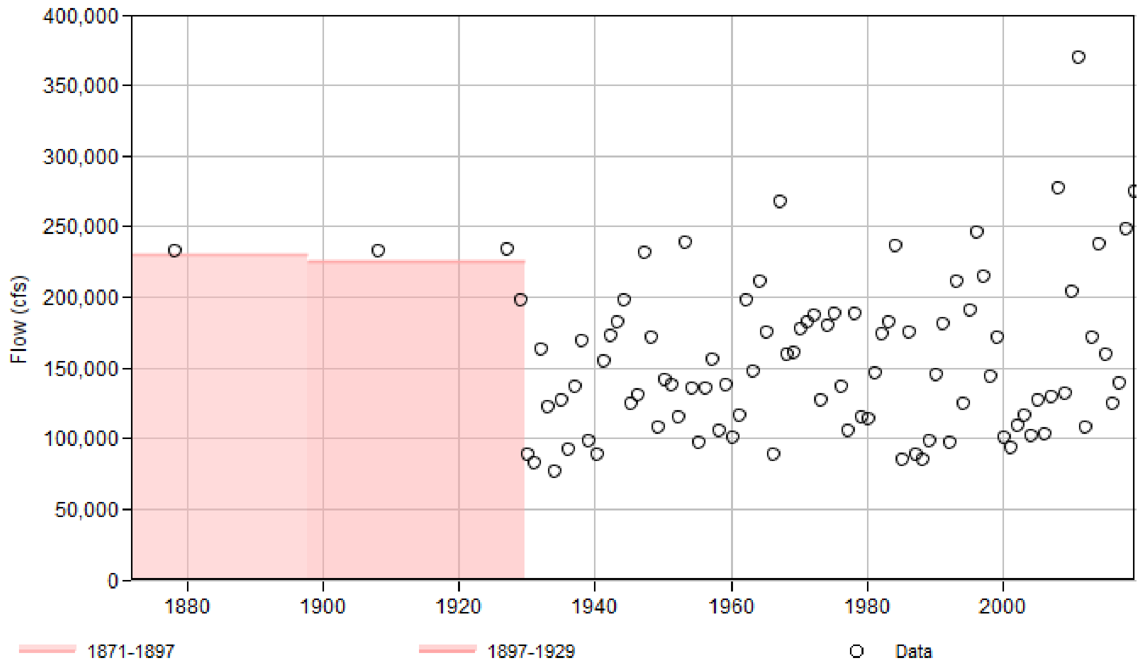


Figure 3-31. Omaha, NE May–Dec Chronology Plot 1872-2019 For EMA Input

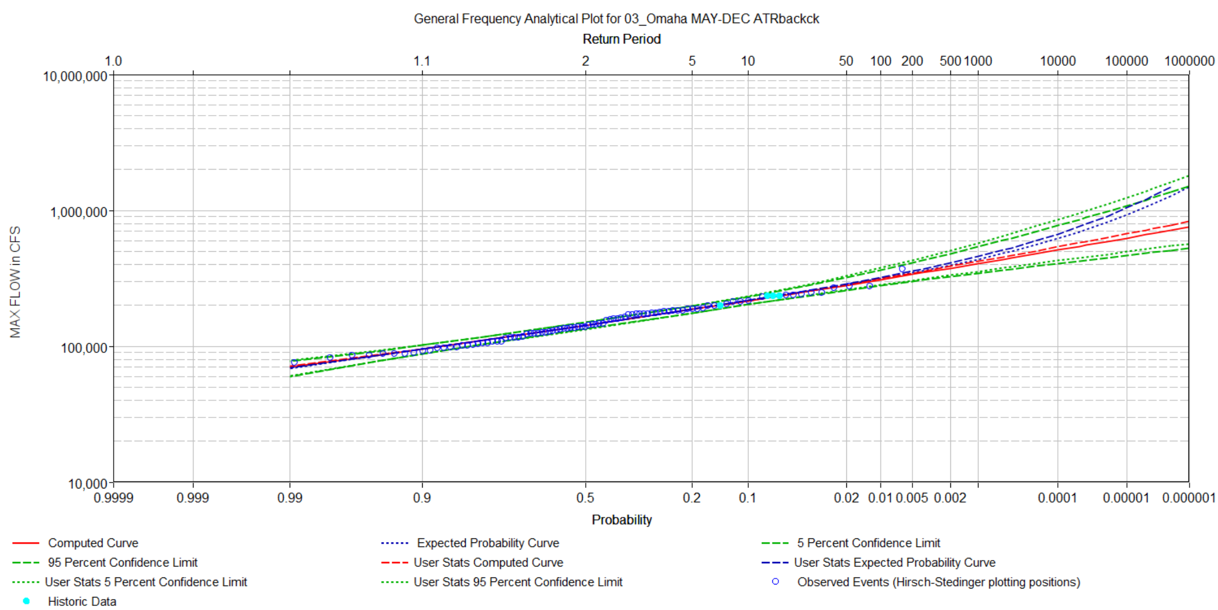


Figure 3-32. Omaha, NE May–Dec Unregulated Flow Frequency Curve

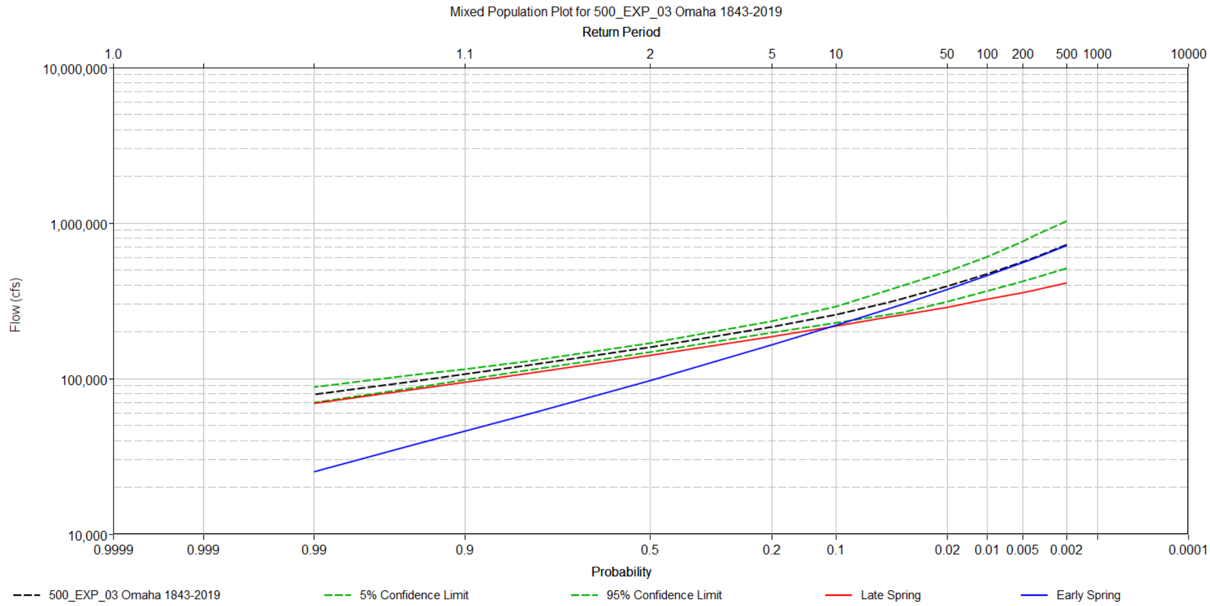


Figure 3-33. Omaha, NE Mixed Population Unregulated Flow Frequency Curve

As seen in the mixed population curves, the early spring, or Jan–Apr frequency curve drives the flow frequency at the Omaha, NE gage for events more extreme than 10% AEP. Table 3-11 presents a summary of the sensitivity analysis for the Omaha gage. As seen in the table, inclusion of the 1898-1929 data significantly decreases the computed frequencies, whereas shortening the period to 1930–2019, 1941–2019 and 1967–2019 results in increasing flows for each period. As reasonableness of the 1898-1929 data was primarily checked for annual volumes in the 2003 UMRSFFS, and it produces significantly different skew and standard deviation than other periods, this data was not entered as systematic data. Instead, the 1898-1929 data was used to inform historic peak flows and perception thresholds in conjunction with historic peak flow estimates from other studies. Ultimately, a consistent period of record of 1843-2019 for the early spring period and 1872-2019 for the late spring period was adopted. For the early spring period, very similar statistics were found at Omaha as compared to a historic period of 1819-2019, reflecting the earliest date of development that can be tied to historical flood information near Omaha with the temporary camp established at Fort Atkinson, present Fort Calhoun, NE.

Sensitivity analysis at Omaha for the treatment of 1898-1929 data was conducted after first verifying the Bulletin 17B calculations compared to the published statistics in the 2003 UMRSFFS Appendix F, Table F-40. Values from HEC-SSP were found to match the mean and skew to within 0.001 and had identical standard deviation to the published values in the report. A review of the Bulletin 17B results showed that 42 and 46 of the 100 events were flagged as high outliers in the Jan–Apr and May–Dec periods, respectively. After confirming the statistics could be reproduced, Bulletin 17C computations were made on the same 2003

UMRSFFS data from 1898-1997. This analysis flagged 38 low outliers of 100 years of data for the May–Dec period, with a Grubbs-Beck critical value of 144,200 cfs and skew of -0.89, lower than the Bulletin 17B station skew of -0.345. However, the Jan–Apr period produced identical statistics between the Bulletin 17B and 17C curves for the 2003 UMRSFFS 1898–1997 data, leaving minimal difference between the two guidelines in results.

Table 3-11. Summary of Jan–Apr Bulletin 17C Unregulated Flow Frequency Sensitivity Analysis at Omaha, NE

Sensitivity Analysis Description	Mean	St Dev	Skew	Historic Period & Effective Record Length	0.2% AEP, Sensitivity / Adopted Flow Ratio	1% AEP, Sensitivity / Adopted Flow Ratio
1898-1997 (UMRSFFS), 17B	5.031	0.243	-0.046	100	0.75	0.86
1898-1997 (UMRSFFS), 17C	5.031	0.243	-0.046	100	0.75	0.86
1898-1997*	5.031	0.243	-0.045	100	0.82	0.88
1898-2019*	5.017	0.246	0.055	122	0.85	0.90
1819, 1898-2019*	5.023	0.247	-0.008	201, 141	0.80	0.88
1930-2019	4.978	0.262	0.363	90	1.19	1.07
1941-2019	4.994	0.268	0.302	79	1.27	1.13
1967-2019	4.971	0.267	0.343	53	1.40	1.14
1875, 1930-2019	4.986	0.262	0.312	145, 112	1.08	1.03
1843, 1930-2019 (adopted)	4.996	0.263	0.200	177, 115	1.00	1.00
1843, 1930-2019, station	4.996	0.263	0.205	177, 115	1.00	1.00
1819, 1930-2019, w/ 1826, 1843	4.996	0.262	0.175	201, 126	0.96	0.98
1819, 1930-2019, w/ 1826, 1843, 1867	4.999	0.263	0.161	201, 127	0.97	0.99

*1898–1929 annual peak data entered from the 2003 UMRSFFS, the remainder from the current study

3.7.4 Nebraska City, NE, Unregulated Flow Frequency

Mixed population analysis was conducted at Nebraska City using the systematic period of 1930 to 2019 and historical flood information. Initial results were computed using flood history information back to the April 1881 flood at Nebraska City, NE. These results were expanded after ATR and TRG review to include the early spring or Jan-Apr historic period back to 1843, a documented flood upstream in Omaha, and downstream in Holt County, MO and Kansas City, MO. Additionally, the late spring or May-Dec historic period was expanded to 1878 to coincide with stage records initiating in Nebraska City.

Figures 3-34 and Figure 3-35 present the chronology for the Jan-Apr early spring season for a historic period of 1881 to 2019 and 1843 to 2019 as adopted, respectfully, with Figure 3-36 presenting the unregulated flow frequency curve. In this analysis, the perception threshold of 256,000 cfs used between 1881 and 1929 based on the April 1884 flood was retained for the period of 1878 to 1929 when stage records are available at Nebraska City. Using the 2003 UMRSFFS data, the largest event between 1898 and 1929 at Nebraska City was 273,000 cfs in April 1899, nearly identical to the historical peak value documented in Section 3.7. At 315,200 cfs, the 1947 Agricultural Levee re-study estimated the early spring 1917 event significantly higher than the 2003 UMRSFFS estimate of 211,000 cfs. Therefore, these numbers were converted to a range and best estimate of 263,000 cfs was assumed. A threshold of 300,000 cfs was set as the detection threshold for 1843 to 1880 based on information downstream in Kansas City with 1858 being the largest event of the period, and considering estimates for 1867 at St. Joseph, the largest flood there since 1844. For the early spring historic period back to 1881, a mean of 5.0581, standard deviation of 0.249, and skew of 0.261 were determined. For the expanded early spring historic period back to 1843, statistical values were reduced to a mean of 5.057, standard deviation of 0.244, and station skew to 0.181, and would decrease the 0.2% and 1% unregulated flow AEP flood by approximately 9% and 5%, respectively.

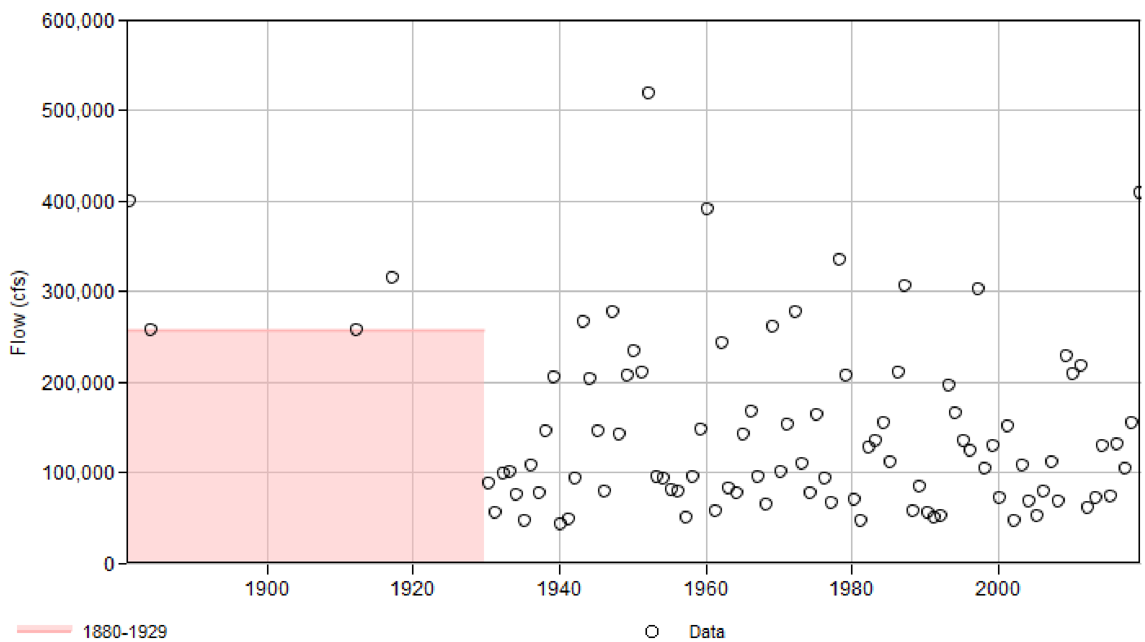


Figure 3-34. Nebraska City, NE Jan–Apr Chronology Plot For EMA Input, 1930 to 2019, Historical Period back to 1881

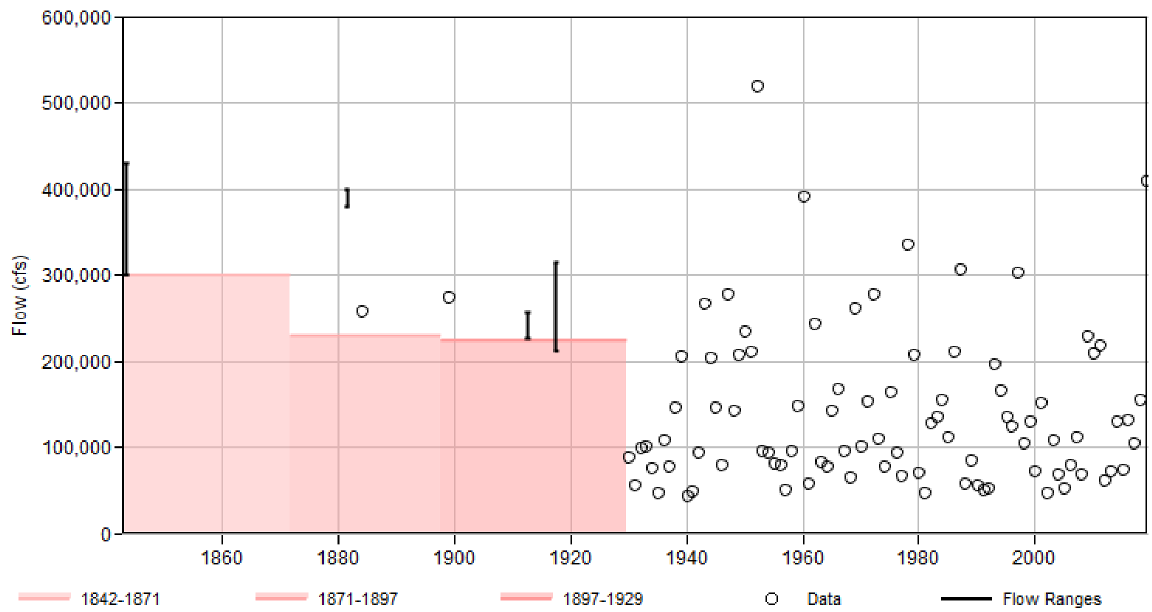


Figure 3-35. Nebraska City, JAN–APR Extended Chronology Plot for EMA Input, 1930-2019, Historical Period back to 1843 (Adopted)

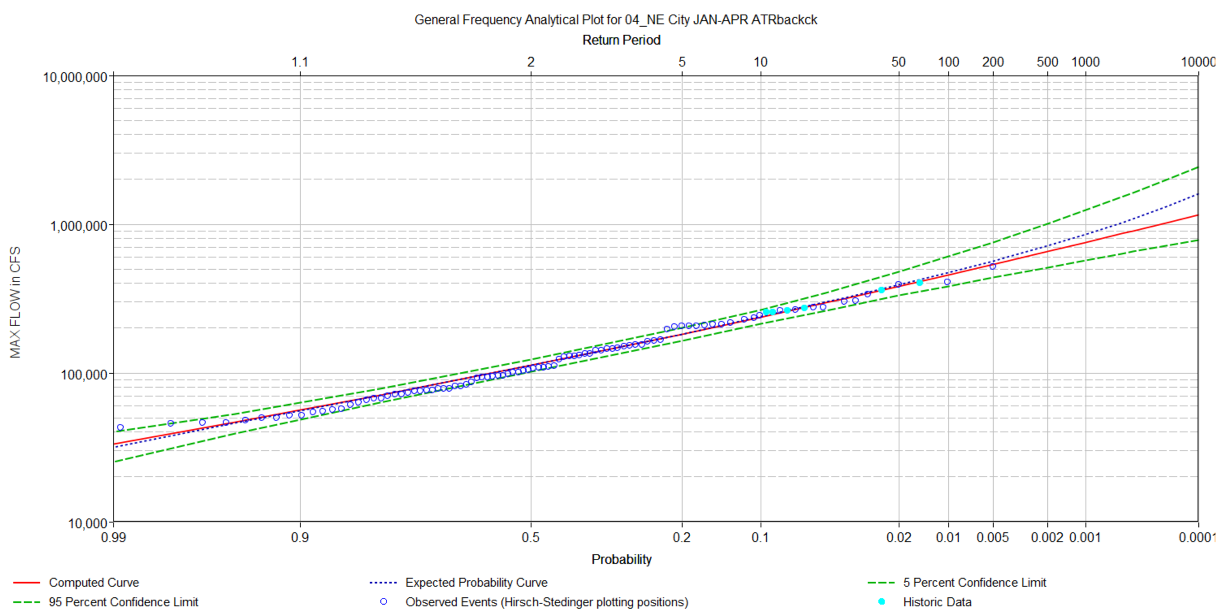


Figure 3-36. Nebraska City, NE Jan–Apr Unregulated Flow Frequency Curve (Adopted)

Figures 3-37 and Figure 3-38 present the chronology for the May-Dec late spring season for a historic period of 1878 to 2019 and the corresponding unregulated flow frequency curve with and without smoothing of station skew to 0.2. Figure 3-39 presents the mixed population unregulated flow frequency, which shows the early spring season produces higher flows than late spring for frequencies less than about 5% (1/20) AEP. Confidence limits shown on the mixed population frequency are from the ordered statistics as discussed further in Section 3.5 and Section 3.8.2.

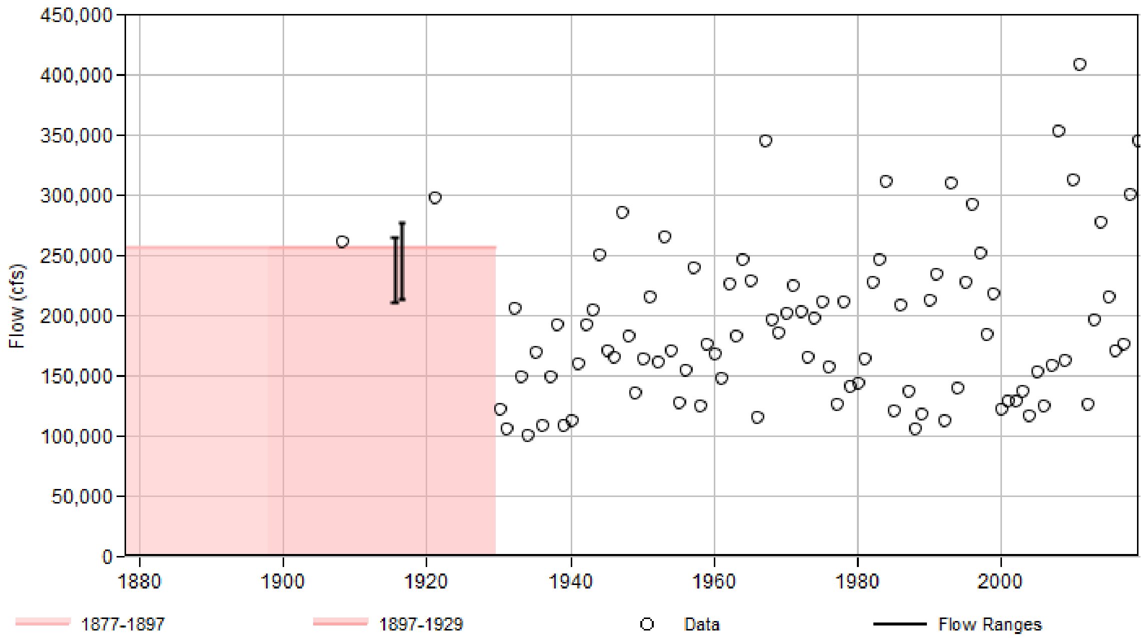


Figure 3-37. Nebraska City, NE May–Dec Chronology Plot For EMA Input

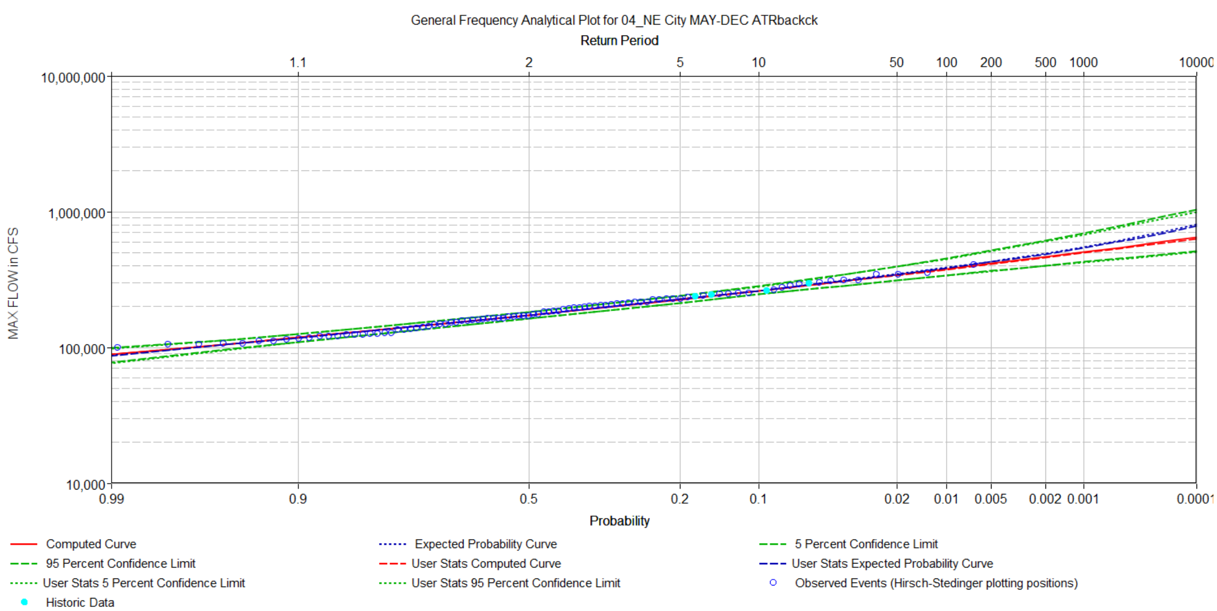


Figure 3-38. Nebraska City, NE May–Dec Unregulated Flow Frequency Curve, With and Without Smoothing of Station Skew

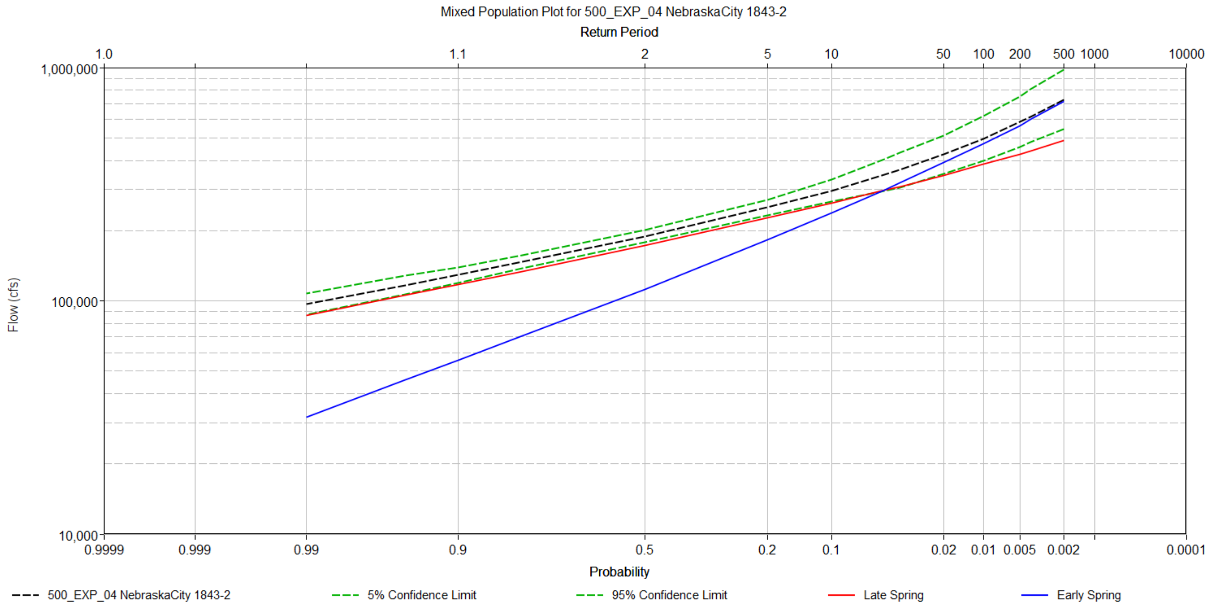


Figure 3-39. Nebraska City, NE Mixed Population Unregulated Flow Frequency Curve

3.8 Kansas City District Unregulated Flow Frequency Analysis

Analysis of the flow frequency at the Rulo, NE, St. Joseph, MO., Kansas City, MO, Waverly, MO, Boonville, MO, and Hermann, MO is presented in the following sections. Due to availability of more detailed historic flood information, additional sensitivity analysis to various historic periods was conducted at Hermann, Boonville, Kansas City, and St. Joseph, as complemented by the analysis of Omaha in Section 3.7.3. In addition to determining sensitivity of unregulated flow frequencies to historic periods, uncertainty of historic flood data provided an opportunity to investigate the sensitivity of methods for inputting historic flood estimates. This included use of the information either as ranges or as point values, and varying the estimates and perception thresholds, finding little difference in computed flows. Given extensive land use changes, the analysis focused on the largest historic floods, which are assumed less impacted by change than the more usual floods as in Section 2.7. Additionally, if estimates of historic floods varied over time as in 1844, the lowest estimates were not adopted, nor were the highest estimates. Generally, flow ranges for historic peaks were used when historical documents show a range for a particular flood, or if the stage was uncertain, whereas point values were used if there was greater confidence in the number or no information existed to estimate a flow range. This section is written from upstream to downstream for consistency within the report. However, as flood history information is generally better at downstream locations since development moved from east to west over time, assumptions made at upstream gages are often informed by downstream gages.

3.8.1 Rulo, NE, Unregulated Flow Frequency

A mixed population analysis was conducted at Rulo using the systematic information and historical flood information. Flood history information at Rulo has not been as extensively recorded as at other sites. With USGS gaging not initiating until 1949, very limited historic flow information is available at the site. However, historic major floods are known to have occurred in 1843, 1844, and 1881 at Rulo. Best available information was compiled from documents to obtain elevations of 1881 from the 1890 Rulo Bridge Report at 865.65 feet (likely preliminary mean tide, with possible adjustments for releveling) on the drawings and the USGS website. With an assumed gage zero of 838.8 feet, legacy datum in 1890, the 1881 USGS website stage of 22.9 feet is reproduced as are published annual maximum stages of 1886 and 1887 of 14.3 and 17.9 feet from USACE 1980 after scaling the flood elevations from the 1890 drawings. For 1844 from USACE high water mark files at Rulo, NE, which list the event in April, rather than June, at 856.9 feet, a gage zero of 837.23 feet NGVD29 was assumed from the gage records, for a stage of 19.7 feet, current gage datum. This April date indicates that the 1844 high water mark at Rulo may not be the maximum for the year, could be mislabeled as April instead of June, or may be confused with April 1843. However, high water mark profiles in the 1946 General DPR, Rulo to the Mouth, Plate number 62 show the same elevation labeled as June 1844 with the same gage zero elevation. A historical peak for April 1843 was assumed to be comparable to June 1844 and April 1881 based on the Holt and Atchison County, Missouri history book. Information indicates that 1844 flows were decreasing with distance upstream from the Kansas River.

With available stage records at Rulo, the 1844 peak was assumed no higher than 300,000 cfs, but is uncertain, whereas 1881 was estimated at 375,000 cfs as scaled between Nebraska City and St. Joseph. Given limited information, a flow of 360,000 cfs for April 1843 was assumed with a range of 300,000 to 450,000 cfs, the lower bound as assumed for 1844, the upper bound slightly lower than the 476,000 cfs estimate in Kansas City. For the June 1844 flood, a range of 250,000 to 350,000 cfs was assumed as informed by St. Joseph information. No historic peak elevations are available for the May–June 1903 flood event at Rulo, NE, leaving only the 2003 UMRSFFS to estimate that flow as 257,000 cfs, unregulated, with a low estimate of 241,000 cfs assumed from the "without depletion" data. MRC stage records between 1886 to 1901 indicate the highest stage occurred in 1899 at 19 feet, which was estimated at an unregulated flow of 267,000 cfs in the 2003 UMRSFFS, the highest flow of 1898-1929 in the May-Dec season, with a similar estimate of 264,000 cfs in Jan-Apr. Two Jan-Apr or early spring floods were estimated higher than 1899 in 1908 and 1921, both approximately 278,000 cfs using 2003 UMRSFFS data. Peak elevations digitized from the 1890 Rulo Bridge Report show higher stages in April 1884 than in 1899 by the MRC records by 0.75 feet, however, 1884 is exceeded by several events at St. Joseph aside from April 1881 between 1873 and 1899, most notably 1883 and 1878. Flood history rating curve information is presented in Figure 3-40. As seen in the figure, the historic data shows lower stages for the same flow as recent data, with an increasing trend over time which can be tied to mostly to private levee improvements below the Rulo Bridge after floods.

A perception threshold of 242,000 cfs Jan–Apr and 251,000 cfs May–Dec was used to produce same-year historic peaks from the 2003 UMRSFFS data 1898–1929 as used at St. Joseph, MO to help generate consistency between the gages. Historic peaks for the period 1898 to 1929 were pulled from the 2003 UMRSFFS data above thresholds as shown on the chronology plots for EMA inputs in Figures 3-41 and 3-42. Prior to 1898, the perception threshold was set at 300,000 cfs for both seasons based on 1858 flood information downstream at Kansas City, and April 1867, and available stage records starting in 1872 at Omaha and Fort Leavenworth, Kansas, and St. Joseph in 1873. Estimates for 1883 and 1884 were not used or made in this analysis at St. Joseph due to limited information, where perception thresholds were set around or above the anticipated magnitude of these events. Sensitivity of the results to 1883 assuming the same flow as St. Joseph was conducted and was found to reduce flows by less than 0.1% at the 0.2% AEP. The June 1883 flood, estimated at 306,000 cfs at St. Joseph, was likely the second largest peak behind 1881 between 1845 and 1897, and likely included a large flow from the Platte River to explain the lower magnitude in 1883 in Omaha. Therefore, a 300,000 cfs perception threshold is reasonable to meet or slightly exceed that event at Rulo. A sensitivity analysis to values assumed for the April, 1843 flood was conducted, increasing the best estimate to 375,000 cfs, same as 1881, or decreasing the estimate to 330,000 cfs in line with the Holt County Missouri History book stating there is but little difference between 1843, 1844, and 1881. These actions impacted the 0.2% AEP flood by less than half a percent. Additional sensitivity analysis was not conducted for Rulo since the data is not as detailed as St. Joseph and considering the relatively small changes in drainage area between the gages.

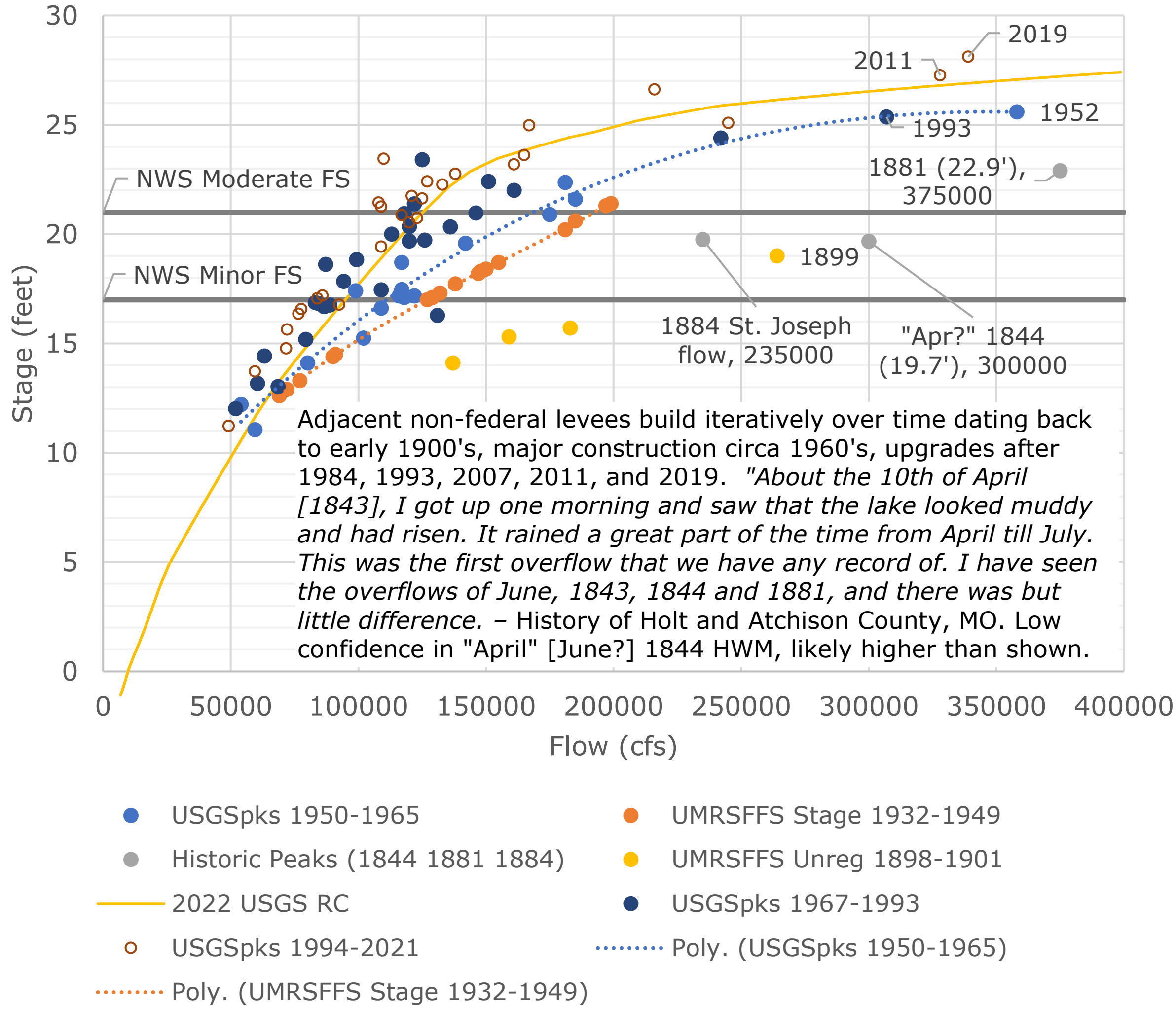


Figure 3-40. Flood History Rating Curve at Rulo, NE

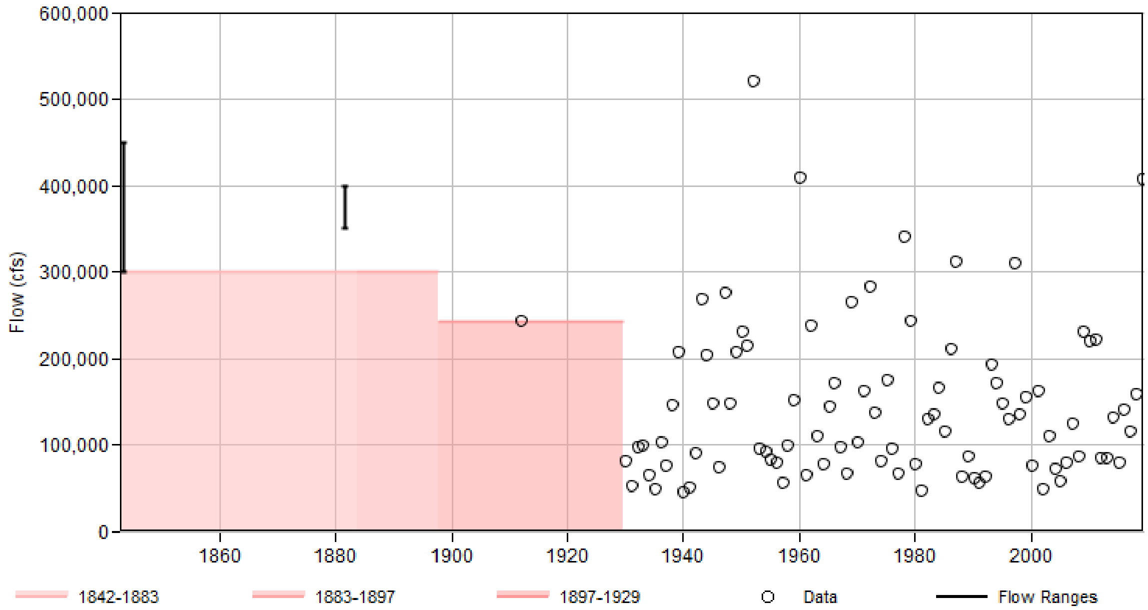


Figure 3-41. Rulo, NE Chronology Plot for Bulletin 17C EMA Input for 1930–2019 JAN–APR, historic back to 1843

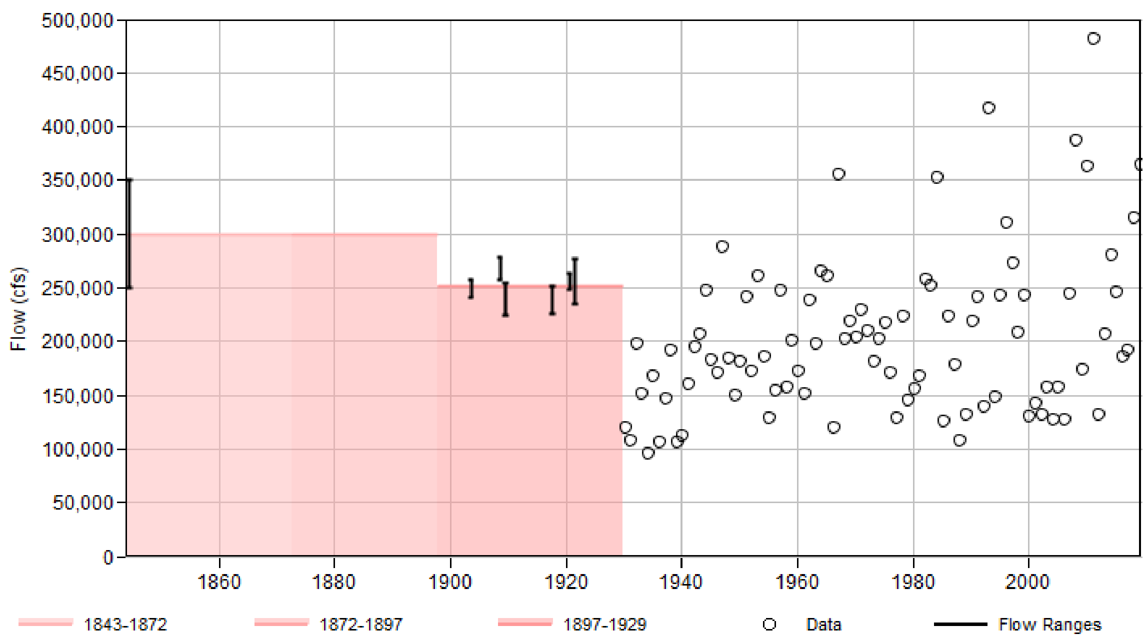


Figure 3-42. Rulo, NE Chronology Plot for Bulletin 17C EMA Input for 1930–2019 MAY–DEC, Historic back to 1844

Figures 3-43 and 3-44 present the Jan–Apr and May–Dec Bulletin 17C flow frequency plots, respectively. Figure 3-45 presents the results of the mixed population flow frequency analysis, which shows the early spring season produces higher flows than late spring for frequencies less than 2% (1/50) AEP. To compute this curve, the expected probability for each season was computed using Bulletin 17C, then copy-pasted into the mixed population analysis option in HEC-SSP and combined using equations summarized in Section 3.5. While the resultant curve is correct and would include the expected probability adjustment, the confidence limits are based on the ordered statistics which would typically provide narrower limits than those from Bulletin 17C. To determine the potential impact, a similar procedure was used to pull the confidence limits from the Nebraska City gage Bulletin 17C analysis and combine the probabilities in a mixed population analysis. Since the results showed that tails or extreme ends were very similar, being only very slightly wider, and the results were not used in computing the regulated flow frequencies, the ordered statistics confidence limits straight from HEC-SSP are shown for the mixed population gages. For additional discussion on the confidence limits shown, which we used little in the analysis, refer to Section 3.5, and the discussion in Section 3.8.2.

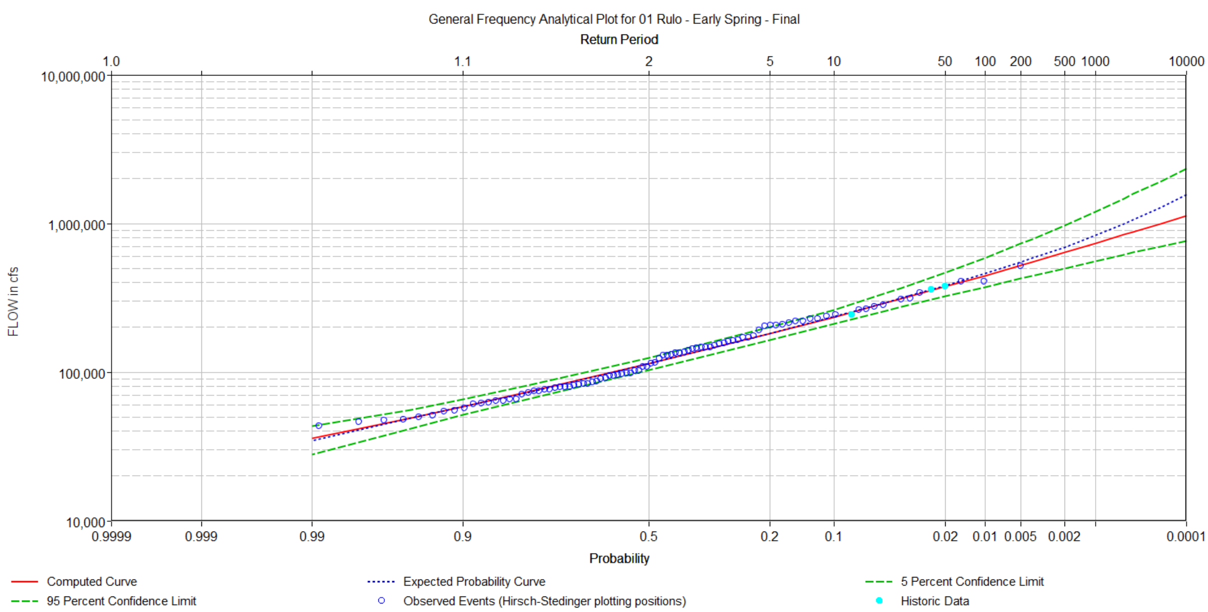


Figure 3-43. Jan-Apr Bulletin 17C Unregulated Flow Frequency Curve, Rulo, NE

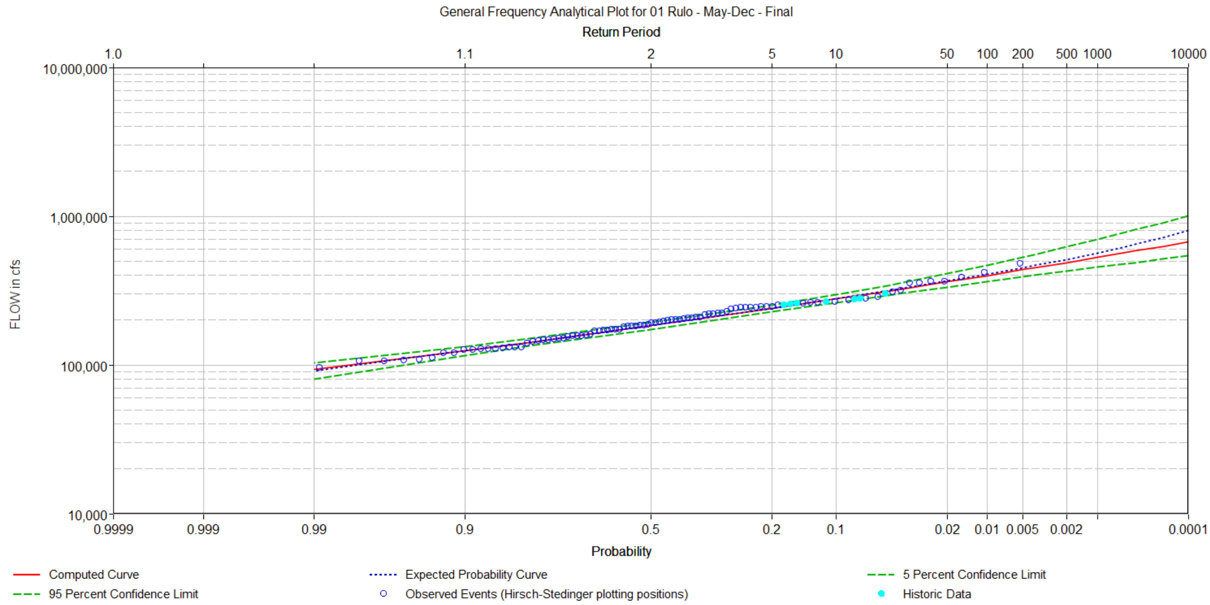


Figure 3-44. May-Dec Bulletin 17C Unregulated Flow Frequency Curve, Rulo, NE

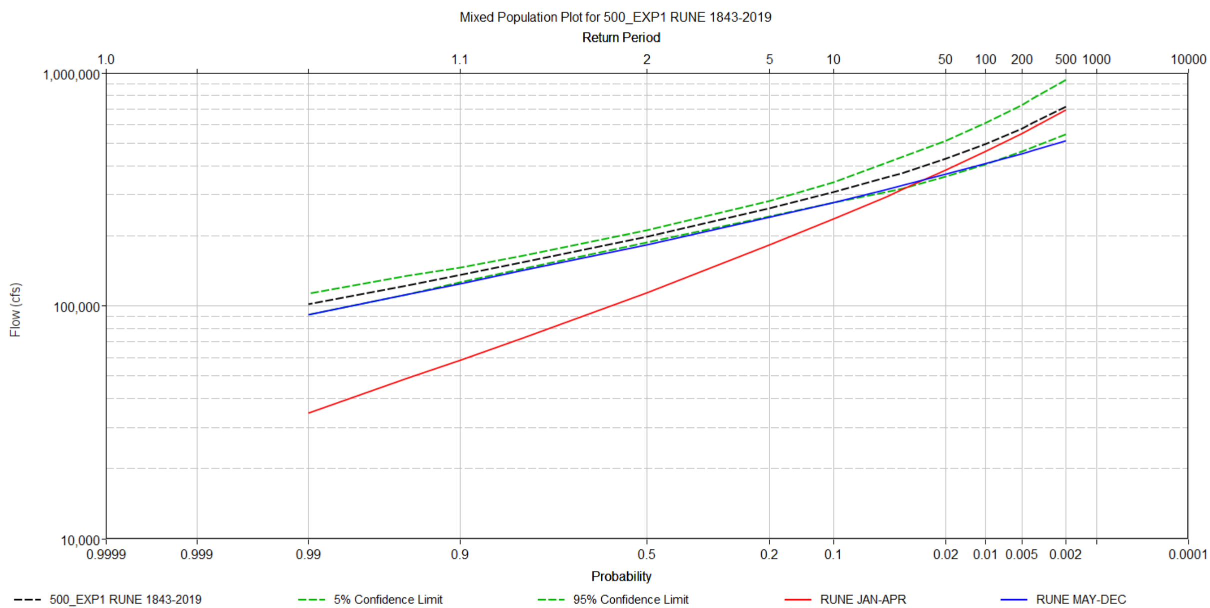


Figure 3-45. Mixed Population Unregulated Flow Frequency Curves for Rulo, NE

3.8.2 St. Joseph, MO, Unregulated Flow Frequency

Annual series and mixed population analysis was conducted at St. Joseph using the systematic information and historical flood information, which can be dated at least back to 1843 with the establishment of St. Joseph, and back to about 1820 given other information. While stage records initiated in 1873, they were considered unreliable prior to 1893 according to the 1947 Levee Definite Project Report, 1946 Hydrology Appendix A for Kansas City District, Plate No. 3. Investigation of the validity of the pre-1893 stage records and the associated flows was conducted by first compiling annual maximum stage records at St. Joseph and other Kansas City District gages from USACE 1980, Potamology Investigation. A historic rating curve was developed for St. Joseph using pre-BSNP USGS annual peak data from 1922 to 1935, and historic peak flows estimated previously for 1844, 1881, 1903, and 1908. While some uncertainty exists as to the accuracy of the stage estimate for the 1844 flood in St. Joseph, it has been long established as being 2.7 feet lower than 1881 by Missouri River Commission Records (MRC 1887). Stages on the NWS website list 1881 at 27.2 feet, and 1844 at 24.5 feet. However, USACE 1980 lists stages of 1877, 1878, 1881, 1883 all as 0.3 feet higher than the NWS website and puts 1881 three feet above 1844. Figure 3-46 presents the historic peak rating curve along with data from other time periods, additional estimates of historic peak flows, and the 2022 USGS rating curve, indicating stages of the largest flows increase as result of federal levee construction after 1952. Stages assumed for the historic peak events used in the historic rating curve were 1908 at 247,000 cfs and 20.4 feet, 1903 at 252,000 cfs and 20.5 feet, both flows from USACE 1947, 1883 at 23.1 feet and 306,000 cfs from USACE 1962, 1844 at 350,000 cfs at 24.5 feet, and 1881 at 370,000 cfs at 27.2 feet, both per the USGS website. As seen in the figure, historic floods passed a larger flow at the same stage as compared to more recent floods, which is attributed to levee construction and channelization from the BSNP (USACE June 2021).

To test the validity of flows derived from MRC stage records prior to 1893, flows from the historic rating curve were compared to the 1962 Levee Restudy Report for 1873, 1877, 1881 and 1882, matching within 2 percent on average, with a maximum difference of 4 percent. Additionally, flows of the largest floods of 1877, 1881, 1883, 1891, and 1892 of the pre-1893 data were compared to estimates of the same year flow at Kansas City (Kansas City information is in Appendix A and Section 3.8.3), yielding a range of 26 percent lower than Kansas City, to 17 percent higher. If adding estimates of 1844 and 1867, the range is St. Joseph 44 percent lower to about 20 percent higher than Kansas City. This range compared well to the 2003 UMRSFFS unregulated data for 1898 to 1997 with St. Joseph between 59 percent lower to 16 percent higher, with a median of 13 percent lower than Kansas City. Therefore, flows derived from the pre-1893 stage records at St. Joseph were deemed reasonable for consideration in this study.

Historic flood damages at St. Joseph were recorded in the Buchannan County History Book and other sources. For example, a steamboat carrying 200 passengers descended from St. Joseph, Missouri, reaching St. Louis about July 17, 1844, many of them flood victims returning to their homes in other states (Barry 1972). A flood reaching 24.5 feet at the gage, current datum as estimated for 1844 represents 7.5 feet above flood stage and is sufficient to flood low-lying portions of the future town of Elwood, KS later established in 1856 across the river from St. Joseph. A flood higher than 24.5 feet in 1844 could have discouraged development of the town of Elwood, which was inundated in 1881 as shown in Doniphan County, Kansas, 1881 flood photographs. Further, as discussed in Section 2.4.9, the flood of 1867 was the largest event since 1844 in St. Joseph, 1867 being 4.9 feet below 1881 at Fort Leavenworth, KS, located about 40 miles downstream and ten miles upstream of the Platte River of MO/IA. Assuming the height below 1881 was similar in St. Joseph to Fort Leavenworth, 1844 would be 2.2 feet higher than 1867 at St. Joseph, which is considered reasonable against the descriptions of the 1867 Flood (see Appendix A, and Section 2.4.9). Holt County history, just upstream from St. Joseph, documents "little difference" between the April 1843, June 1844, and April 1881 floods (see Section 2.4.6). Dates that St. Joseph was established being near that time, coupled with flood victims in 1844, make it uncertain whether they were aware of the April 1843 flood, or if the flood was lower at St. Joseph than in Holt County. As many people arrived in 1844 according to the Buchannan County History and considering Kansas City and Omaha records which show a large flood occurred in 1843, the estimate of 1843 as comparable to 1844 and 1881 from Holt County was retained for St. Joseph.

Analysis of the floods of the period indicate events of magnitude approaching 300,000 cfs were detected after 1844 and prior to gaging as found in multiple newspaper articles and history books in the area as in 1858, 1862 and 1867. After stage records initiated in 1873, similar sized events tended to generate the most attention, such as June 1883, which impacted mostly below the Platte River peaking just above 300,000 cfs at St. Joseph. Therefore, 300,000 cfs was used as the perception threshold for the early spring and late spring seasons from 1843/1844 to 1897. Prior to 1843, the best estimate assumed for 1843 of 360,000 cfs, comparable to the 1826 flood estimate at Kansas City, was applied as the perception threshold for the historic periods back to 1820, the date a flood smaller than 1826 was detected upstream near Omaha at Fort Atkinson. A best estimate of 350,000 cfs, and range of 300,000 to 400,000 cfs was assumed for April, 1826, whereas 360,000 cfs was assumed for April 1843 with a range of 300,000 cfs to 450,000 cfs, given uncertainties with stage in St. Joseph, coupled with Kansas City and Omaha estimates. After the 2003 UMRSFFS data was available, a perception threshold of 268,000 cfs was adopted as estimated for 1912, the largest early spring flood between 1898 and 1929 in St. Joseph. For the late spring period, peak flows exceeding 268,000 cfs were entered as historic peak flows using best estimates of the 2003 UMRSFFS unregulated flows, and low estimates as estimated in the 2003 UMRSFFS from stage records. The chronology plots for EMA input for the mixed population flow frequency analysis are presented in Figures 3-47 and Figure 3-48 using the 1930 to 2019 systematic data, and historical information back to 1843 or 1844 as adopted in this study. Chronology plots for the early spring, or Jan-Apr extended historic periods back to 1820 are presented in Figure 3-49, reflecting information previously described for historic peaks and perception thresholds. Appendix A presents the final perception thresholds and historic peak flows used in the adopted analysis.

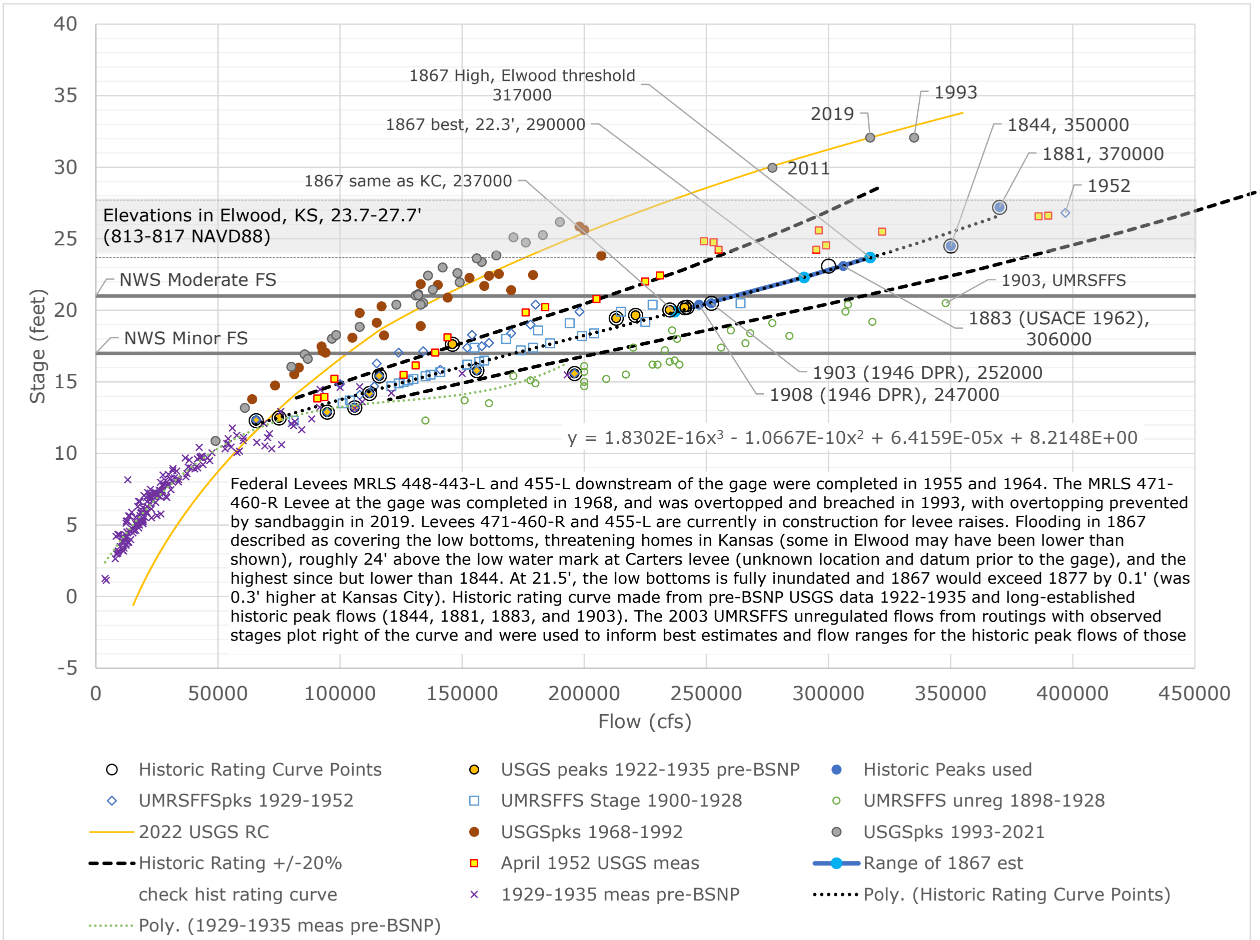


Figure 3-46. Flood History Rating Curve at St. Joseph, MO

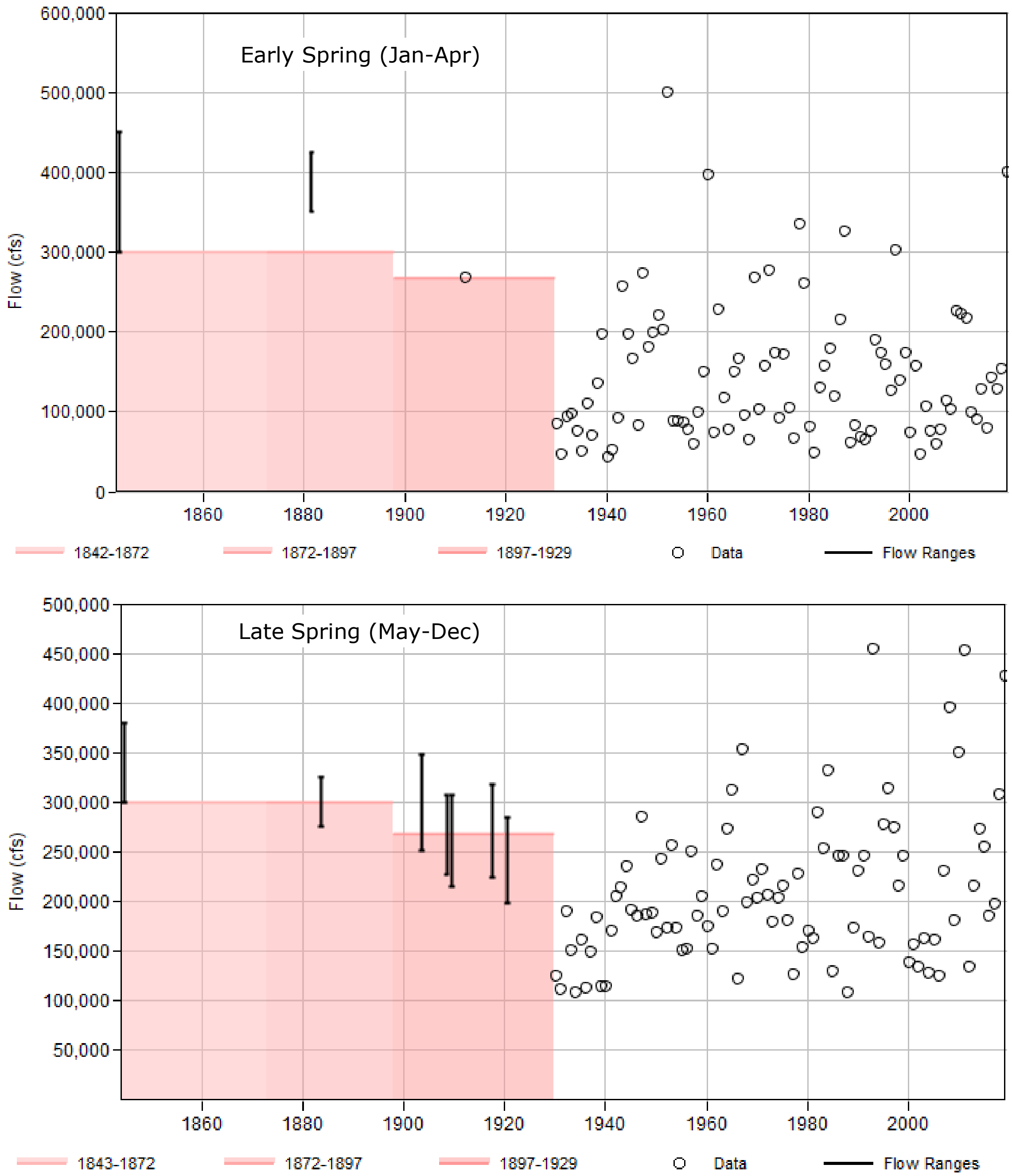


Figure 3-47. St. Joseph, MO Chronology Plot for Bulletin 17C EMA Input for 1930–2019, and the Historic Period back to 1843/1844 for the Early Spring and Late Spring Seasons (Adopted)

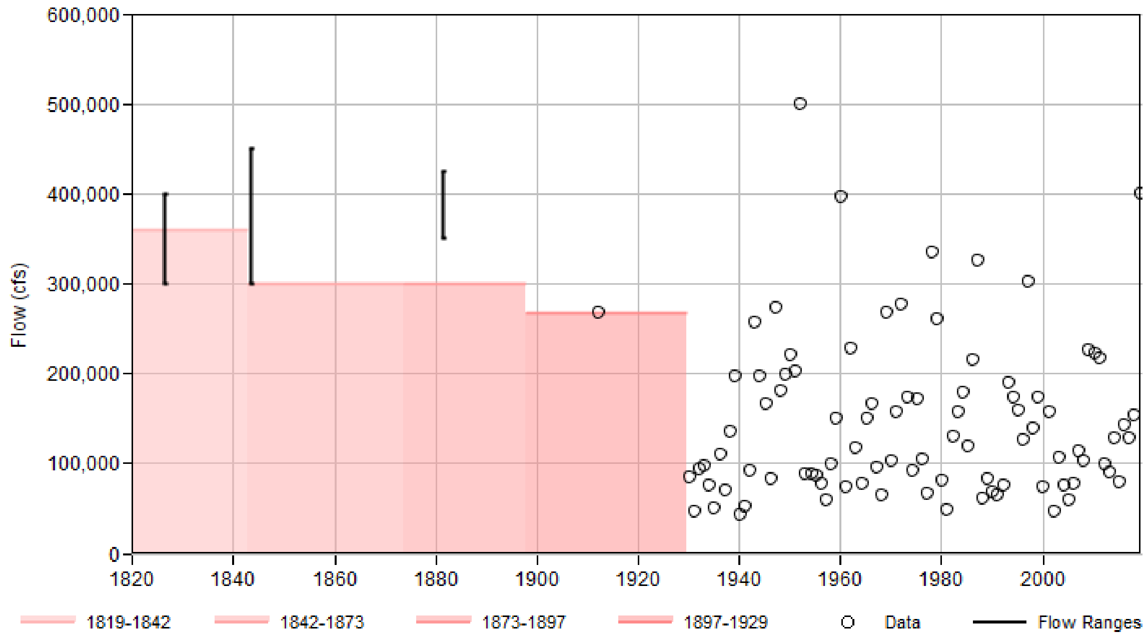


Figure 3-48. St. Joseph, MO Chronology Plot for Bulletin 17C EMA Input for 1930–2019, JAN-APR, Historic back to 1820

Figure 3-49 and Figure 3-51 present the Bulletin 17C unregulated flow frequency curves for the Jan–Apr and May–Dec seasons at St. Joseph, MO, respectively. Figure 3-52 presents the results of the mixed population curve for St. Joseph, Missouri. As seen in the figure, for events more extreme than approximately 2% AEP, the early spring (Jan–Apr) frequency curve drives the mixed population flow frequency curve. This shows a decreasing impact of the early spring period on flow frequencies with drainage area and as the river direction continues south. To compute this curve, the expected probability for each season was computed using Bulletin 17C, then copy-pasted into the mixed population analysis option in HEC-SSP and combined using equations summarized in Section 3.5. While the resultant curve is correct and would include the expected probability adjustment, the confidence limits are based on the ordered statistics which would typically provide narrower limits than those from Bulletin 17C. To determine the potential impact, a similar procedure was used to pull the confidence limits from the Nebraska City gage Bulletin 17C analysis and combine the probabilities in a mixed population analysis. Since the results showed that tails or extreme ends were very similar, being only very slightly wider, and the results were not used in computing the regulated flow frequencies, the ordered statistics confidence limits straight from HEC-SSP are shown for the mixed population gages.

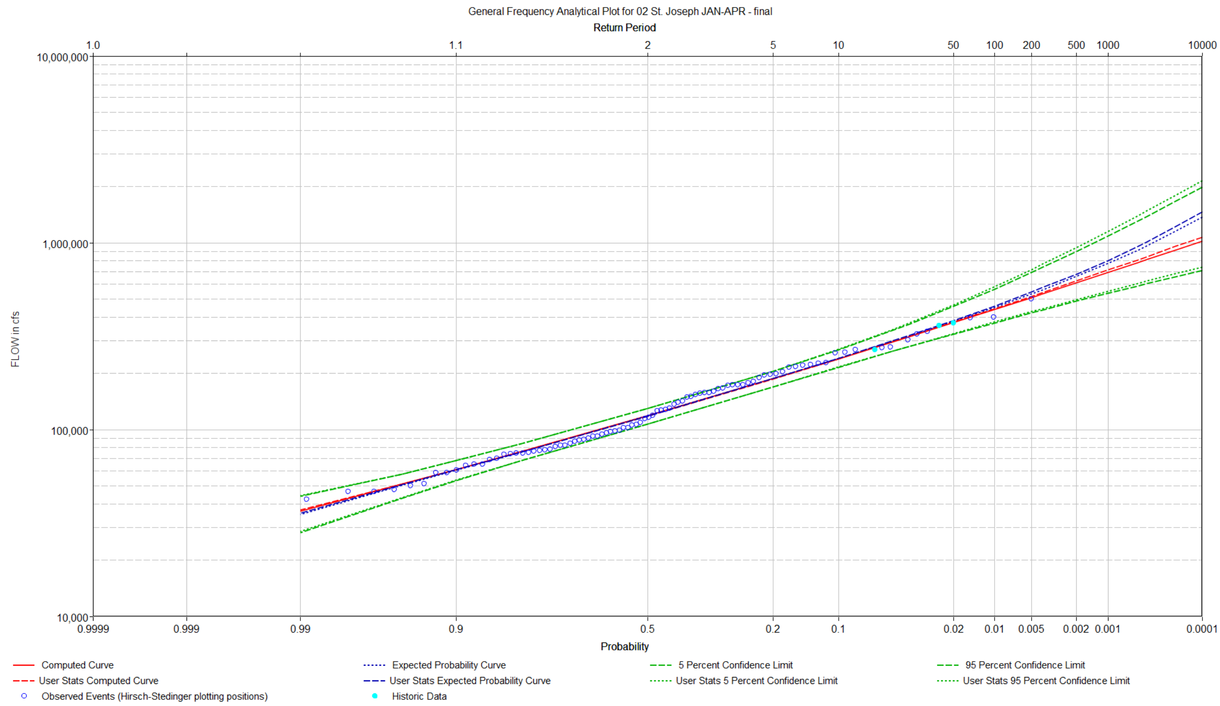


Figure 3-49. JAN–APR Bulletin 17C Unregulated Flow Frequency Curve, St. Joseph, MO, 1930-2019, Historic Period to 1843 With and Without Smoothing of Skew (Adopted)

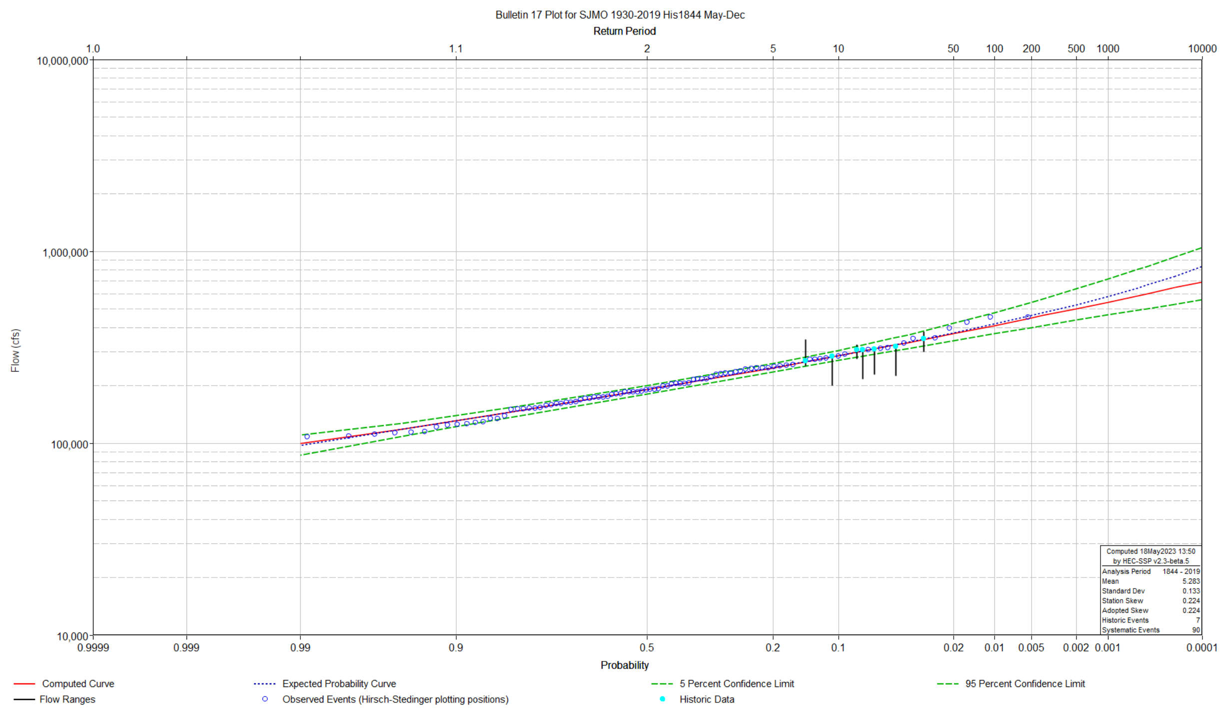


Figure 3-50. May–Dec Bulletin 17C Unregulated Flow Frequency Curve, St. Joseph, MO, 1930-2019, Historic Period to 1844 (Adopted)

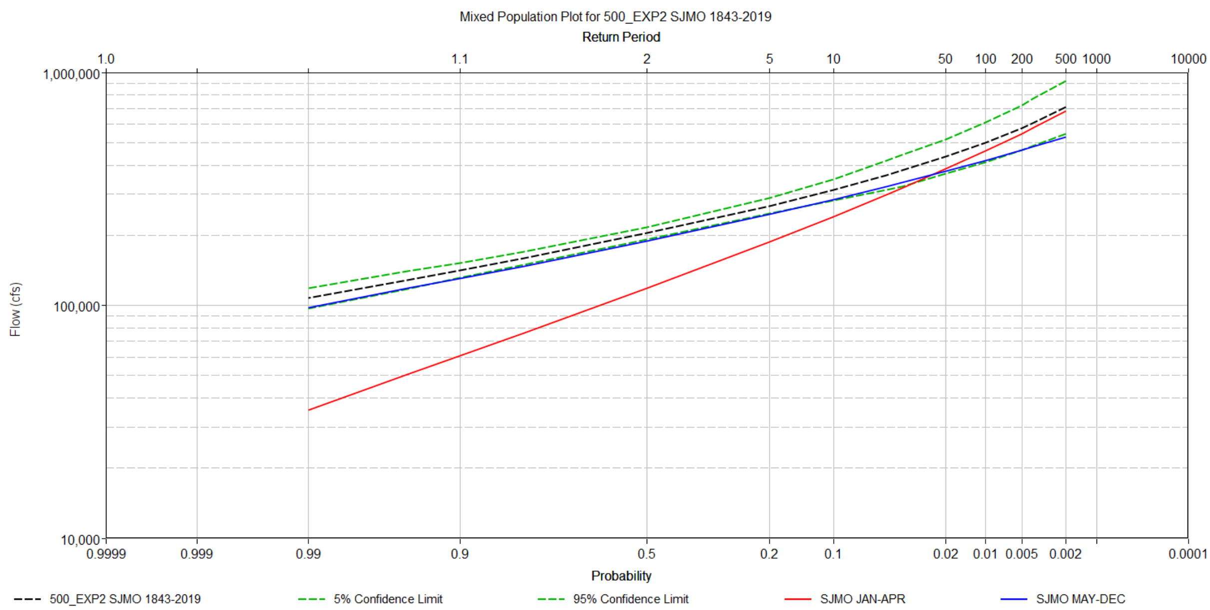


Figure 3-51. Mixed Population Unregulated Flow Frequency Curve for St. Joseph, MO

Bulletin 17C unregulated flow frequency results are presented in Table 3-12 for various time periods and data sets, including single season and mixed population results. Results of these analysis show that mixed population analysis produces higher flows than annual series analysis at St. Joseph, and that incorporation of historic information serves to reduce the flow frequencies as compared to the systematic period. With St. Joseph being in the same reach between the Platte and Kansas Rivers as the Omaha District analysis in Appendix D of Nebraska City, use of the 2003 UMRSFFS data from 1898 to 1929 was not adopted into the final study results. However, mixed population analysis of the period of 1829 to 2019, which utilized the 2003 UMRSFFS data prior to 1930, yields similar results, only 5% higher at the 1% AEP, to the adopted historic period based on the 1930 to 2019 systematic data, and largest historic peaks prior to 1930 back to 1843. Adopted results are also comparable to the annual series or single season analysis of the 1930 to 2019 systematic data, matching within 2% at the 0.2% AEP. Though statistics are different, results of the two routing methods, either the ResSim as adopted, or the HEC-RAS as further discussed in Section 4, are within 2% at the 0.2% AEP, with HEC-RAS being 8% lower at the 1% AEP. Using the full historic period at St. Joseph back to 1820, as informed by Omaha and Kansas City, would result in minor decreases in flows of approximately 2% at the 1% AEP event compared to the adopted results. Smoothing of skew applied to the early spring period from a station skew of 0.136 to 0.018 in the adopted results increased the 1% AEP flow by 1%, and 0.2% AEP flow by 3%. Varying the method of inputting historic peaks as point values of the best estimate as opposed to the ranges shown altered flows of either season by less than 0.1%.

Table 3-12. Bulletin 17C, Unregulated Flow Frequency, Expected Probability Flows for Different Data Sources and Time Periods, Missouri River at St. Joseph, Missouri

Annual Exceedance Probability (percent)	cfs						
	1930–2019 Annual	1898–2019 Annual	1930–2019 Mixed	1930–2019 RAS Mixed	1898–2019 Mixed	1930–2019, 1843/44 Mixed (adopted)	1930–2019, hist 1820 / 1844 Mixed
0.1	825000	665000	1140000	1143000	851000	828000	781000
0.2	719000	603000	926000	906000	731000	707000	676000
0.4	630000	546000	763000	729000	632000	607000	587000
0.5	604000	529000	718000	682000	604000	578000	562000
1	531000	479000	601000	557000	526000	500000	491000
2	466000	431000	507000	461000	459000	435000	430000
4	407000	386000	429000	384000	401000	379000	376000
5	389000	371000	407000	363000	384000	362000	360000
10	335000	327000	344000	303000	333000	314000	313000
20	282000	281000	287000	251000	284000	268000	268000
50	206000	213000	212000	187000	216000	205000	205000
80	154000	162000	162000	146000	167000	160000	160000
90	134000	141000	142000	130000	147000	141000	142000
95	119000	125000	128000	119000	133000	128000	128000
99	95000	100000	107000	103000	111000	107000	107000
Mean (J-A)	5.32	5.33	5.089	5.059	5.102	5.079	5.081
Std Dev (J-A)	0.154	0.142	0.242	0.226	0.228	0.231	0.232
St. Skew (J-A)	0.251	0.103	0.264	0.455	0.134	0.136	0.113
Adopt Skew (J-A)						0.18	
Mean (M-D)			5.295	5.243	5.304	5.283	5.283
Std Dev (M-D)			0.145	0.135	0.137	0.133	0.133
St. Skew (M-D)			0.348	0.617	0.203	0.224	0.224
Grubs-b cr	0	0	0	0	0	0	
#Historic	0	0	0	0	0	3 / 7	4 / 7
Low Outliers	0	0	0	0	0	0	0
Missing Flows	0	0	0	0	0	84	106
#Systematic	90	122	90	90	122	90	90
Historic Period	90	122	90	90	122	177	200
Equiv Length	90	122	90	90	122	117	125.5

Note: Table column headings reflect data used as follows: The 1930–2019 data is the HEC-ResSim based routings except for the column labeled "1930–2019 RAS" which are HEC-RAS based routings from Section 4 of the report. The word "annual" reflects the annual maximum series, whereas "mixed" reflects the mixed population frequency analysis. Flows from 1898–1929 reflect 2003 UMRSFFS data. Where historic events were used the earliest date of the historic period for each season (early and late) is indicated.

3.8.3 Kansas City, MO, Unregulated Flow Frequency

Annual series and mixed population analysis was conducted at Kansas City using the 90-year systematic period and historical flood information, which is more detailed and reliable than at most locations. This includes a well-established 1844 high water mark by bridge engineer Octavius Chanute, who compared over ten nearby eye-witness high water marks which agreed well when accounting for slope of the river, thus translating them to the original bridge within 200 feet of the current USGS gage. Historic peak flows of 1903 and 1844 were made by USACE in the "308 report" of 1932/1935 and have been deemed reasonable over time. An estimate of the 1858 flood height relative to 1844 and statement that this was the largest event between 1844 and 1870 was also documented (Chanute, 1870). Similarly, the July 1858 flood is documented as the largest event on the Kansas River between 1844 and 1903 (USACE 2021, KC Levees). Relatively reliable estimates of the flood heights of April 1826 and April 1843 in relation to each other and as being ten feet and six feet below 1844, respectively, were established by comparing accounts of John McCoy, a land surveyor and one of the founders of Kansas City, the Chouteau family, and naturalist John Audubon against floodplain topography. Stage records are available from 1867 to June 1869 from Chanute, and from 1873 to present. No large floods were detected in the approximately three-year gap in stage records (see Section 2.4.9).

Figure 3-52 presents the historic peak rating curve for Kansas City, including uncertainty estimates for floods referenced as ranges of feet below 1844, which in common in historical records for floods prior to stream gaging. As seen in the figure, historical peak flows of 1951 plot similarly to the earlier historical peak flow estimates for the largest flows such as 1844 and 1903. While most Missouri River levees held during 1951, flows of the Kansas River were entering the right bank of the Missouri River both upstream and downstream of the gage by overtopping the newly completed Central Industrial District floodwall from the land side throughout its length. Channel width was essentially levee-to-levee in 1951, spanning between the North Kansas City and East Bottoms Levees below the gage, whereas by 1993, channel width had narrowed significantly, largely in response to the BSNP (USACE 2021, KC Levees). This channel narrowing and federal levee construction, which included the construction of two large channel cutoffs downstream of Kansas City at Liberty Bend intended to help reduce stages and improve the navigation alignment, help explain the somewhat higher stages at high flows as seen on the 2022 USGS rating curve as compared to historic data. Lower portions of the 2022 USGS rating curve match more recent low stages, which reflect over 10 feet of bed degradation in response to sand and gravel mining, and response to large floods, which was shown to be minor until after the 1990's. Common of all four of the largest events at Kansas City is a large flow of the Kansas River as in 1844, 1903, 1951, and 1993. Appendix A includes a summary of historic coincident peak flows of the Kansas and Missouri Rivers prior to 1930.

Permanent settlers have inhabited the Kansas City area since approximately 1819 when the Chouteau family established the first of many of their fur trading warehouses near the confluence of the Missouri and Kansas Rivers. A Missouri River Chouteau trading post was established on the north bank three miles below the current USGS gage as early as 1822 and was destroyed in the flood of April 1826 (Marra and Boutros 2001). Land was purchased by the Chouteau family in the current East Bottoms Leveed area within Kansas City Levees after observing that the property did not flood in 1826 (1872 interview w/ P.M. Chouteau in Marra and Boutros 2001, page 203) where they would build expensive buildings for a home, warehouse, steamboat landing and their farm (McCoy 1881). However, 2 feet of water was documented in the Choteau home in current East Bottoms in late April 1843 (Audubon, 1843), which was flooded to the second story, destroyed, and abandoned after 1844 based on accounts of P.M. Chouteau in 1872, and J. McCoy in 1881.

After 1844, perception thresholds are set at or just below the 1858 flood, estimated at 301,000 cfs using the stage from Chanute 1870, for periods where stage data was not available. Detailed analysis of the April 1867 flood which peaked lower than 1858 as documented in Section 2.4.9 and Appendix A shows that flows after 1844 and prior to stage records did not likely exceed 300,000 cfs at Kansas City. Given uncertainty with flows estimated from stage records, the 300,000 cfs perception threshold was ultimately maintained for the period prior to 1930, inputting historic peak flows higher than this flow, such as but not limited to 1844, 1881, 1903, 1908, and 1915 as documented in Appendix A. Figure 3-53 presents the chronology plot for EMA input for the adopted analysis with a historic period dating back to 1844 with historic peaks and perception thresholds as previously described, with the corresponding unregulated flow frequency curve presented in Figure 3-54.

Additionally, the 1898 to 1929 data from the 2003 UMRSFFS was entered as systematic record as one part of the sensitivity analysis, then was used with more detailed flood history information back to 1819 as a second sensitivity analysis. For this analysis, a best estimate of 362,000 cfs was used for 1826 in Kansas City, with a perception threshold of 350,000 cfs assumed for 1819 to 1826. Given relocation of the Chouteau facility to higher ground, this threshold was raised to 400,000 cfs for the period of 1826 to 1844, knowing something slightly lower than 1843 would have been detected by the Chouteau family. For the period of 1845 to 1866, a detection threshold of 300,000 cfs was selected based on the 1858 flood. A known flood occurred in 1845 to include a short overflow of the Kansas River which destroyed crops of native tribes in the Kansas River floodplain as documented by the Bureau of Indian affairs, and in Barry 1972 for a gentleman waiting to cross a ferry on the Kansas River (see dates in Appendix A). However, with nearly all buildings in Kansas City destroyed the previous year, no estimate of its magnitude could be made. Still 1845 is assumed smaller than 1858 based on Chanute 1870. Between 1867 to 1897 before the 2003 UMRSFFS data is available, a detection threshold of 240,000 cfs, only slightly out of bank, was selected when stage records were available, and at 300,000 cfs for the three years of 1870 to 1872 without stage records. Figure 3-55 presents the chronology plot for EMA input for an extended as previously described and more detail historic period back to the first arrival of permanent settlers in Kansas City in 1819, which includes use of the 2003 UMRSFFS flows from 1898 to 1929. This extended analysis was intended to provide an estimate using the most detailed historic flood information available at Kansas City for comparison to the results with less detail as used at other study gages.

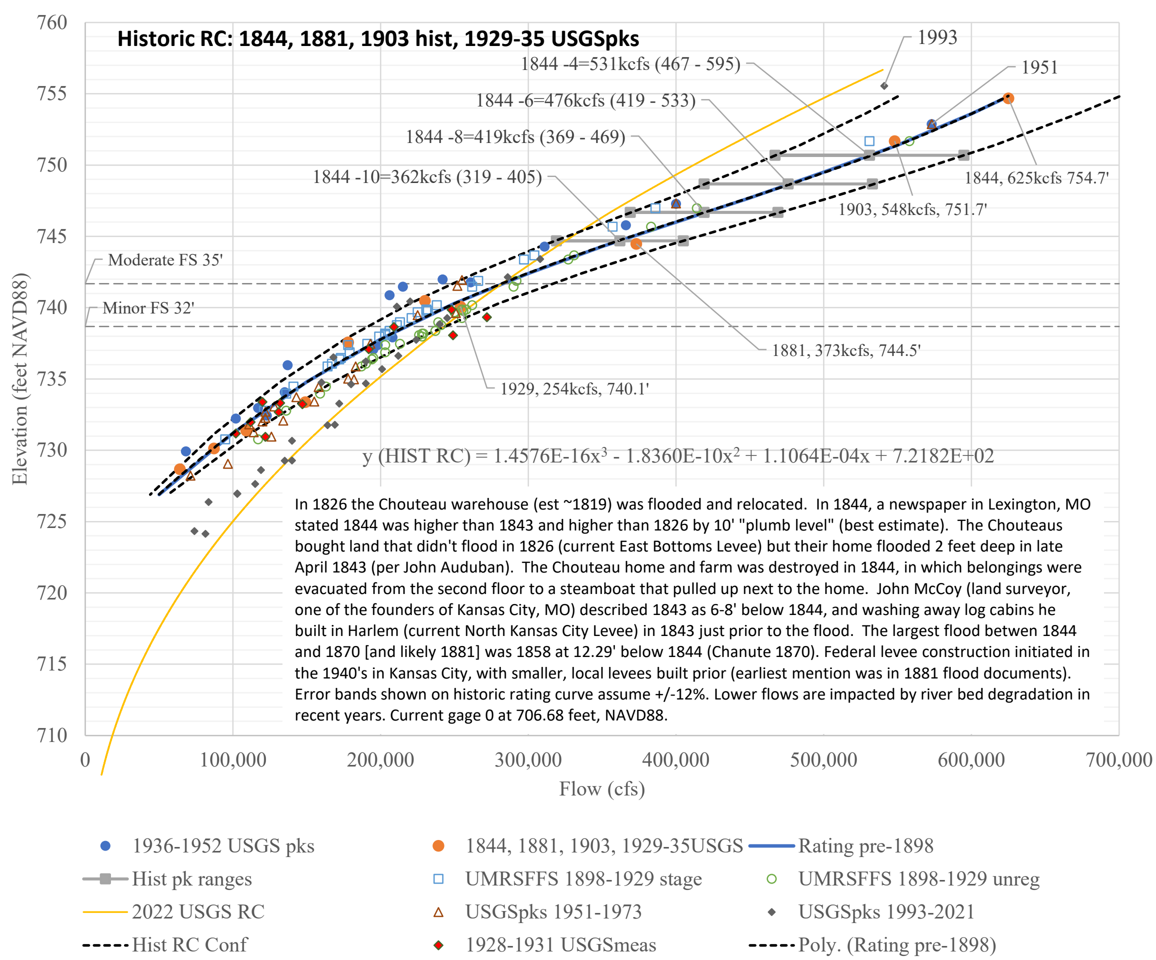


Figure 3-52. Historic Rating Curve at Kansas City, MO

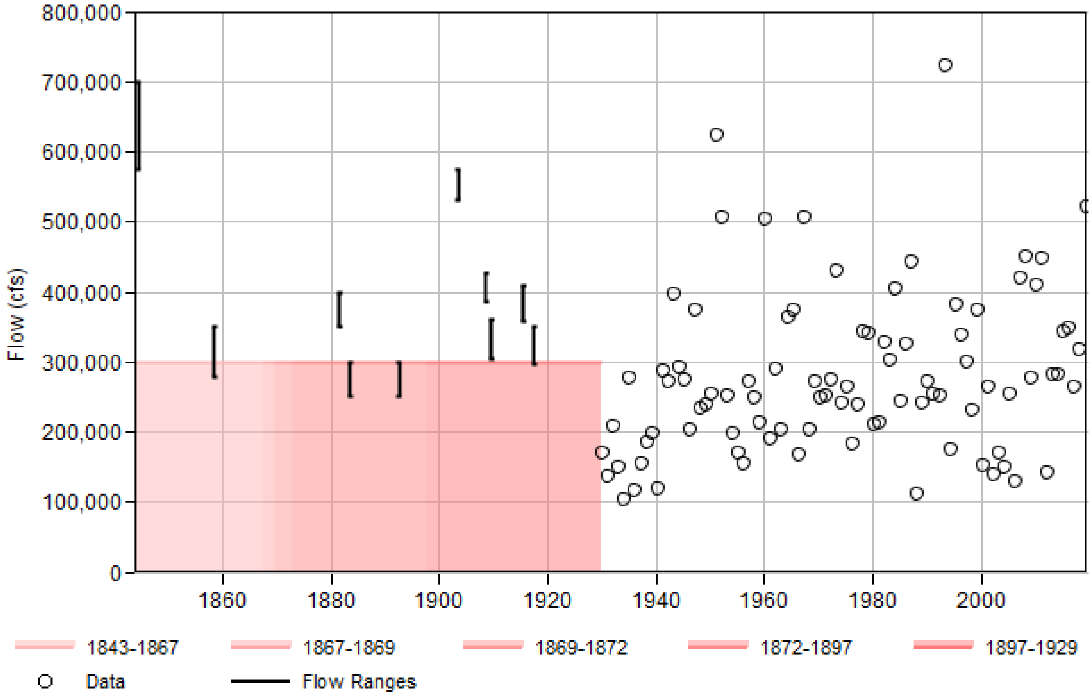


Figure 3-53. Kansas City, MO Chronology Plot for EMA Input, 1930–2019 and Historic Floods back to 1844 (Adopted)

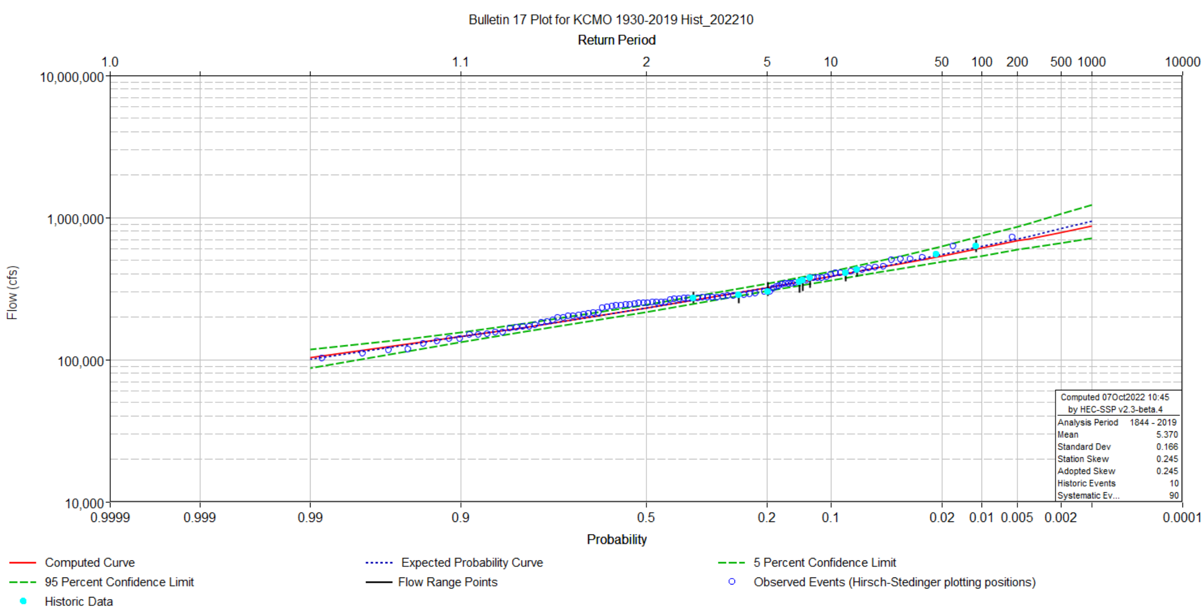


Figure 3-54. Kansas City, MO Bulletin 17C Unregulated Flow Frequency for 1930–2019 and Historic Floods back to 1844 (Adopted)

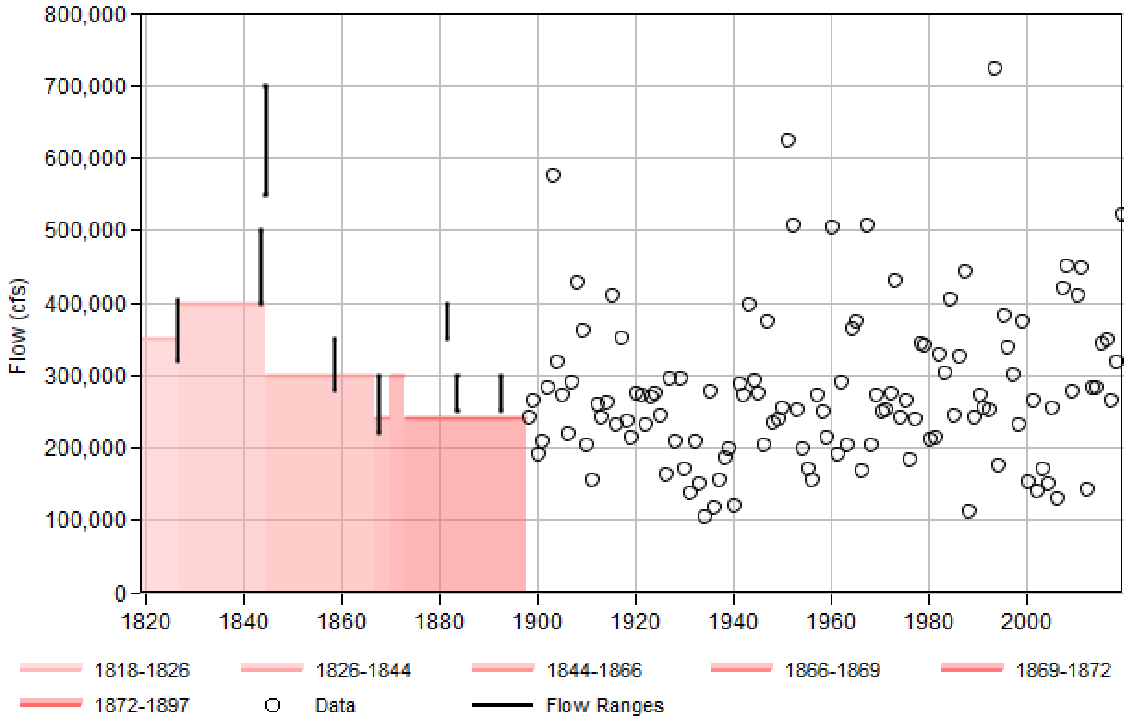
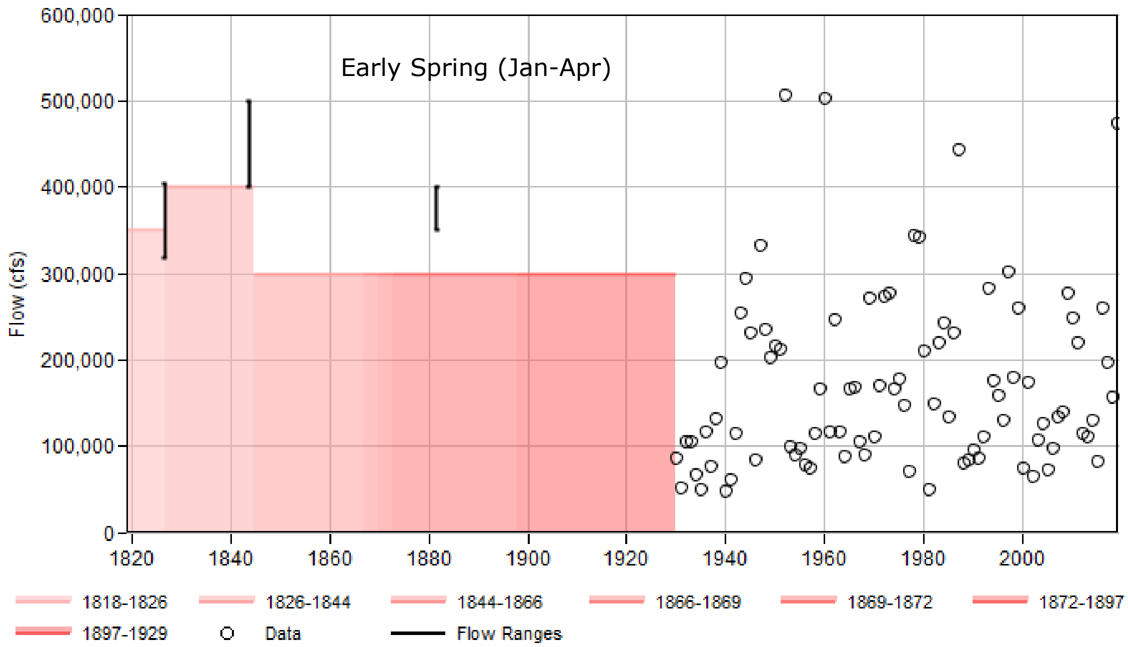


Figure 3-55. Kansas City, MO, Chronology Plot for Bulletin 17C EMA Input for 1898–2019, and Historic Floods back to 1819

Mixed population analysis was also conducted for the Kansas City gage, also using Jan-April as the early spring season after verifying the major floods of the season upstream in April did not peak in May in Kansas City. In addition to historic peaks of April 1826, 1843, and 1881, the major systematic early spring floods included 1952, the record unregulated peak upstream of Kansas City, and 1960, the largest rain on snow event known to impact the Kansas River, both exceeding 500,000 cfs, and March 2019 as the third highest event. One other rain on snow event was documented in the upper Kansas River Basin on the Republican River in 1935, however, flows attenuated significantly before reaching Kansas City. Figure 3-56 presents the mixed population chronology plots for EMA input of both seasons for a historic period back to the first arrival of permanent settlers in Kansas City in 1819, treating the historic period similarly to the adopted analysis prior to 1930. Figure 3-57 presents the results of the mixed population analysis for the historic period back to 1819. As seen in the figure, the late spring flows plot higher than the early spring season, which is the opposite of upstream gages which produce higher flows in early spring for probabilities greater than approximately 10% AEP upstream of the Platte River and decreasing in frequency to approximately 2% AEP by St. Joseph. This highlights the large impact that the Kansas River has on the hydrology of the Missouri River.



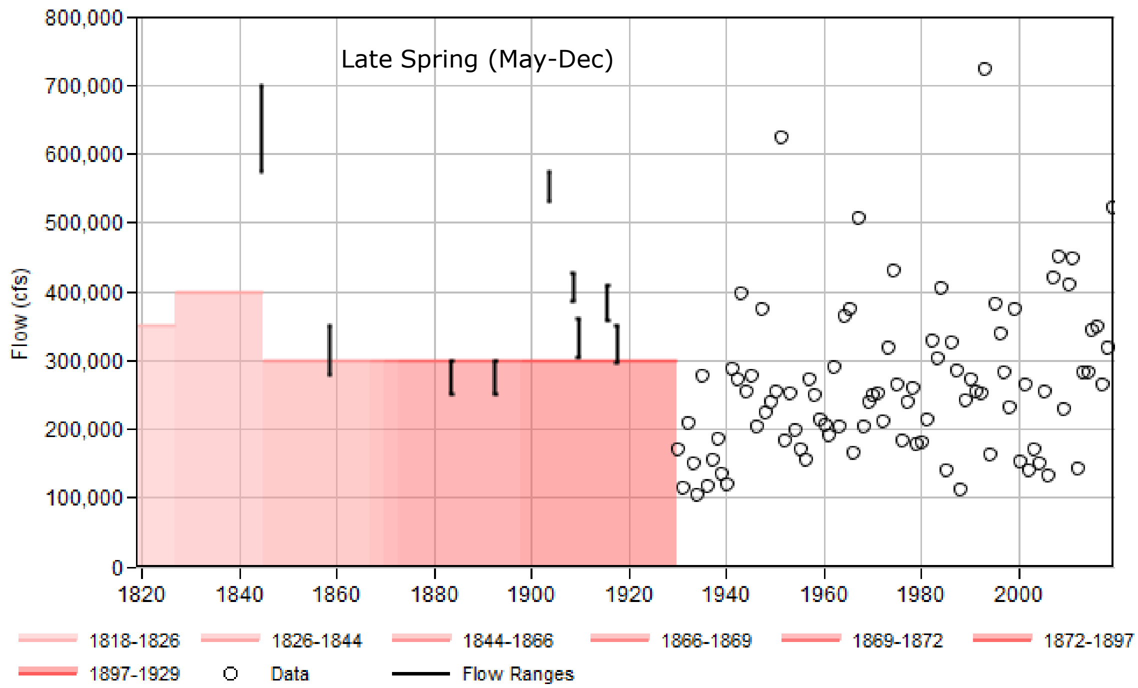


Figure 3-56. Kansas City, MO, Early and Late Spring Chronology Plots for Bulletin 17C EMA Input, 1930–2019 and Historic Floods back to 1819

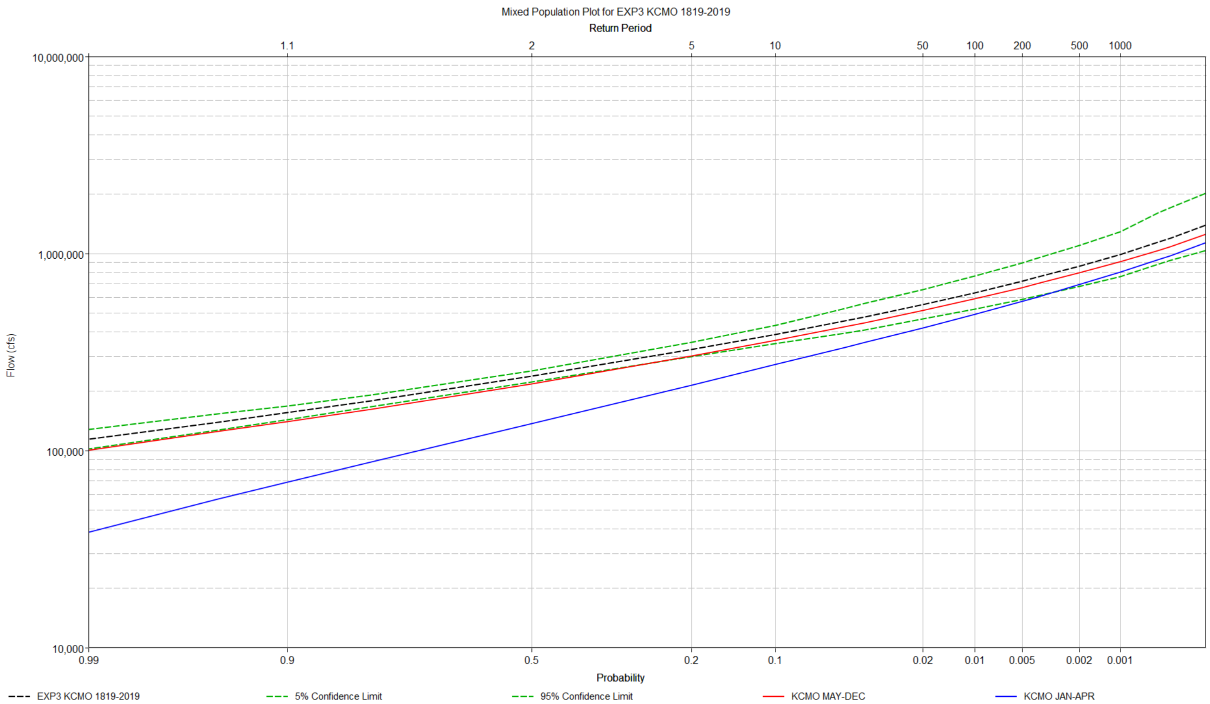


Figure 3-57. Kansas City, MO, Mixed Population Unregulated Flow Frequency Curves, 1930–2019 and Historic Period back to 1819

Unregulated Bulletin 17C flow frequency analysis results are presented in Table 3-13 for various time periods, data sets, and annual series and mixed population analysis. Additionally, a summary of sensitivity analysis to include consideration of the 2003 UMRSFFS data for comparison to the current study using both Bulletin 17B and 17C methods is presented in Table 3-14. As seen in the tables, extending the historic period prior to 1930 lowers the flows for both the annual series and mixed population analysis. At a 1% AEP, the 122-year period of 1898 to 2019, and mixed population analysis with a historic period back to 1819 produce similar results to the adopted analysis, which uses a single season with a historic period back to the 1844 flood. Though not tabulated, methods of inputting historic peak flows as either point values, or ranges of flows, were found to have very minor impact on computed flow frequencies. Mixed population analysis for the historic period back to 1819 results in flows only slightly higher than adopted with the late spring producing higher flows than early spring as previously discussed. For the systematic period of 1930 to 2019, the mixed population analysis showed comparable flows for both seasons at a 0.2% AEP. Therefore, no mixed population analysis was retained in the adopted unregulated flow frequency curve, consistent with the 2003 URMSFFS, which cited little evidence of a mixed population below the Kansas River. Further, as result of the Kansas City analysis, no additional mixed population analysis was deemed warranted downstream due to increasing tributary flows much less likely to be impacted by rain on snow or frozen ground events.

In analysis for the Kansas City Levees (USACE 2021, Kansas City Levees), sensitivity back to the 1785 flood and 1699 historic period yielded similar conclusions to Hermann and Boonville and were not included. Although data is limited for 1785, the Kansa Tribe relocated from the Missouri River Bluffs in the vicinity of St. Joseph, MO and Atchison, KS, to the Kansas River floodplain within a few years after the 1785 flood, selecting high terraces for their homes that did not flood in 1951, which peaked at 510,000 cfs at Bonner Springs, and likely not also in 1844 (similar flows to 1951), although there is some debate in the literature whether Fool Chief Village west of Topeka Kansas fully or partially flooded in 1844 (USACE 2021, KC Levees). Best information using a hydraulic model and all available high water marks indicate the village at most only partially flooded in 1844, consistent with the historical accounts of the village being an island during the flood, as told by the nearby Potawatomie Tribe (Flora 1952, USACE 2021, KC Levees). Combined with other statements of Native Americans warning early settlers to build higher (Flora 1952), there is a strong indication of the awareness of the native tribes who had lived in the area for some time to flood risk. For example, Paxtun 1897 reported that native tribes described large floods occurring approximately every 14 years in the Platte County, Missouri, history, which is located immediately upstream of the Kansas River confluence.

Results of each sensitivity analysis were summarized using the mean log of flow, standard deviation, skew, historic period and effective record length if different from the historic period, and ratios of the results of the sensitivity analysis divided by the adopted results for the 0.2% and 1% AEP events. The 2003 UMRSFFS estimated approximately 14% and 7% lower results at the 0.2% and 1% AEP compared to the adopted frequency curve. Over half of this difference is attributed to the regional skew smoothing in the 2003 study, which decreased the station skew from 0.287 to 0.17, then 2-3% is attributed to use of expected probability rather than computed probability. The remainder of the difference is attributed to differences in the flow records, both for systematic data, 22 years of new data, and treatment of historic peaks from Bulletin 17C. Shortened periods using only the systematic data showed higher flows of 4–9% for the 0.2% AEP and 8–10% for the 1% AEP with skews closer to 0 or negative. Using the 2003 UMRSFFS data and switching to Bulletin 17C procedures instead of Bulletin 17B results in flows matching the adopted results within 2% for both a systematic period of 1898 to 1997 and 1898 to 2019. Extending the period back to 1819 results in a 5% reduction of flows at the 0.2% AEP and by 3% for the 1% AEP. As results of more detailed flood history do not result in major changes in the flows, the overall approach for incorporating historic flood information for a consistent historic period at all ten study gages is considered reasonable, as also informed by more detailed analysis at Omaha, St. Joseph, Boonville, and Hermann.

Table 3-13. Bulletin 17C, Unregulated Flow Frequency, Expected Probability Flows for Different Data Sources and Time Periods, Missouri River at Kansas City, Missouri

Annual Exceedance Probability (percent)	cfs						
	1930–2019	**Mixed 1930-2019**	**1930–2019 RAS**	**1898–2019**	**1930–2019, hist to 1844 (adopted)**	**1898–2019, hist to 1819**	**Mixed 1930-2019, hist to 1819**
0.1	1025000	1295000	1018000	910000	947000	885000	992000
0.2	906000	1088000	881000	818000	835000	790000	865000
0.4	801000	922000	765000	735000	738000	705000	756000
0.5	771000	876000	732000	710000	709000	679000	724000
1	683000	750000	637000	637000	624000	603000	632000
2	603000	645000	553000	568000	547000	533000	551000
4	528000	553000	478000	503000	476000	468000	478000
5	505000	525000	455000	482000	454000	447000	456000
10	433000	444000	386000	419000	387000	385000	389000
20	362000	368000	320000	354000	322000	324000	325000
50	256000	263000	227000	257000	231000	236000	238000
80	182000	192000	164000	188000	169000	175000	179000
90	151000	164000	140000	159000	145000	151000	156000
95	130000	144000	122000	139000	128000	134000	139000
99	182000	113000	95000	106000	100000	107000	114000
Mean- A/ES	5.409	5.159	5.361	5.411	5.37	5.378	5.138
Std Dev- A/ES	0.176	0.247	0.171	0.162	0.166	0.158	0.231
Skew- A/ES	-0.006	0.133	0.213	0.034	0.244	0.231	0.046
Mean- LS		5.384					5.347
Std Dev- LS		0.175					0.161
Skew- LS		0.127					0.333
#Historic	0	0	0	0	10	8	12*
Low/high Out	0	0	0	0	0	0	0
#Missing	0	0	0	0	76	71	99*
#System	90	90	90	122	90	122	90
Hist Period	90	90	90	122	176	201	201
Eq. Length	90	90	90	122	119.761	147.426	130.528*

*For mixed population, the combined historic peaks and missing years for both seasons, and longest effective record length from both seasons, which was the May-Dec or late spring / summer season are tabulated.

Note: Table column headings reflect data used as follows: The 1930–2019 data is the HEC-ResSim based routings except for the column labeled "1930–2019 RAS" which are HEC-RAS based routings from Section 4 of the report. Flows from 1898–1929 reflect 2003 UMRSFFS data when entered as systematic record (two columns). Where historic events were used the earliest date of the historic period is indicated. Mixed denotes the two mixed population analysis columns, all others are annual series, this is denoted as "A" for annual, and ES for the Jan-Apr early spring season, and LS for the May-Dec late spring season for mean, standard deviation, and skew.

Table 3-14. Unregulated Flow Frequency Sensitivity Analysis Results Summary, Expected Probability, Missouri River at Kansas City, Missouri

Period, Data, Method (Bulletin 17C unless labeled as 17B)	Mean	St Dev	Skew	Historic Period & Effective Record Length	0.2% AEP, Sensitivity / Adopted Flow ratio	1% AEP, Sensitivity / Adopted Flow Ratio
1898-1997, UMRSFFS, 17B, station skew	5.414	0.143	0.287	100	0.93	0.98
*1898-1997, 17B, UMRSFFS, skew 0.17***	*5.414*	*0.143*	*0.17*	*100*	*0.86*	*0.93*
1898-1997, 17B, UMRSFFS, skew 0.17	5.414	0.143	0.17	100	0.89	0.95
1930-1997, UMRSFFS	5.412	0.155	0.225	68	1.09	1.06
1898-1997, UMRSFFS	5.414	0.143	0.287	100	0.98	0.99
1898-1997*	5.408	0.157	0.137	100	1.00	1.02
1898-1997 UMRSFFS, 1998-2019	5.416	0.151	0.114	122	0.95	0.99
1898-2019*	5.411	0.162	0.034	122	0.98	1.02
1930-2019, hist 1844 (adopted)	**5.37**	**0.166**	**0.244**	**176, 120**	**1.00**	**1.00**
1898-2019*, hist 1819	5.378	0.158	0.231	201, 147	0.95	0.97
Mixed 1930-2019, hist 1819				201, 131	1.04	1.01
Mixed 1930-2019				90	1.30	1.20
1930-2019	5.409	0.176	-0.006	90	1.09	1.09
1941-2019	5.438	0.162	0.044	79	1.08	1.10
1967-2019	5.44	0.167	-0.168	53	1.04	1.08

*1898–1929 annual peak data from the 2003 UMRSFFS, current study flows after 1929

**Reflects a reproduction of the 2003 UMRSFFS Results, Computed Probability

3.8.4 Waverly, MO, Unregulated Flow Frequency

Annual series analysis was conducted at Waverly using the systematic information and historical flood information. No historic peak flow estimates were found in the literature review for Waverly, MO other than the 2003 UMRSFFS data starting in 1898, and data from the 1962 hydrology study also back to 1898. Additionally, this site did not have stage records available for the full 2003 UMRSFFS study period, where data was filled in by flow routings from 1900 to 1915. Available high water mark profiles for historic floods were reviewed and stages were interpolated to the gage for 1844 and 1903 as summarized in Table 3-15, which also includes the largest stage from early Missouri River Commission

Records of 1883. Flows included in Table 3-15 were scaled by drainage area using peak flow estimates upstream at Kansas City and downstream at Boonville but were rounded to the nearest 10,000 cfs due to uncertainty with the estimates.

Table 3-15. Historic Peak Flow Estimates at Waverly, MO

Event	Gage Height (feet)	Estimated Peak Flow (cfs)	High Water Mark Elevation* (feet, legacy datum)	Elevation Source
1844 HWM ~	28.1	640000	673.6	USACE High water mark profiles
1903 HWM ~	23.0	550000	668.5	USACE High water mark profiles
1881 est.	22	370000	n/a	Estimated elevation, assumed from Kansas City flow
1883	19.6	280000	n/a	MRC Stage Records

*Legacy NGVD 29 gage zero elevation 645.49 feet; current gage zero is at 646.17 feet NAVD88; elevation taken from profile plots in Plate 10 of the 1946 Appendix A to the 1947 Levees DPR

Flows scaled to Waverly by drainage area between Kansas City and Boonville for all four floods and rounded to the nearest 10,000 cfs; 12.5% of the drainage area change occurs by Waverly, the remainder between Waverly and Boonville, including three large tributaries of the Grand, Chariton, and Lamine/Blackwater Rivers.

A difficulty with very large floods at Waverly, MO is the extremely wide floodplain at the gage location compared to over gages, aside from perhaps Rulo. This wide floodplain results in differences in peak stages of 1903 relative to 1844 as compared to the Kansas City and Boonville locations. Figure 3-58 presents historic and current rating curve information, plotting data from different periods and labeling the largest floods of each to include 1844, 1903, 1951, and 1993. As seen on the figure, the rating curve at Waverly can be relatively flat for portions of the overbank flow even in large floods like 1903 and 1951 until the full floodplain is conveying water, as assumed in 1993 and 1844. Shifts in the stage discharge relationship correspond to BSNP construction and subsequent locally built levees, which happened essentially at the same time starting soon after 1930. These privately built levees have increased in height over time, as seen when comparing USGS peak data from 1929 to 1952 and 1993 to 2021. Recent floods have exceeded the stage of 1993 at approximately half of the flow. Once levees are overtopped, which usually leads to breaches above Waverly and manual breaches to let water out below Waverly, the very wide floodplain conveys a considerable amount of flow without increasing the height of the flood as seen in the 2022 USGS rating curve on the figure. While uncertainty bounds were not plotted as they were at Kansas City and Boonville, the estimated peak flows plot in line between data for similar sources and time periods as the upstream and downstream locations and are assumed reasonable. Sensitivity analysis was limited at this location as the upstream and downstream statistics were used to inform the reasonableness of the Waverly Bulletin 17C analysis. The adopted chronology plot for the EMA input and Bulletin 17C flow frequency curve for Waverly, MO is presented in Figure 3-59 and Figure 3-60, respectively.

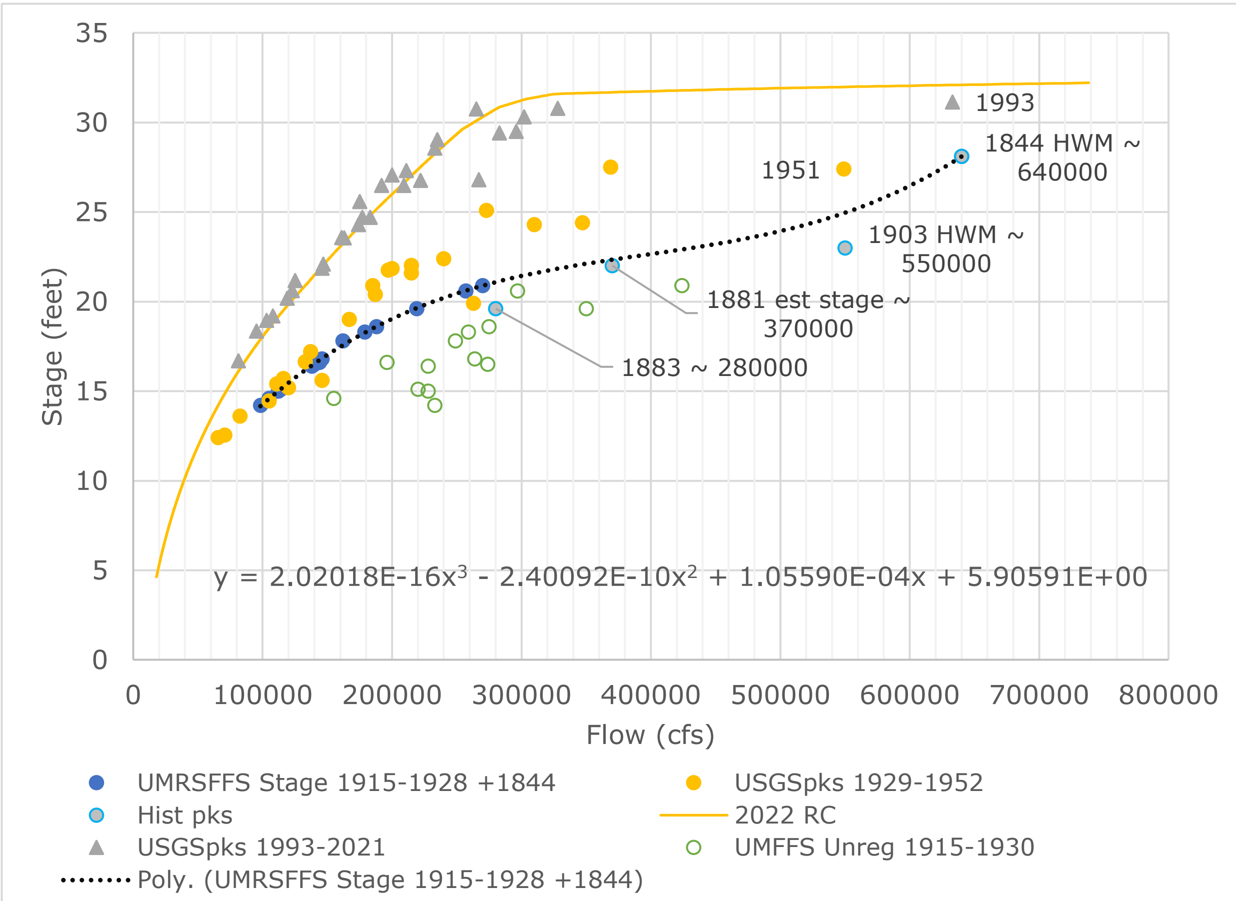


Figure 3-58. Historic Peak Rating Curve at Waverly, MO

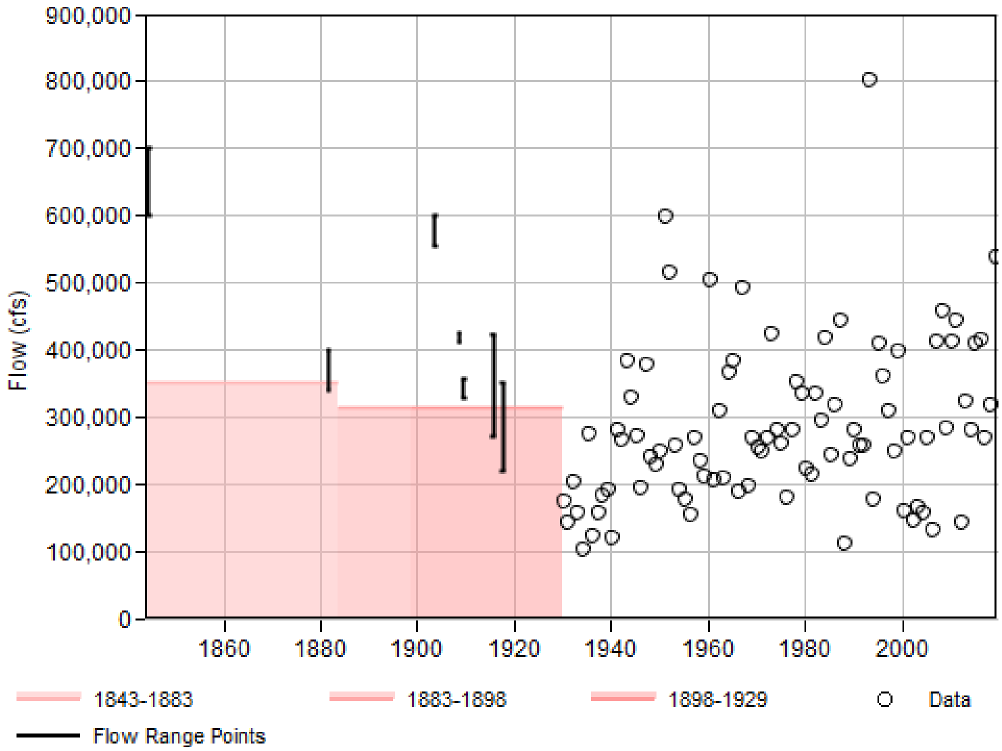


Figure 3-59. Waverly, MO Chronology Plot for Bulletin 17C EMA Input for 1930–2019, Historic back to 1844

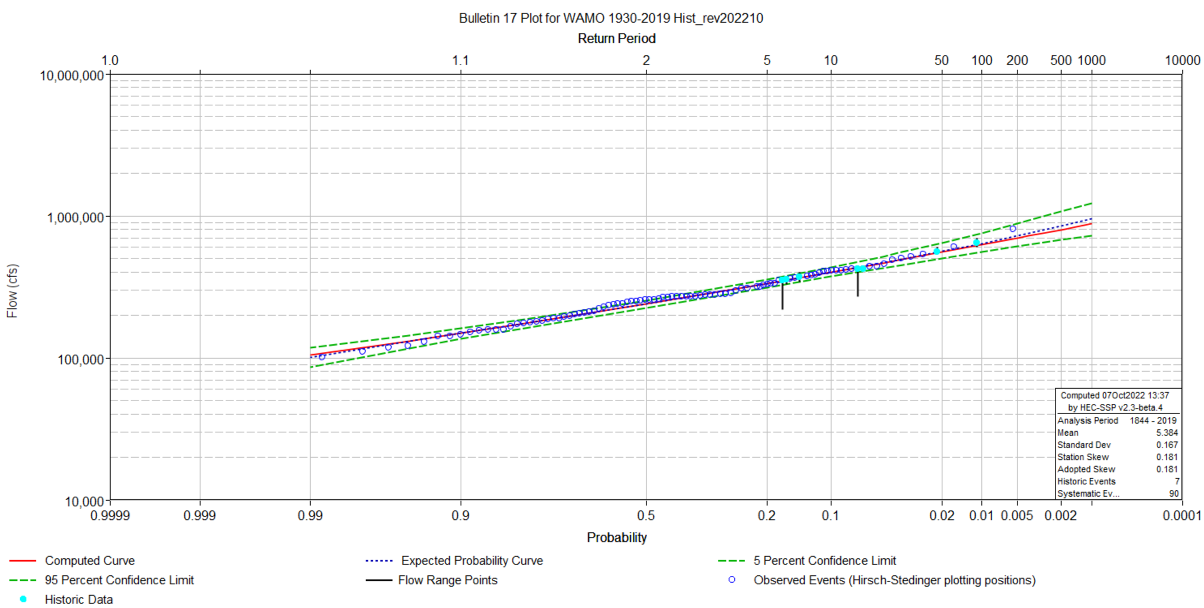


Figure 3-60. Bulletin 17C Unregulated Flow Frequency Curve, Waverly, MO

3.8.5 Boonville, MO, Unregulated Flow Frequency

Annual series analysis was conducted at Boonville using the systematic information and historical flood information. Historical information at Boonville that can be tied to flood heights begins in 1816 with the establishment of Franklin on the north or left descending bank at the current USGS gage. Franklin, MO was an important stop on the Santa Fe Trail and had over 2,000 inhabitants during the 1826 flood. A best estimate of 1826 peaking 8 feet below 1844 was adopted for the study as consistent with quotes of Phil Chappell, who was born after the flood (circa 1837) but learned of it from others to place it 6-8 feet below 1844 (Chappell 1908). This range was coupled with the Missouri Intelligencer Newspaper of Franklin and Major Kearney's journal from the Fort Atkinson Historic Site Website (Kearney, 1826) compared to topography. Quotes from Major Kearney and the Missouri Intelligencer Newspaper documenting the 1826 flood are below. Additional information on the location of Franklin in relation to the gage, to include older topographic mapping from 1948, is provided in Appendix A.

> *"Reach Franklin at ½ past 11 dined & left there at ½ past 1 p.m. – the skirts of town are overflowed – not much damage done"* – Major J.W. Kearney, May 8, 1826, on his trip from the original Council Bluffs (Fort Atkinson) to St. Louis. He reported overtaking the peak of the flood just below Jefferson City and above the Osage River later that day.

> "The Missouri River has risen higher the present season than has been known for thirty years. We learn by a gentleman from Council Bluffs, that all the bottom lands between that place and this, were overflowed – whole farms inundated, and crops destroyed – fences swept away, hogs and cattle drowned, and the inhabitants obligated to remove. Franklin has fortunately escaped; considerable apprehension, however, prevailed during the rise. Several of the inhabitants, lining immediately on the river, on ground less elevated, were obliged to remove. The river has now been falling for several days. We anticipate the most distressing accounts from those living on the bottoms." – May 12, 1826, Missouri Intelligencer Newspaper, Franklin, Missouri

Figure 3-61 presents the historic rating curve for Boonville to include the elevation range in Franklin, which still had visible building foundations indicating little change due to sedimentation until a scour hole developed in the 1993 flood. Also shown on the figure is how stages increased after 1935, which is attributed to BSNP construction and subsequent private levee construction, as indicated by USGS annual peak data from 1935 to 1952. This period plots about half-way between older historic data and stage data from 1993 to 2021 and the 2022 USGS rating curve, showing an increased stage over time, likely due to improvements to the private levees after the 1951 and 1993 floods.

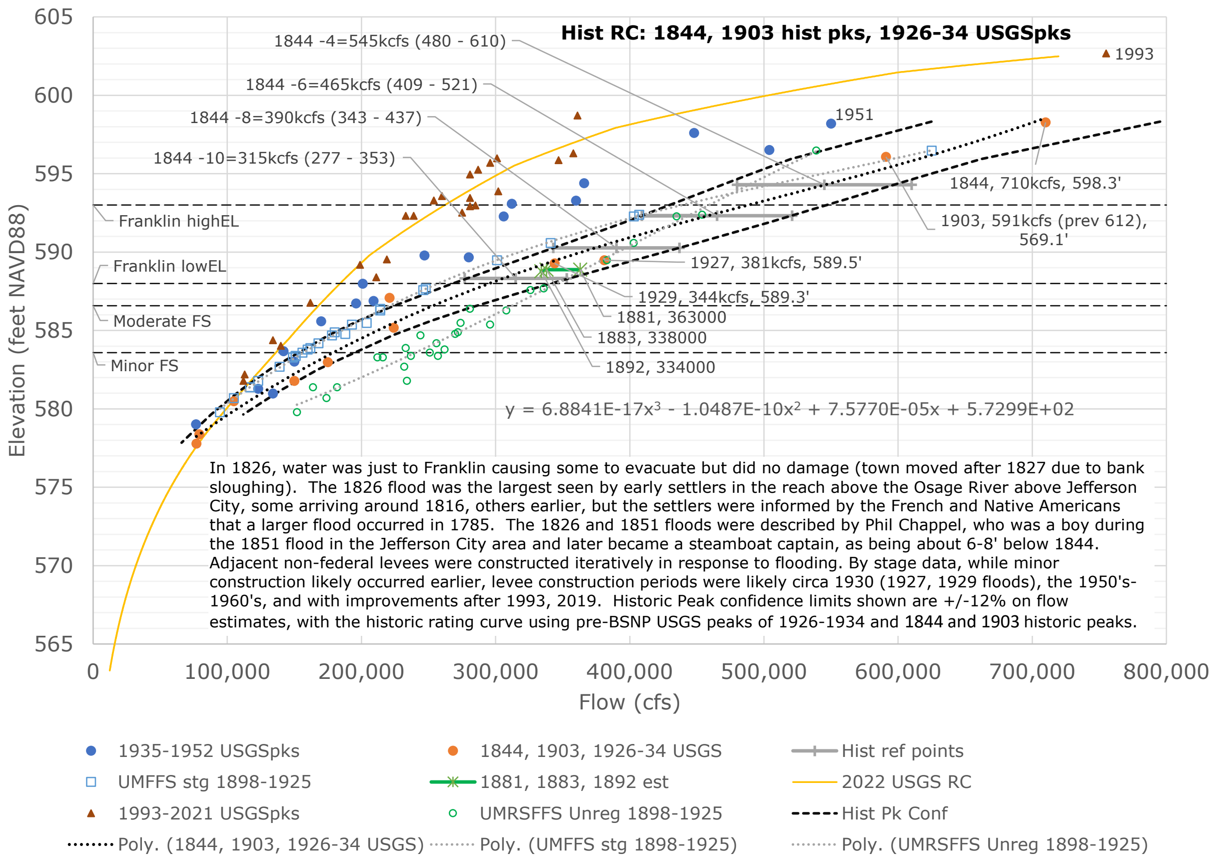


Figure 3-61. Historic Peak Rating Curve information at Boonville, MO

While Franklin escaped with "little damage" due to flooding in 1826, the town began to relocate in 1827 after a portion of the town eroded into the river. With a best estimate 8 feet below 1844, which would put some water in low-lying areas around the town, coupled with the historic rating curve based on a polynomial trendline fit of pre-BSNP annual peaks from USGS from 1926 to 1934 and estimates of 1903 at 591,000 cfs and 1844 at 710,000 cfs, a flow estimate of 390,000 cfs was obtained for 1826. While the newspaper claimed a period of 30 years since a flood of that size occurred, few eyewitnesses would have been present to know if 1811 met or exceeded 1826 near Boonville, and no documentation of that fact has been found. Early settlers who arrived in the Jefferson City area also in 1816 claimed they were told by the French and Native Americans a flood larger than 1826 occurred in 1785 (Chappell 1908). Therefore, 390,000 cfs as estimated for 1826 was used as a perception threshold from 1816 until 1827. Afterwards, the perception threshold was increased to 450,000 cfs from 1827 until 1851 due to the relocation of Franklin, and the approximate size of the floods of 1851, assumed at 7 feet below 1844 based on information summarized in Section 2.4.7. This period also included the great flood of 1844, which destroyed the remaining buildings in Franklin. For 1852 to 1872, a perception threshold of about 350,000 cfs was assumed based on the best estimate for the 1858 flood at Boonville at 9 feet below 1844 as informed by estimates upstream at Kansas City, downstream at St. Louis, and Glasgow Weekly Times articles as summarized in Section 2.4.8. From 1873 until 1897, a perception threshold of 330,000 cfs was adopted as informed by stage records and documentation of the largest historic peaks during that period in 1881, 1883, and 1892, all about the same stage at Boonville. This same 330,000 cfs perception threshold was also retained for the 1898 to 1929 period when 2003 UMRSFFS records were available.

In a sensitivity analysis for the period of 1699 to 1815, a perception threshold of 900,000 cfs was assumed for Boonville as at Hermann, which has seen similar flows to Hermann in some large floods such as 1993 as observed and 1844 according to some estimates. This threshold assumes a large percentage of the flow of the April 1785 flood, the largest between development of the Mississippi River floodplain adjacent to St. Louis starting in 1699 and the 1844 flood, was derived from the Missouri River. Peak flow of the 1785 event was assumed at a minimum at least 25% larger than 1826, and as a best estimate similar in magnitude to 1844 at 710,000 cfs, given high water marks both higher and lower than 1844 on the Mississippi River between the Missouri and Ohio Rivers. Multiple iterations of the perception threshold and flow ranges of historic peaks were considered, and the analysis was not overly sensitive to these values. For example, dropping the perception threshold back to 1699 to a maximum of 710,000 based on the best 1844 estimate reduced the 0.2% AEP flows less than 4%. Figures 3-62 through 3-64 present the chronology plots for EMA input for Boonville, MO for each of the historic periods, back to 1844 as adopted, back to 1816, and back to 1699, respectively as previously described. The 1898 to 1929 data were taken from the 2003 UMRSFFS and entered as flow ranges using stage record flows and the unregulated flows from the report for the historic period back to 1816 but were used as point estimates for the period back to 1699. Little difference in results was determined between these methods for inputting historic peak flows. Figure 62 presents the Bulletin 17C flow frequency curve of the adopted analysis to include smoothing of skew to 0.04 as discussed in Section 3.5. The results of the Bulletin 17C sensitivity analyses are presented in the Table 3-16. Annual peak flows, perception ranges and historic peak flows used in the adopted analysis are tabulated in Appendix A.

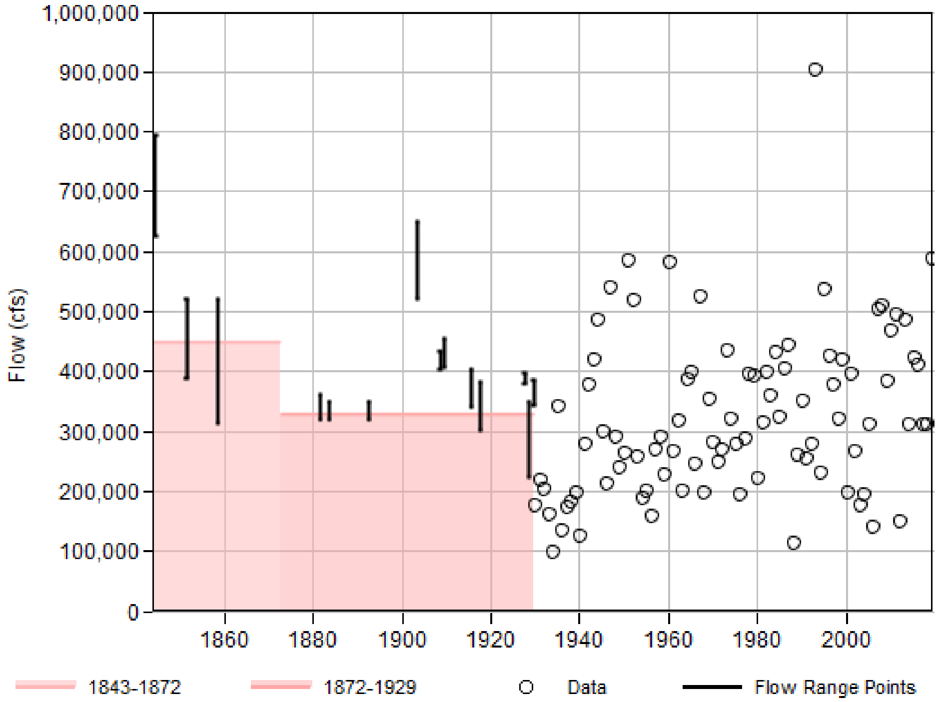


Figure 3-62. Boonville, MO Chronology Plot for Bulletin 17C EMA Input for 1930–2019, Historic Period back to 1844 (Adopted)

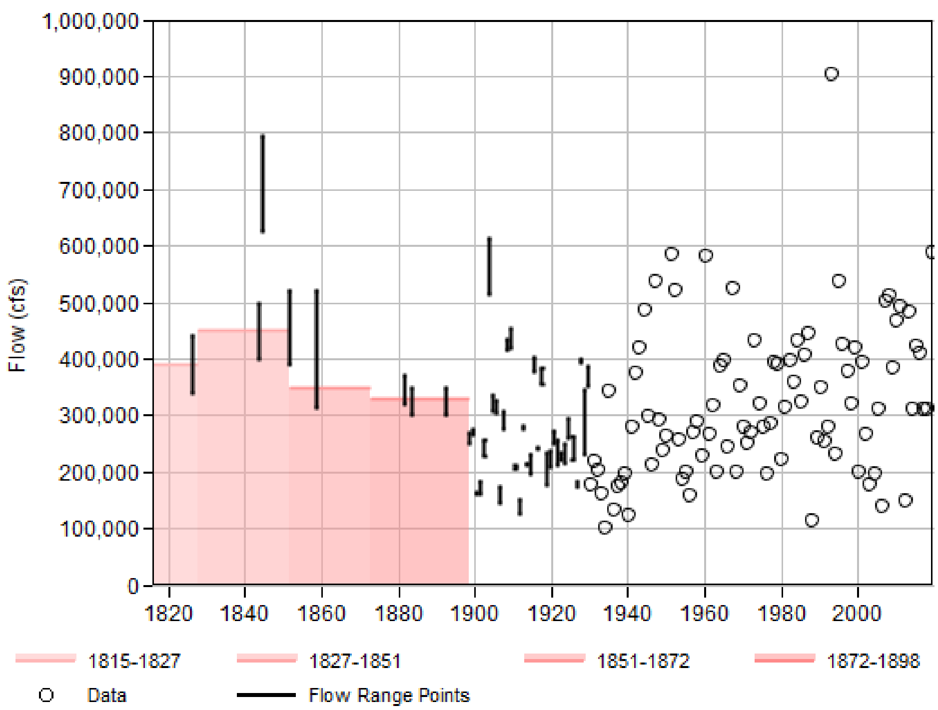


Figure 3-63. Boonville, MO Chronology Plot for Bulletin 17C EMA Input for 1898–2019, Historic Period back to 1816

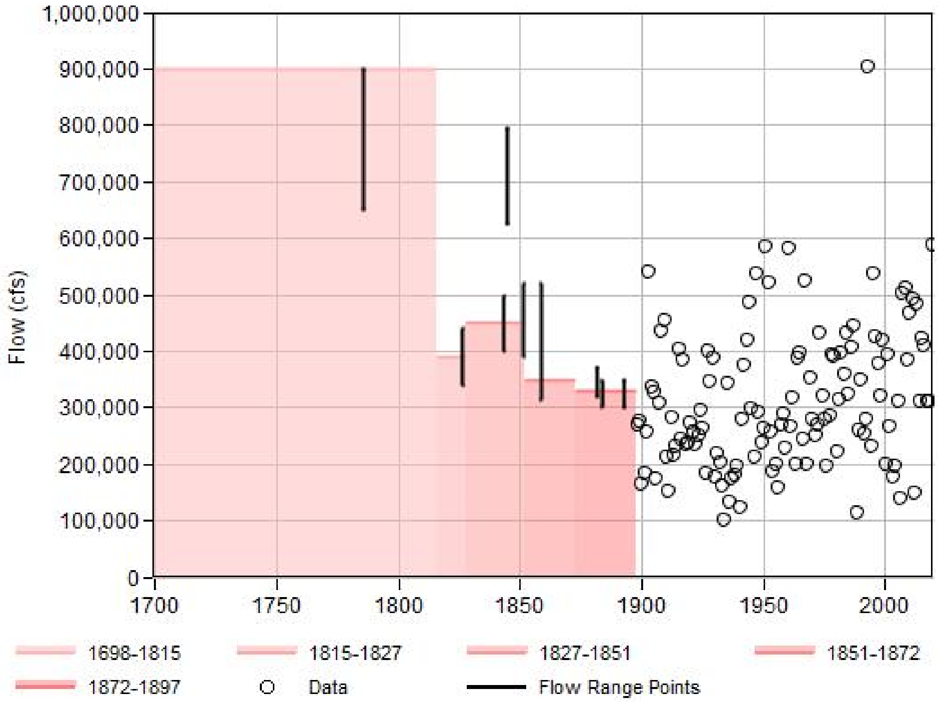


Figure 3-64. Boonville, MO Chronology Plot for Bulletin 17C EMA Input for 1898–2019, Historic Period back to 1699

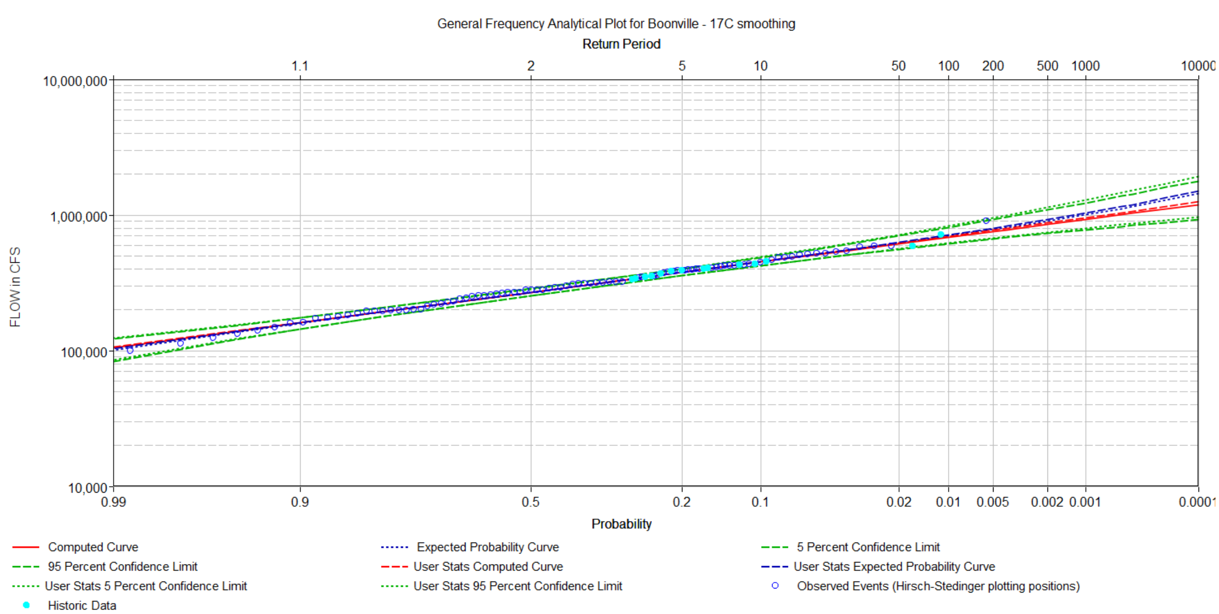


Figure 3-65. Bulletin 17C Unregulated Flow Frequency Curve, Boonville, MO

Table 3-16. Unregulated Bulletin 17C, Expected Probability Flows (cfs) for Different Data Sources and Time Periods, Missouri River at Boonville

Annual Exceedance Probability (percent)	1930–2019	1930–2019 RAS	1898–2019	1930–2019, hist to 1844	1930–2019, hist to 1844 Smooth Skew (Adopted)	1898–2019, hist to 1699	1898–2019, hist to 1816
0.1	1069000	1016000	1010000	1000000	1030000	952000	955000
0.2	968000	900000	916000	900000	924000	864000	863000
0.4	876000	799000	830000	809000	827000	782000	779000
0.5	848000	770000	804000	781000	798000	757000	753000
1	764000	685000	725000	699000	711000	682000	677000
2	686000	606000	651000	622000	630000	610000	604000
4	609000	533000	578000	548000	553000	541000	534000
5	584000	510000	555000	525000	528000	519000	512000
10	507000	440000	483000	453000	454000	450000	443000
20	425000	369000	407000	379000	379000	379000	373000
50	300000	265000	292000	270000	269000	274000	270000
80	207000	190000	207000	191000	191000	198000	195000
90	169000	160000	172000	160000	160000	167000	165000
95	141000	138000	147000	137000	138000	145000	143000
99	98000	103000	107000	101000	103000	110000	109000
Mean	5.471	5.423	5.462	5.431	5.431	5.438	5.432
Std Dev	0.185	0.17	0.173	0.175	0.175	0.167	0.166
Skew	-0.212	0.011	-0.111	-0.016	-0.016	0.023	0.034
Ad. Skew					0.04		
#Historic	0	0	0	14	14	9	8
High Out							
Low Out	0	0	0	0	0	0	0
#Missing	0	0	0	72	72	190	74
#System	90	90	122	90	90	122	122
Hist Period	90	90	122	176	176	321	204
Eq. Length	90	90	122	121.191	121.191	176.555	144.73

Note: Table column headings reflect data used as follows: The 1930–2019 data is the HEC-ResSim based routings except for the column labeled "1930–2019 RAS" which are HEC-RAS based routings from Section 4 of the report. Flows from 1898–1929 reflect 2003 UMRSFFS data. Where historic events were used the earliest date of the historic period is indicated.

3.8.6 Hermann, MO, Unregulated Flow Frequency

Annual series analysis was conducted at Hermann using the systematic data 1930 to 2019 and historical flood information. A historic rating curve was created at the site using very limited pre-BSNP data from USGS, namely the three largest measurements in 1929 of 285,000 cfs, 333,000 cfs, and 411,000 cfs, and the 1903 and 1844 historic peak flows. For 1903, the best estimate of 676,000 cfs was retained in the analysis consistent with the USGS website, however, the historic rating curve yields a flow of 649,000 cfs, slightly lower at the same stage as 1903. In the 1844 estimate, a peak flow of 800,000 cfs was assumed as the best estimate at Hermann, reflecting the midpoint of the range of previously published estimates. Uncertainty estimates of approximately 12% above or below this value were found to capture the range of historic peak flow estimates made at this site for 1844, and visually captured ranges of estimates from other historic flood events, aside from some of the flows estimated from stage records in the 2003 UMRSFFS. However, the 2003 UMRSFFS unregulated flows paired with observed stages generally plotted within the 12% range on the confidence limits from the historic rating curve. Figure 3-66 presents the historic and current rating curve for Hermann, Missouri, including flow estimates for various ranges of flood height referenced below 1844, and USGS data for various periods including the 2022 rating curve. As seen in the figure, the historic data prior to the BSNP and subsequent private levee construction produced lower stages for the same flow than for the 1930 to 1952 period, or more recent rating curves, reflecting levee improvements after large floods such as 1951 and 1993. Additional information regarding variation of estimates for 1844, 1903, and 1881 with various documents is presented in Appendix A.

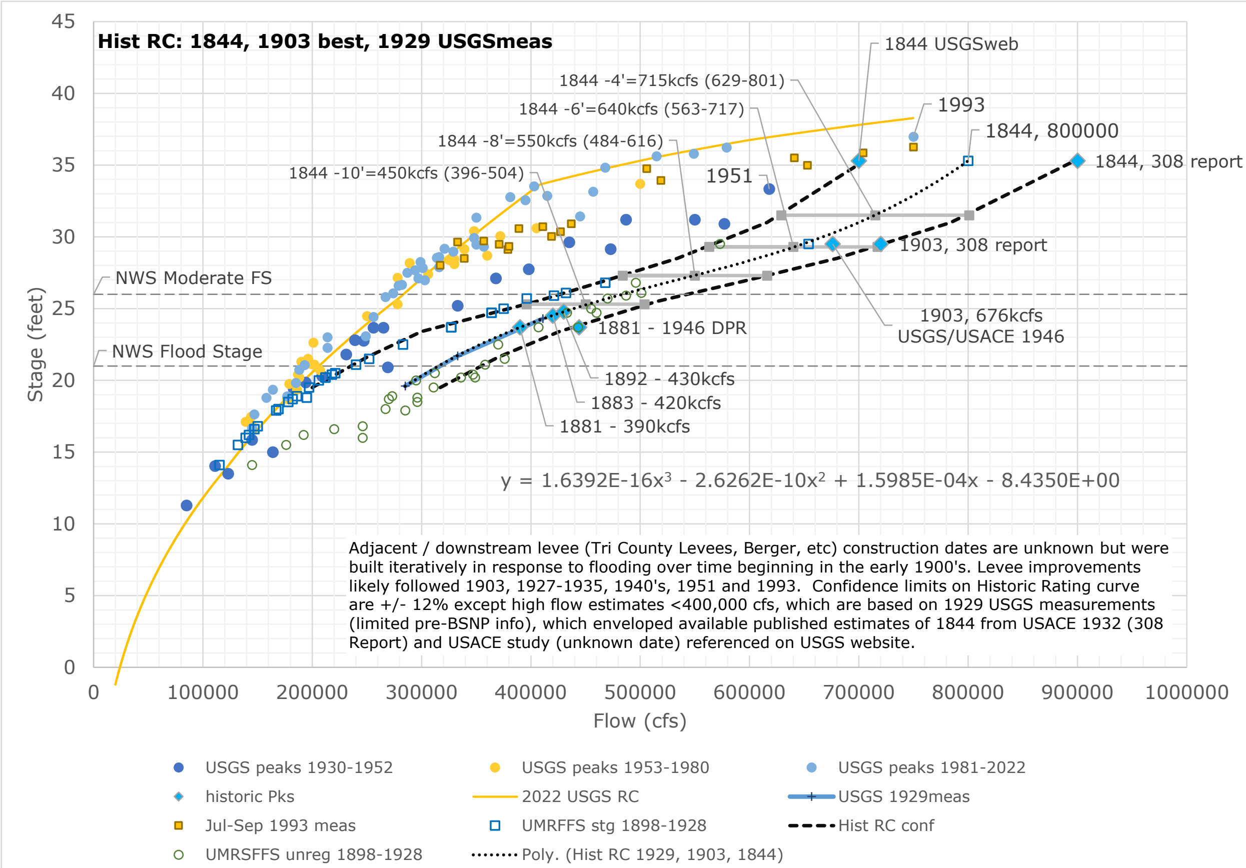


Figure 3-66. Hermann Historic Peak Flow Estimates and Estimated Rating Curve With Uncertainty

The historic rating curve for Hermann was further investigated using stage data at St. Charles, 1892 flow measurements at St. Charles from the "308 Report", and historic flow information at Hermann and or St. Charles, which are often reported interchangeably in historic documents. St. Charles is located 27.8 miles above the present-day confluence with the Mississippi River and is immediately upstream of the "cross-over" reach where Missouri River flows split with portions flowing into the Mississippi River above the confluence during large floods. The "cross-over" area between the Missouri and Mississippi Rivers immediately above the confluence is currently provided flood risk reduction by the 37-mile-long Consolidated North Federal Levee System. The Consolidated North Levee overtops during large floods at a probability of approximately 5% (1/20) AEP in any given year (National Levee Database, viewed in Nov 2022) and has not shown a dramatic impact on the rating curve at St. Charles since the federally constructed portions of the levee system was completed in 2004. Very minor amounts of drainage area and short travel times exist between Hermann and St. Charles, however, for some events, Mississippi River flows can induce backwater that may impact the St. Charles rating curve.

With these potential backwater effects in mind, the data was plotted along with more recent rating curve information as shown Figure 3-67. In the figure, all flows can be assumed to be as reported at Hermann, except those as labeled "308 report" in the data legend, which are at St. Charles, whereas all stages are shown at St. Charles. As no data plotted excessively high stage wise for a given flow, the backwater impacts were assumed minor for the Missouri River flood events documented in the Figure. Since the historic peak information plots reasonably well with stage, given potential errors with 1892 measurements in getting accurate bed measurements as noted on the figure, the comparison at St. Charles further indicates that historic peak flows generated at Hermann are reasonable. Additionally, peak flows appear to be similar between locations, with the assumed 1844 flow plotting realistically against 1993 and the current rating curve shape, which is less impacted by levee construction than many upstream Missouri River locations. For the 308 report flows, WB indicates stages measured at the Weather Bureau gage, whereas COE denotes the nearby Corps of Engineers gage, both gages being at St. Charles.

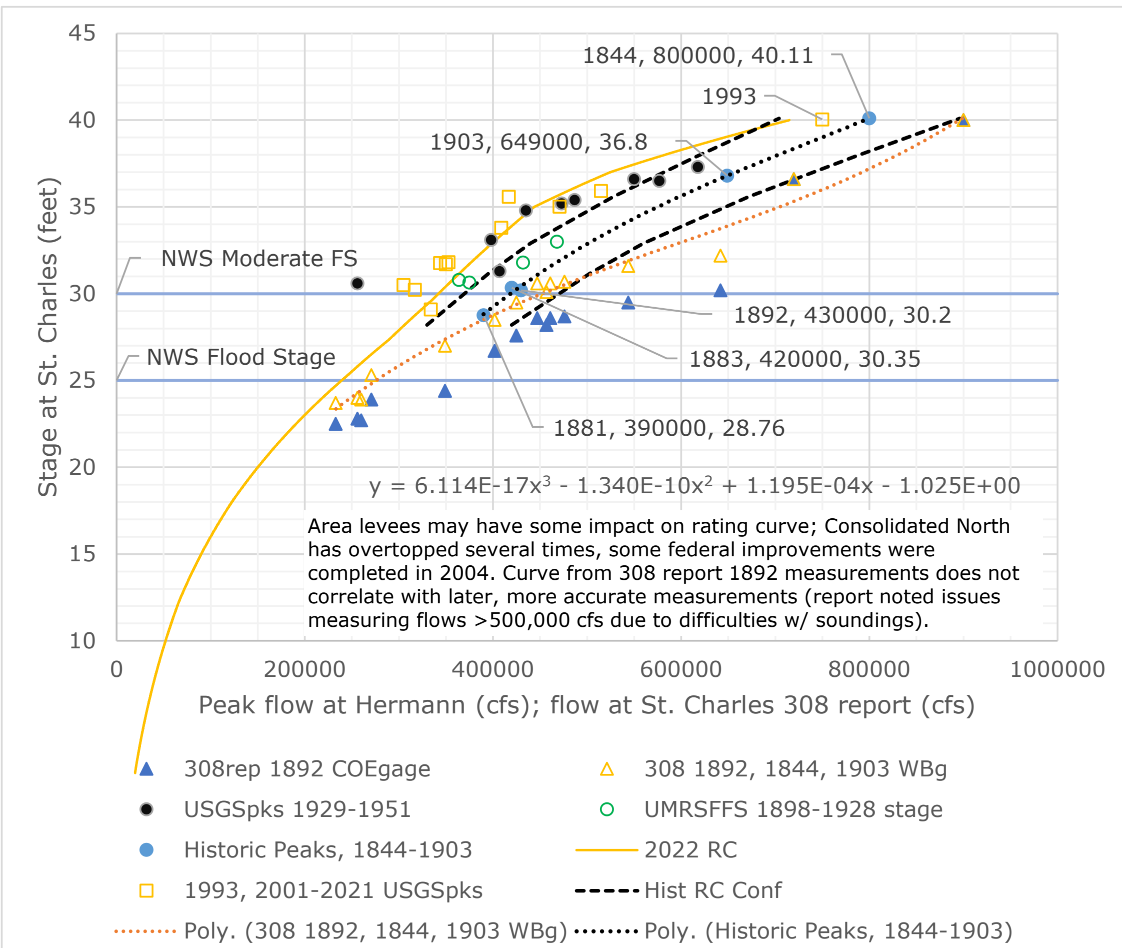


Figure 3-67. Historic Rating Curve at St. Charles, MO

Given similarities at St. Louis and information upstream at Glasgow, and from Phil Chappell near Jefferson City, the floods of 1851 and 1858 were both estimated at seven feet below 1844, approximately 595,000 cfs at Hermann. Since these floods were documented, it was assumed a flow of 500,000 cfs would have been detected at Hermann or St. Charles after settlement of the floodplain became more widespread around 1816 until 1873 when stage records started at Hermann. This perception threshold approximately represents moderate flood stage at Hermann and was judged to be comparable to the April 1843 flood, which had some documentation of high water near Hermann, as did a flood of 1837, which was largely derived from the Osage River. Both the 1837 and 1843 floods were over-shadowed by 1844 which had much more historical records. An example newspaper article quote made during the rise of 1843, which would have peaked in early May at St. Charles, is below. However, given limited writing of the event afterwards, the 1843 flood, estimated at 476,000 cfs in Kansas City, was unlikely to have caused major damages in the lower river.

> *"The Missouri River* [at St. Charles, Missouri,] *is far higher* [on April 21, 1843] *than it has ever been known at this season of the year and it is still rising. A few feet more will cause it to overflow the lower parts of the river bottom. The river is as high as it has been at any time since July 1837."*
> -- reprint of the St. Charles, Missouri, Advertiser in the April 28, 1843, Bloomington, Iowa, Herald

After stage records became available, a perception threshold of 350,000 cfs was assumed, below the historic peak flows of 1881, 1883, and 1892, and approximately two feet above flood stage at Hermann. The chronology plot for the period of 1930 to 2019, with a historic period back to 1844 as adopted is presented in Figure 3-68, in which the 2003 UMRSFFS data from 1898 to 1929 and historical peak flows were used to develop flow ranges for historic peak flows above the perception threshold. Final historic peak flows and perception thresholds are documented in Appendix A. Chronology plots for two additional historic periods using the 2003 UMRSFFS as systematic data for 1898 to 1929 and a historic period back to 1816 and 1699 are included in Figures 3-69 to 3-70, respectively. For the historic period back to 1699, given even reasonably low contributions of flow on the upper Mississippi River, the establishment of Cahokia, IL and soon after Kaskaskia, IL provides a case that the major floods of 1785 and 1844 would not have been exceeded at Hermann dating back to at least 1699 (see also Section 3.6.1).

In using the historic peak for 1785, knowing it was bigger than 1826, a minimum flow at least 20% larger than the 1826 flood best estimate was established, whereas the high estimate was assumed slightly higher than 1844 since upper bound stages place 1785 nearly one-foot above 1844 in St. Louis. Best estimates assumed that the 1785 flood was comparable to 1844. Another flood between 1785 and 1826 was documented in 1811, likely with its largest peak in July but with flooding also occurring earlier in the spring. However, there is no reliable information to estimate its magnitude in the lower Missouri River or

Middle Mississippi River. Best estimates indicate 1811 was comparable to 1826 in St. Louis. Based on journals of Bradberry and Brackenridge, the 1811 flood is not believed to have overflowed farms on the high bottoms in the Boonville area, though it was out of bank upstream of Kansas City. Still, the perception threshold based on the 1785 flood was used prior to 1816 due to less settlement before that time. Hermann was the only location where the Bulletin 17C analysis flagged low outliers, where the Grubs Beck test filtered off 40 of the 90 annual peak flows for the 1930 to 2019 period. Due to highly negative skew that resulted from this, a low flow threshold of 100,000 cfs was adopted for the study. For the 1930 to 2019 systematic period, applying this threshold reduced 1% AEP flows by about 7 percent. As discussed in Section 3.5, the station skew of the 1930 to 2019 systematic data with a historic period back to 1844 was retained in the final analysis. Figure 3-71 presents the unregulated Bulletin 17C flow frequency curve. Table 3-17 presents the unregulated Bulletin 17C flow frequency results for various historic periods and data sets.

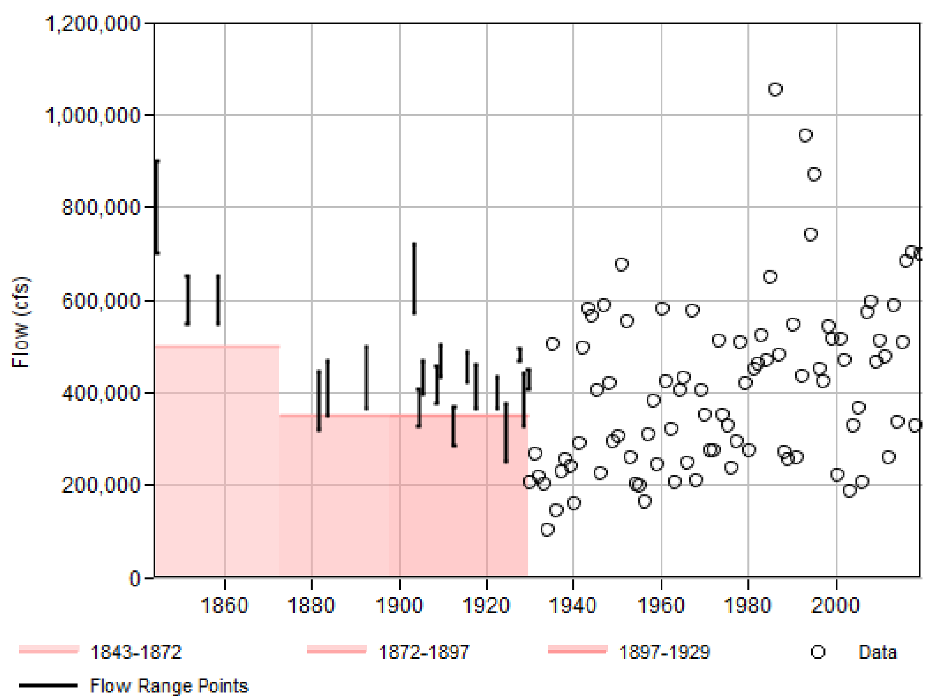


Figure 3-68. Hermann, MO Chronology Plot for Bulletin 17C EMA Input for 1930–2019, Historic Period Back to 1844 Flood (Adopted)

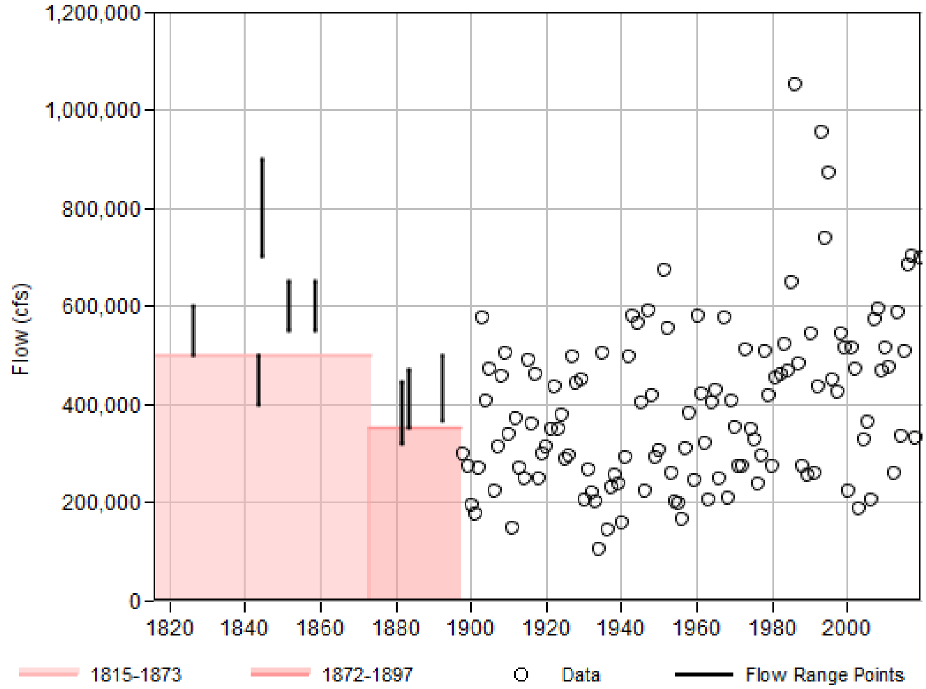


Figure 3-69. Hermann, MO Chronology Plot for Bulletin 17C EMA Input for 1898–2019, Historic Period Back to 1816

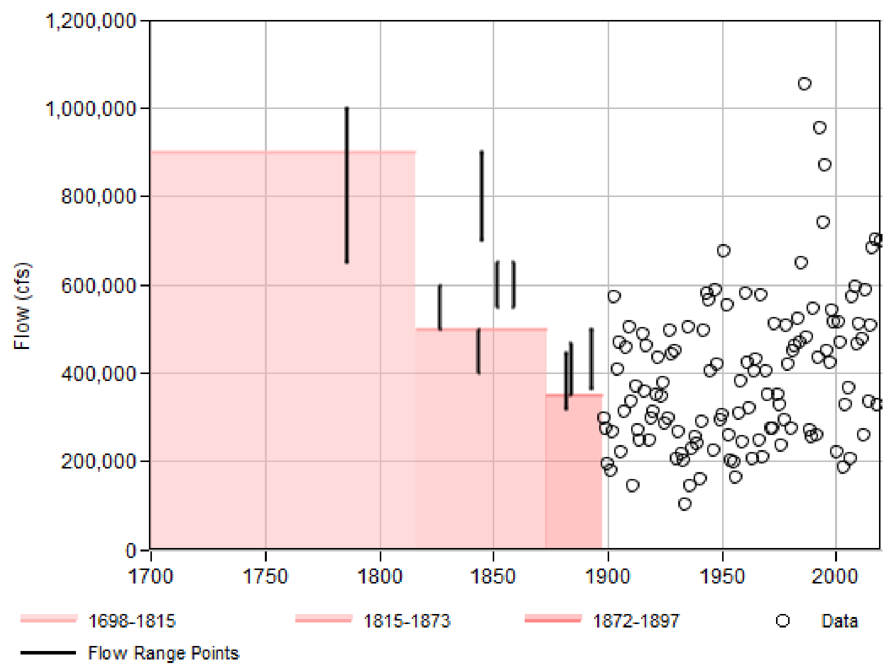


Figure 3-70. Hermann, MO Chronology Plot for Bulletin 17C EMA Input for 1898–2019, Historic Peaks Back to 1699

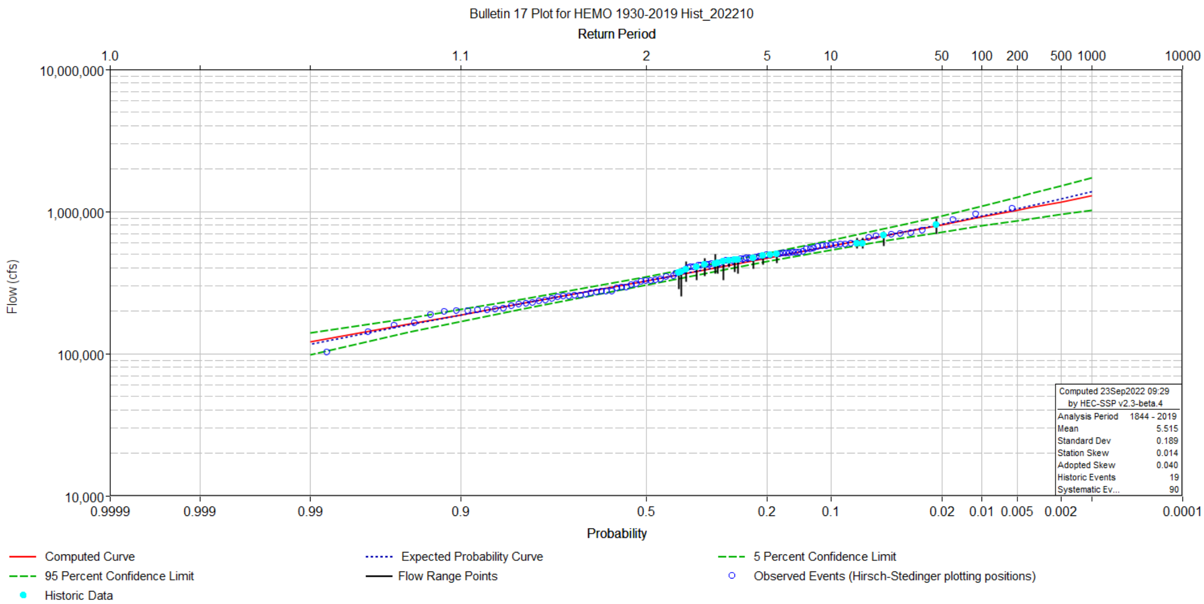


Figure 3-71. Bulletin 17C Unregulated Flow Frequency Curve, Hermann, MO

Table 3-17. Unregulated Bulletin 17C, Expected Probability Flows (cfs), for Different Data Sources and Time Periods Missouri River at Hermann

AEP (percent)	1930–2019	1930–2019 w/ low outliers	1930–2019 RAS	1898–2019	1930–2019, hist to 1844 (adopted)	1898–2019, hist to 1816	1898–2019, hist to 1699
0.1	1540000	1280000	1630000	1350000	1380000	1260000	1180000
0.2	1370000	1180000	1410000	1220000	1230000	1130000	1080000
0.4	1220000	1080000	1230000	1100000	1090000	1020000	979000
0.5	1180000	1050000	1180000	1060000	1050000	982000	949000
1	1040000	965000	1030000	953000	928000	878000	856000
2	924000	881000	890000	850000	816000	780000	766000
4	808000	795000	765000	750000	710000	686000	678000
5	772000	766000	727000	718000	676000	656000	650000
10	659000	670000	612000	619000	575000	564000	561000
20	544000	560000	499000	516000	473000	470000	470000
50	372000	370000	340000	361000	327000	331000	332000
80	249000	220000	233000	249000	226000	233000	233000
90	200000	158000	191000	203000	186000	193000	193000
95	166000	115000	162000	171000	158000	165000	165000
99	112000	53000	117000	121000	115000	121000	120000
Mean	5.565	5.549	5.533	5.553	5.515	5.52	5.52

AEP (percent)	1930–2019	1930–2019 w/ low outliers	1930–2019 RAS	1898–2019	1930–2019, hist to 1844 (adopted)	1898–2019, hist to 1816	1898–2019, hist to 1699
Std Dev	0.2	0.233	0.195	0.187	0.189	0.18	0.18
Skew	-0.178	-0.721	0.047	-0.142	0.014	-0.026	-0.074
Grubs-b cr	100000	0	0	0	100000	0	0
#Historic	0	0	0	0	19	8	9
Low Out	0	40	0	0	0	0	0
#Missing	0	0	0	0	67	74	190
#System	90	90	90	122	90	122	122
Hist Period	90	90	90	122	176	204	321
Eq. Length	90	89.885	90	122	121.477	148.804	189.673

Note: Table column headings reflect data used as follows: The 1930–2019 data is the HEC-ResSim based routings except for the column labeled "1930–2019 RAS" which are HEC-RAS based routings from Section 4 of the report. Flows from 1898–1929 reflect 2003 UMRSFFS data when used as systematic peaks. Where historic events were used the earliest date of the historic period is indicated. The "1930–2019 low outliers" was the raw computation from HEC-SSP, which generated 40 low outliers and unreasonable negative skew.

Table 3-18 presents additional sensitivity analysis results including consideration of the 2003 UMRSFFS data for comparison to the current study using both Bulletin 17B and 17C methods and the impact on 0.2% and 1% AEP flows. Additionally, the 2003 UMRSFFS adopted a skew of 0.17 downstream of the Kansas River, and did not use expected probability, so sensitivity comparing to a reproduction of the 2003 UMRSFFS was included. As seen in the Tables, the reproduced 2003 UMRSFFS estimates are approximately 10% and 6% lower at the 0.2% and 1% AEP compared to the adopted results. Differences between computed and expected probability, data sets, and historic period are partially offset by the higher skew used in UMRFFS. Use of 1898-1929 data from the 2003 UMRSFFS reduced flows when used in the analysis. Shortened periods using only the systematic data showed variable results, with the 1941–2019 period, which avoids the drought of the 1930's, very closely matching the adopted results. In contrast, the longer 1930–2019 and shorter 1967–2019 systematic periods would result in 11% and 29% higher flows for the 0.2% AEP than as adopted, or 13% higher if using the UMRSFFS data from 1930-1997. Using the full 100 years of the 2003 UMRSFFS data and switching to Bulletin 17C procedures instead of Bulletin 17B, results in flows matching the adopted results within 8% at the 0.2% and within 6% at the 1% AEP. Extending the historic period back to 1816 results in an 8% reduction of flows at the 0.2% AEP, with 5% decrease at the 1% AEP. Considering a longer historic period back to 1699, based on limited and uncertain data, would result in decreases of 12% and 8% at the 0.2% and 1% AEP events, respectively. Given all sensitivities to varying the record length, the adopted results are considered reasonable and a best estimate of unregulated flow frequencies at this time.

Table 3-18. Unregulated Flow Frequency Sensitivity Analysis Results Summary, Expected Probability, Missouri River at Hermann, Missouri

Period, Data, Method (Bulletin 17C unless labeled as 17B)	Mean	St Dev	Skew	Historic Period & Effective Record Length	0.2% AEP, Sensitivity / Adopted Flow Ratio	1% AEP, Sensitivity / Adopted Flow Ratio
1898-1997, UMRSFFS data, 17B	5.535	0.166	0.051	100	0.88	0.93
*1898-1997, UMRSFFS data, 17B, computed curve, skew 0.17***	*5.535*	*0.166*	*0.170*	*100*	*0.90*	*0.94*
1898-1997, UMRSFFS	5.534	0.166	0.051	100	0.92	0.94
1930-1997, UMRSFFS	5.540	0.176	0.160	68	1.13	1.06
1898-1997*	5.536	0.186	-0.022	100	1.04	1.04
1898-2019*	5.553	0.187	-0.142	122	0.99	1.03
1930-2019, hist 1844 (adopted)	**5.515**	**0.189**	**0.014**	**176, 121**	**1.00**	**1.00**
1898-2019*, hist 1816	5.520	0.180	-0.026	204, 149	0.92	0.95
1898-2019*, hist 1699	5.520	0.180	-0.074	321, 190	0.88	0.92
1930-2019	5.565	0.200	-0.178	90	1.11	1.12
1941-2019	5.598	0.180	-0.053	79	0.99	1.02
1967-2019	5.627	0.177	-0.050	53	1.29	1.24

*1898–1929 annual peak data used from the 2003 UMRSFFS, remainder from current study

**Reflects a reproduction of the 2003 UMRSFFS Results, Computed Probability

3.9 Unregulated Flow Frequency Results Tables

Table 3-19 shows the final unregulated expected probability flow frequency curves at the ten Missouri River stations analyzed, whereas Table 3-20 presents the statistics. Based on the immediate needs for the flow information, this analysis focused on expected probability flows. Plots of the frequency curves are also provided in Sections 5 and 7 of the report along with the regulated flow frequency curves. While this report uses expected probabilities throughout, certain uses of the data require the computed probability. These uses can include certain risk assessments that separately account for uncertainty, such as studies leveraging HEC-FDA, to avoid double counting this adjustment. Therefore, Table 3-21 presents the final unregulated flow frequencies based on the computed probabilities from HEC-SSP. Differences between expected and computed probability flows are defined in the HEC-SSP user's manual as follows:

"The expected probability adjustment is a correction for bias in the computed frequency curve. The bias is caused by uncertainty due to the shortness of the data record. The method of moments estimation of the Log Pearson III parameters produces a median estimate of each frequency curve quantile, and the adjustment changes to a mean (unbiased) estimate, which is different from the median because of the skewness of the uncertainty distribution. The use of the expected probability curve is a policy decision. The expected probability curve is most often used in establishing design flood criteria. When use of the frequency curve includes uncertainty analysis, the expected probability adjustment is made implicitly. Therefore, the computed flood frequency curve without the expected probability adjustment is the curve used in computation of confidence limits, risk analysis, and in obtaining weighted averages of independent estimates of flood frequency discharge (Interagency Advisory Committee on Water Data, 198249)."

Table 3-19. Final Unregulated Bulletin 17C Flow Frequency Expected Annual Exceedance Probability % (Flow in CFS)

AEP (%)	Yankton	Sioux City	Omaha	Nebraska City	Rulo	St Joseph	Kansas City	Waverly	Boonville	Hermann
0.2	686,000	719,000	727,000	730,000	715,000	707,000	835,000	848,000	924,000	1,230,000
0.4	565,000	591,000	602,000	617,000	608,000	607,000	738,000	751,000	827,000	1,090,000
0.5	531,000	555,000	567,000	584,000	578,000	578,000	709,000	723,000	798,000	1,050,000
1	438,000	458,000	471,000	497,000	497,000	500,000	624,000	639,000	711,000	928,000
2	362,000	378,000	391,000	424,000	429,000	435,000	547,000	562,000	630,000	816,000
4	301,000	313,000	327,000	364,000	372,000	379,000	476,000	490,000	553,000	710,000
5	283,000	295,000	309,000	346,000	356,000	362,000	454,000	468,000	528,000	676,000
10	236,000	246,000	258,000	296,000	307,000	314,000	387,000	401,000	454,000	575,000
20	196,000	203,000	215,000	251,000	262,000	268,000	322,000	334,000	379,000	473,000
50	144,000	150,000	159,000	189,000	198,000	205,000	231,000	239,000	269,000	327,000
80	110,000	114,000	121,000	147,000	154,000	160,000	169,000	174,000	191,000	226,000
90	96,200	99,500	106,000	129,000	136,000	141,000	145,000	148,000	160,000	186,000
95	86,400	89,300	95,500	117,000	123,000	128,000	128,000	130,000	138,000	158,000
99	70,900	73,200	78,600	96,600	101,000	107,000	100,000	101,000	103,000	114,600

Note: See Table 3-21 for unregulated computed probabilities.

Table 3-20. Unregulated Flow Frequency Bulletin 17C Statistics

	Yankton		Sioux City		Omaha		Nebraska City	
Statistics of Log	**Jan–Apr**	**May–Dec**	**Jan–Apr**	**May–Dec**	**Jan–Apr**	**May–Dec**	**Jan–Apr**	**May–Dec**
Mean	4.948	5.113	4.964	5.128	4.996	5.155	5.057	5.242
Standard Deviation	0.270	0.139	0.271	0.140	0.263	0.139	0.244	0.135
Skew	0.229	0.070	0.215	0.117	0.205	0.124	0.181	0.230
Adopted Skew	0.2	0.2	0.2	0.2	0.2	0.2		0.2

	Rulo		St. Joseph					
Statistics of Log	**Jan–Apr**	**May–Dec**	**Jan–Apr**	**May–Dec**	**Kansas City**	**Waverly**	**Boonville**	**Hermann**
Mean	5.064	5.268	5.079	5.283	5.370	5.384	5.431	5.515
Standard Deviation	0.235	0.135	0.231	0.133	0.166	0.167	0.175	0.189
Skew	0.222	0.188	0.141	0.224	0.244	0.181	-0.016	0.014
Adopted Skew			0.18				0.04	

*Adopted skew values not entered indicate station skews were utilized

Table 3-21. Final Unregulated Bulletin 17C Flow Frequency Computed Annual Exceedance Probability % (Flow in CFS)

AEP (%)	Yankton	Sioux City	Omaha	Nebraska City	Rulo	St Joseph	Kansas City	Waverly	Boonville	Hermann
0.2	619,000	648,000	657,000	658,000	646,000	638,000	788,000	798,000	876,000	1,160,000
0.4	525,000	549,000	560,000	573,000	566,000	564,000	709,000	720,000	797,000	1,050,000
0.5	497,000	520,000	531,000	547,000	542,000	542,000	684,000	696,000	772,000	1,010,000
1	418,000	437,000	449,000	475,000	476,000	479,000	610,000	624,000	696,000	907,000
2	351,000	366,000	379,000	413,000	418,000	423,000	539,000	554,000	622,000	804,000
4	295,000	307,000	321,000	358,000	366,000	373,000	472,000	486,000	549,000	704,000
5	279,000	290,000	304,000	342,000	351,000	357,000	450,000	465,000	525,000	672,000
10	234,000	244,000	256,000	295,000	305,000	312,000	386,000	399,000	452,000	573,000
20	195,000	203,000	214,000	250,000	261,000	267,000	321,000	333,000	378,000	473,000
50	144,000	149,000	158,000	189,000	198,000	204,000	231,000	239,000	269,000	327,000
80	110,000	114,000	121,000	147,000	154,000	160,000	169,000	175,000	192,000	227,000
90	96,300	99,600	106,000	129,000	136,000	142,000	145,000	149,000	161,000	187,000
95	86,700	89,600	95,800	117,000	123,000	129,000	128,000	131,000	140,000	160,000
99	71,900	74,300	79,600	98,300	103,000	108,000	103,000	104,000	106,800	119,300

Note: See Table 3-19 for unregulated expected probabilities.

4. Evaluation of Routing Methods with HEC-RAS

While every effort was made to ensure that models were routing flows as reasonably as possible, each hydrologic software package has computational limitations that should be understood. The ResSim model relies on coefficient routing for river reaches, a form of hydrologic routing, which can be viewed as more of an empirical method that does not account for the physics of levee overtopping, levee breaches, backwater at major tributaries, or other river hydraulics that could impact routings as a program such as RAS can do. Ungaged flow is back-calculated at each streamgage in ResSim, where upstream flows are routed to the gage of interest and compared to streamflow records, and the difference in the flows is computed as ungaged inflow at that location. More detailed hydraulic models can better account for where the ungaged flows are entering the system between gages and the corresponding impact on flow routings, for example accounting for backwater when tributaries are flooding or where levees are overtopped. While leveed areas and overbank flow cannot be modeled directly in ResSim and may not be properly accounted for with the coefficient routing scheme, the coefficient routing was calibrated to large floods to mitigate this limitation as summarized in Section 3.2. Still, a concern existed that flows above the threshold that would spill out of bank and overtop levees are possibly overestimated as overbank flow and levee overtopping would reduce the peak flow rates. Therefore, an analysis with RAS was conducted to determine the impact of these effects on flow frequency. While the ResSim results were ultimately adopted, which simplified the WAT-Monte Carlo analysis, routings in RAS showed that the ResSim routings produced similar results and therefore were considered adequate for the study. The following sections present how the period of record flow datasets developed with ResSim were routed with RAS to help assess how well the limitations of the hydrologic routing methods within the ResSim model could be overcome with hydraulic routing in RAS.

4.1 Source Model

Two existing one-dimensional (1D) unsteady HEC-RAS models were leveraged for producing modeled output for this Missouri River Flow Frequency Study. One HEC-RAS model for the Omaha District (Omaha Model) and one HEC-RAS model for the Kansas City District (Kansas City Model) were used to provide results at the mainstem gage locations. Extents of the Omaha Model begin at Gavins Point Dam in South Dakota (river mile 811) and extend to St Joseph, Missouri (RM 448). Extents of the Kansas City Model begins at Nebraska City, Nebraska (RM 527) to the confluence of the Mississippi River (RM 0), and a segment of the Mississippi River necessary to provide a reasonable downstream boundary condition at the confluence. Overlap of the Omaha Model and the Kansas City Model from Nebraska City to St Joseph was necessary to model the Rulo area, which has a wide floodplain with a complicated configuration of levees and railroad/ highway embankments. A total of twentytwo tributaries with the most significant impact to the Missouri River were modeled as reaches of river with cross sections starting at from the most downstream United States Geologic Survey (USGS) tributary gage to the confluence with the Missouri River. The Omaha and Kansas City model's extents are shown in Figure 4-1 and Figure 4-2.

Both models were originally developed in support of the Man Plan EIS in 2018. Construction and calibration of the Man Plan geometries was completed in 2012–2014 and was documented in *Missouri River Unsteady HEC-RAS Model Calibration Report Appendix D Gavins Point Dam to Rulo, NE* (USACE, July 2018) and *Missouri River Unsteady HEC-RAS Model Calibration Report Appendix E Rulo to the Mouth* (USACE, July 2018). The reports on model development are available for download at https://www.nwo.usace.army.mil/mrrp/mgmt-plan/. The primary purpose of the Man Plan models was to simulate and analyze wide-scale watershed alternatives using an 82-year period of record (POR) from 1930 to 2012. For the Kansas City Model only, additional improvements were made to the geometry in 2017 under the Silver Jackets Interagency Project: Missouri River Flood Event Simulation Mapping and was documented in *Memorandum for Record: Updates to the 2015 Missouri River Unsteady HEC-RAS Model* (USACE, 26 SEP 2017). Updates included creating a RAS mapper terrain with low water LiDAR from 2013–2014 and bathymetry data from 2013. New cross sections were generated from the terrain, and the Kansas City Model was recalibrated to USGS and National Weather Service (NWS) rating curves as of June 2017. As seen in Figure 4-2, several streamgages from smaller tributaries in the Kansas City model generally less than 300 sq miles were added as lateral flows, even though they may be some distance from the river. During the 2018 Man Plan study, these tributaries were modeled using HEC-RAS and the river routing results were not sensitive to the differences in routing from the gage to the Missouri River versus just adding daily flows directly to the Missouri River. Therefore, hydraulic routing along smaller tributaries was not conducted for this study, but the flows were utilized.

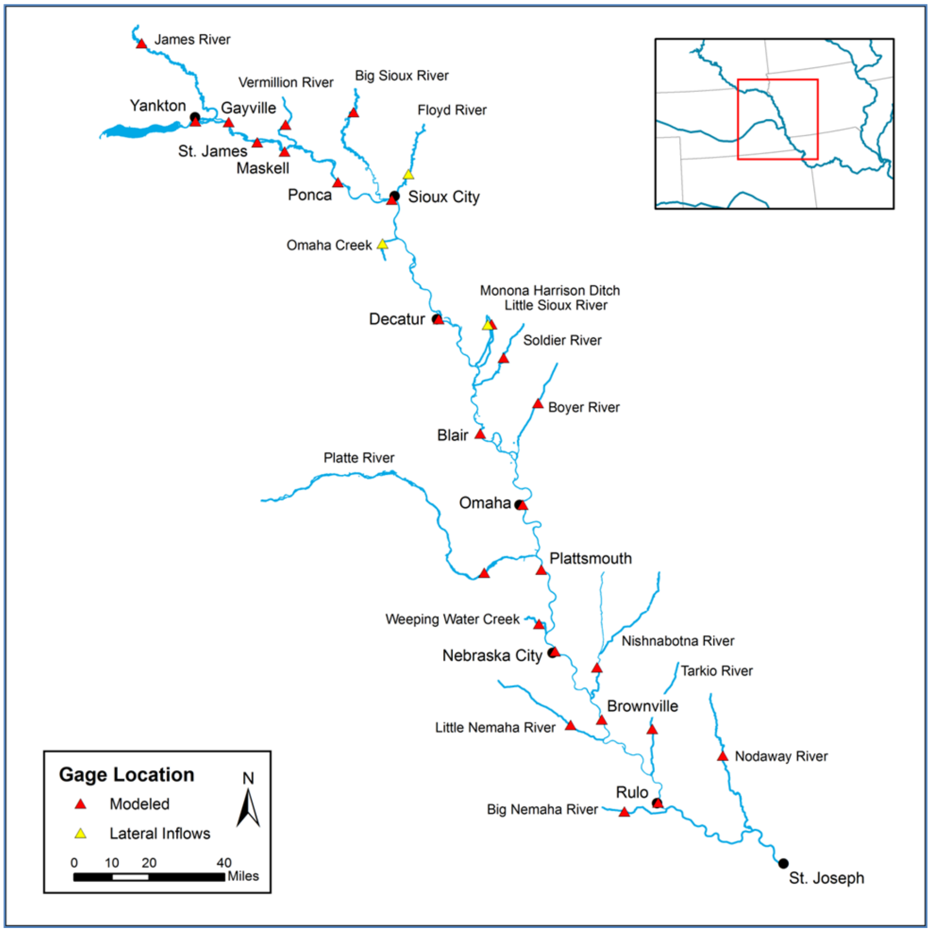


Figure 4-1. Omaha HEC-RAS RAS Model Extents

Figure 4-2. Kansas City RAS Model Extents

Both HEC-RAS geometries are one-dimensional (1D), which means the geometry consists of cross sections to represent the river, and levees in the floodplain are represented by lateral structures and 1D storage areas. Storage area connections allow the transfer of water between two storage areas. Flow moving over lateral structures and storage area connections is determined by the weir equation, which is a function of the length of the weir, the elevation of water over the structure/connection elevation, and a weir coefficient. There are no two-dimensional (2D) components in the models at this time. However, many floodplain areas contained within the levee systems would be better represented with a 2D grid computation.

Data sources for both models' geometries were the best available at the time of model creation. Data sources included LiDAR with collection dates ranging from 2006 to 2014, Missouri River bathymetry collected from 2011 – 2013, and National Levee Database top of levee surveys from the late 2000s. The vertical datum for both models is North American Vertical Datum of 1988 (NAVD88). The horizontal projection for both models is North American Datum of 1983 (NAD83) UTM Zone 15N (US Feet). Small adjustments were made to the existing geometry for stability in running extreme low flows and extreme high flows, but changes were minimal and did not affect calibration or annual peak results.

4.2 Data Development

Simulations performed in HEC-RAS in support of this Missouri River Flow Frequency Study included three computations of the POR, representing observed, unregulated, and regulated conditions. The POR for this study is 90 years in length from 1930 to 2019. All simulations were continuous, unsteady, and were computed with HEC-RAS 5.0.7. Several of the largest floods on record were scaled and run in HEC-RAS to define the highest part of the regulated-unregulated relationship. Boundary conditions required to run the various HEC-RAS simulations are discussed below. All input flow hydrographs are daily average, which is interpreted by HEC-RAS as a once per day value.

The observed HEC-RAS simulation represents flows into the Missouri River as they occurred in history, routed through the present-day river channel and floodplain configuration. Observed flows are non-homogeneous, as nearly all of the regulatory dams were constructed and became operational between the years of 1950 to 1970, and depletions have changed over the decades. Boundary conditions for the Missouri River mainstem and tributaries to the Missouri River are as recorded at gaging stations by USGS or USACE. An observed POR simulation was necessary for computing ungaged, or missing, flows as well as validation of results before running the unregulated and regulated POR.

The unregulated simulation (also referred to as natural or no regulation/no irrigation) represents the POR as it may have occurred if there were no dams regulating the flow of water, and no depletions of water for irrigation or other water uses. The regulated simulation (also referred to as present condition) represents the POR as it may have occurred if present-day water resources development were as they are today for the entire POR. Boundary conditions that were modified for unregulated/regulated simulations include:

- The Missouri River flow out of Gavins Point Dam
- The flow for 4 tributaries that have regulatory dams in their watershed
  - Platte River (Missouri)
  - Kansas River
  - Chariton River
  - Osage River
- Depletions, added or removed in each reach of the Missouri River, and for each tributary, from Gavins to the mouth

Boundary conditions for the HEC-RAS models and how they were modified to simulate the observed, unregulated, and regulated PORs are described in the following paragraphs.

Stream gage locations that provided flow inputs to the HEC-RAS models, as well as upstream and downstream boundary conditions to the two HEC-RAS models are listed in Table 4-1. USGS/USACE tributary records were often incomplete and had to be extended or gap filled to provide a continuous boundary condition to the HEC-RAS simulations. The observed flow dataset that was developed for the Man Plan EIS was used for 1930 to 2012 and was extended with recent records to include the high flow events of 2019, which were considered vital to this study. Detailed documentation of the data collection and extension/gap fill techniques are provided in *Missouri River Recovery Management Plan Time Series Data Development for Hydrologic Modeling* (USACE, July 2018). Table 4-1 also indicates which boundary conditions were swapped for the unregulated and regulated simulations and a brief description of the data source, described in more detail elsewhere in this report.

Depletions were obtained from Reclamation, refer to Section 2.5 for further explanation. The Reclamation depletions were divided into HUC-8 areas, but the HEC-ResSim analysis had already divided them by the mainstem gage reaches thus in a format available for use in the HEC-RAS simulations. For the Omaha Model, the mainstem reach depletions were given a depletion ratio based on river miles. The percentage by reach values are shown in Table 4-2. The depletions were input as uniform lateral inflows that spanned the entire reach. For the Kansas City Model, reach depletions were typically very small compared to the overall Missouri River flow. Therefore, for simplicity and consistency with the ResSim analysis, reach depletions were applied as a lateral inflow in the cross section immediately upstream of the downstream gage location.

Table 4-1. HEC-RAS Stream Gage Boundary Conditions

River	Mo RM	Gage Location	Observed Record	RAS Boundary Condition Description	Unregulated Description	Regulated Description
Missouri River*	811	Gavins Point Dam release	1955–2019	Upstream Boundary, Omaha Model	Natural Condition flow from ResSim	Present Condition flow from ResSim
James River	801	Scotland, SD	1930–2019	Tributary reach modeled with cross sections	Same as observed POR	Same as observed POR
Vermillion River	772	Vermillion, SD	1983–2019	Tributary reach modeled with cross sections	Same as observed POR	Same as observed POR
Big Sioux River	734	Akron, IA	1930–2019	Tributary reach modeled with cross sections	Same as observed POR	Same as observed POR
Floyd River	731	James, IA	1934–2019	Lateral Inflow at RM 731.35	Same as observed POR	Same as observed POR
Omaha Creek	720	Homer, NE	1945–2019	Lateral Inflow at RM 720.03	Same as observed POR	Same as observed POR
Monona-Harrison Ditch	670	Turin, IA	1942–2019	Lateral Inflow at RM 670.25	Same as observed POR	Same as observed POR
Little Sioux River	669	Turin, IA	1942–2019	Tributary reach modeled with cross sections	Same as observed POR	Same as observed POR
Soldier River	664	Pisgah, IA	1940–2019	Tributary reach modeled with cross sections	Same as observed POR	Same as observed POR
Boyer River	635	Logan, IA	1937–2019	Tributary reach modeled with cross sections	Same as observed POR	Same as observed POR
Platte River	595	Louisville, NE	1953–2019	Tributary reach modeled with cross sections	Same as observed POR	Same as observed POR
Weeping Water Creek	569	Union, NE	1950–2019	Tributary reach modeled with cross sections	Same as observed POR	Same as observed POR
Missouri River	562.74	Nebraska City, NE	1929–2019	Upstream Boundary, Kansas City model	Omaha Model unregulated simulation	Omaha Model regulated simulation
Nishnabotna River	542	Hamburg, IA	1928–2019	Tributary reach modeled with cross sections	Same as observed POR	Same as observed POR
Little Nemaha River	527	Auburn, NE	1949–2019	Tributary reach modeled with cross sections	Same as observed POR	Same as observed POR
Tarkio River	507	Fairfax, MO	1922–1990, 2007–2019	Tributary reach modeled with cross sections	Same as observed POR	Same as observed POR
Big Nemaha River	495	Falls City, NE	1944–2019	Tributary reach modeled with cross sections	Same as observed POR	Same as observed POR

River	Mo RM	Gage Location	Observed Record	RAS Boundary Condition Description	Unregulated Description	Regulated Description
Nodaway River	463	Graham, MO	1982–2019	Tributary reach modeled with cross sections	Same as observed POR	Same as observed POR
Missouri River	448.16	St. Joseph, MO	n/a	Normal depth downstream boundary, Omaha Model	Same as observed POR	Same as observed POR
Platte River	391	Sharps Station, MO	1978–2019	Tributary reach modeled with cross sections	Includes lake holdouts routed downstream	Spreadsheet routing for regulated
Kansas River	367	Desoto, KS	1917–1973	Tributary reach modeled with cross sections	Includes lake holdouts routed downstream	ResSim regulated simulation
Blue River	358	Stadium Drive	2002–2019	Lateral Inflow at RM 358	Same as observed POR	Same as observed POR
Little Blue River	339	Lake City, MO	1948–2019	Lateral Inflow at RM 339	Same as observed POR	Same as observed POR
Crooked River	314	Richmond, MO	1948–1970, 2007–2019	Lateral Inflow at RM 314	Same as observed POR	Same as observed POR
Wakenda Creek	263	Carrollton, MO	1948–1970, 2008–2013	Lateral Inflow at RM 263	Same as observed POR	Same as observed POR
Grand River	250	Sumner, MO	1924–2019	Tributary reach modeled with cross sections	Same as observed POR	Same as observed POR
Chariton River	239	Prairie Hill, MO	1929–2019	Tributary reach modeled with cross sections	Includes lake holdouts routed downstream	ResSim regulated simulation
Blackwater River	202	Blue Lick, MO	1922–1933, 1938–2019	Tributary reach modeled with cross sections	Same as observed POR	Same as observed POR
Lamine River	202	Otterville, MO	1987–2019	Tributary reach modeled with cross sections	Same as observed POR	Same as observed POR
Moniteau Creek	186	Fayette, MO	1948–1969, 2002–2019	Lateral Inflow at RM 186	Same as observed POR	Same as observed POR
Petite Saline Creek	177	Boonville, MO	2007–2019	Lateral Inflow at RM 177	Same as observed POR	Same as observed POR
Hinkson Creek/ Perchee Creek	170	Columbia, MO	1966–1981, 1986–1991, 2007–2019	Lateral Inflow at RM 170	Same as observed POR	Same as observed POR
Moreau River	138	Jefferson City, MO	1947–1974, 2000–2019	Tributary reach modeled with cross sections	Same as observed POR	Same as observed POR
Osage River	130	St. Thomas, MO	1931–2019	Tributary reach modeled with cross sections	Includes lake holdouts routed downstream	ResSim regulated simulation
Maries River	130	Westphalia, MO	1947–1970, 2002–2019	Lateral Inflow on Osage at RM 09	Same as observed POR	Same as observed POR

River	Mo RM	Gage Location	Observed Record	RAS Boundary Condition Description	Unregulated Description	Regulated Description
Gasconade River	104	Rich Fountain	1921–1959, 1986–2019	Tributary reach modeled with cross sections	Same as observed POR	Same as observed POR
Mississippi River	n/a	Lock & Dam 25 Tailwater	1938–2019	Upstream boundary	Same as observed POR	Same as observed POR
Illinois River	n/a	Valley City, IL	1938–2019	Lateral Inflow on Mississippi at RM 220	Same as observed POR	Same as observed POR
Mississippi River	n/a	St. Louis, MO	n/a	Rating curve downstream Boundary, KC model	Same as observed POR	Same as observed POR

* A minimum flow for Gavins Point Dam releases of 15,000 cfs was used in the Omaha model for all simulations. This generally occurred during the winter months and didn't affect the peaks.

Table 4-2. Depletion Ratio per Reach

Reach	U/S XS	D/S XS	Total RM	Percent	Ratio
Gavins to Sioux City	810.87	732.37	78.5	100%	
Gavins to James	810.87	800.6	10.27	13%	0.13
James to Vermillion	800.58	771.79	28.79	37%	0.37
Vermillion to Big Sioux	771.77	734.12	37.65	48%	0.48
Big Sioux to Little Sioux (Sioux City)	734.1	732.37	1.73	2%	0.02
Sioux City to Omaha	732.37	615.99	116.38	100%	
Big Sioux to Little Sioux (Sioux City)	732.37	669.34	63.03	54%	0.54
Little Sioux to Soldier	669.32	664.05	5.27	5%	0.05
Soldier to Boyer	664.03	635.24	28.79	25%	0.25
Boyer to Platte (Omaha)	635.22	615.99	19.23	17%	0.17
Omaha to Nebraska City	615.99	562.74	53.25	100%	
Boyer to Platte (Omaha)	615.99	595.02	20.97	39%	0.39
Platte to Weeping Water	595	568.72	26.28	49%	0.49
Weeping Water to Nishnabotna (Nebraska City)	568.7	562.74	5.96	11%	0.11
Nebraska City to Rulo	562.74	498.06	64.68	100%	
Weeping Water to Nishnabotna (Nebraska City)	562.74	542.04	20.7	32%	0.32
Nishnabotna to Little Nemaha	542.02	527.82	14.2	22%	0.22
Little Nemaha to Tarkio	527.8	507.7	20.1	31%	0.31
Tarkio to Big Nemaha (Rulo)	507.68	498.06	9.62	15%	0.15

Note: Method of uniform lateral inflow distributed by reaches only used by the Omaha Model from Gavins to Rulo. For Kansas City Model from Nebraska City downstream to the mouth, depletions were applied as a point inflow at the gage location.

For the unregulated simulation, historic depletion flows were calculated as an estimation of flow removed from the river for water use, and therefore typically had a negative value. To apply this correctly to the HEC-RAS simulation for unregulated, the historic flow depletions were given a multiplier in HEC-RAS of -1, which means estimated depletions were added as positive flow in the river. Historic depletions have the largest values at present day in the POR, approaching zero in the early years of the POR.

For the regulated simulation, present day incremental depletion flows were applied to the POR as an estimation of flow that should be removed from the river to match current depletion demands. Present day depletions also typically have a negative value, but opposite the historic depletions, they approach zero at present day in the POR, and are increasingly larger for years further back in time. These negative values were applied as-is to the HEC-RAS simulation for regulated, which means water was typically removed from the river.

4.3 Computation of Ungaged Flow

Ungaged flows represent flow that is missing from the HEC-RAS simulation when only observed stream gage records are used for boundary conditions. Any rainfall-runoff that enters the system downstream of the tributary gage is present in the mainstem USGS gage flow record but is missing from the RAS model computation. Approximately 6% of the basin area from Gavins to Rulo and 10% of the basin area from Rulo to the mouth of the Missouri River is ungaged, which can result in a substantial difference between RAS flows and observed flows. This difference is especially noticed when there is heavy local rain on the Missouri River system. For example, Figure 4-3, shows the 1993 HEC-RAS modeled results at Hermann before ungaged flows were computed (red) compared to the USGS daily flow (green). The RAS simulation is missing 300-kcfs at the peak of the flood event. Without accounting for ungaged flows in a sophisticated manner, the HEC-RAS model could not be used for evaluating annual peaks for the flow frequency study.

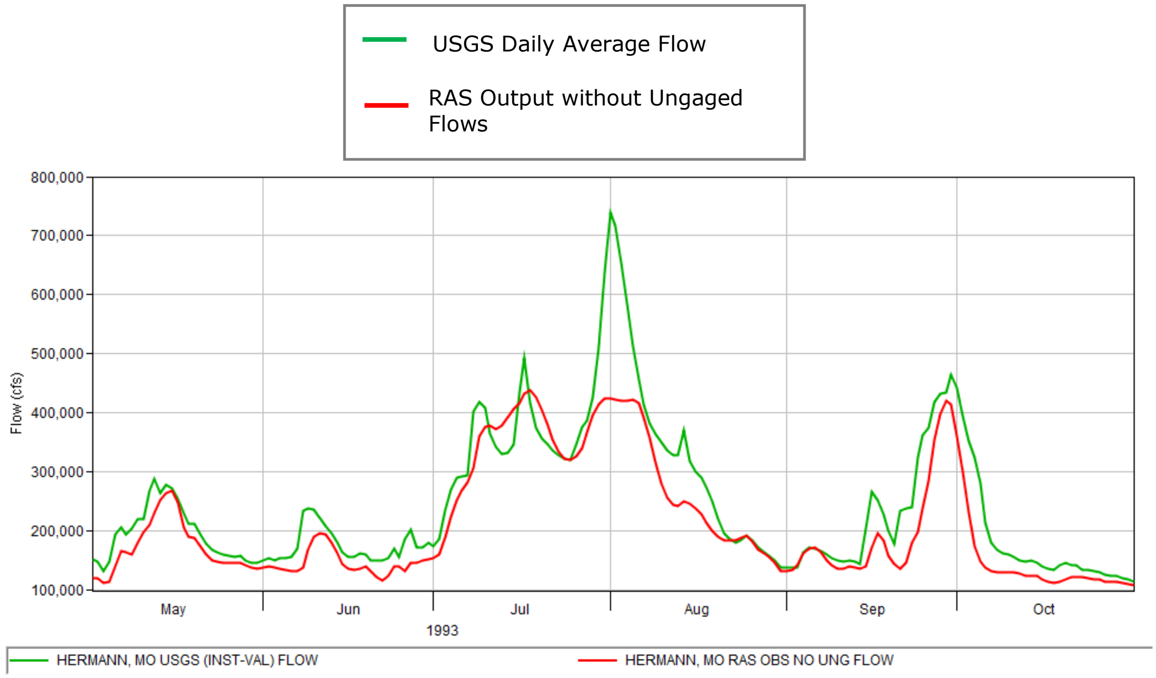


Figure 4-3. HEC-RAS Model Output at Hermann, MO Without Ungaged Flows

There are multiple methods that could be used to estimate the ungaged flow contribution, each with their own strengths and weaknesses. For this study, ungaged flows were back calculated from the observed record, similar to the ResSim, but utilizing the HEC-RAS model for routing. Ungaged flows for the HEC-RAS POR were calculated using two different tools. The first tool was the ungaged flow calculator within HEC-RAS. The second tool was a customized Jython script that was written in HEC-DSSVue and mimics the computation process of the HEC-RAS flow calculator. The Omaha Model used both tools to calculate ungaged flow while the Kansas City Model used only the Jython script. The decision to use two tools is due to the limitation of the ungaged calculator within RAS, which is only able to consider flow in the cross sections, not storage areas. Upstream of Omaha the cross sections extend from bluff to bluff. From Omaha downstream to the mouth, the Missouri River is heavily leveed on nearly every bend of the river, and to reflect this the HEC-RAS model has lateral structures and storage areas adjacent to almost every cross section. During floods, a significant amount of water can move in the downstream direction through the storage areas, circumventing the river cross sections. The script allowed for the addition of flow through the storage areas, with the added benefit of more transparency in calculations.

To compute the ungaged flows with the ungaged flow calculator within HEC-RAS, calculations are made between two gages on the mainstem Missouri River which have a continuous record of both stage and flow. The ungaged flow calculation is made by running the unsteady model with internal stage and flow boundaries at the downstream end of ungaged reaches. At the endpoint, the HEC-RAS calculated flow hydrograph is compared to the USGS daily average flow hydrograph, and the difference is calculated. The difference is put back into the model between the two gages at user specified locations with a backwards lag in time and the model is run again. A minimum flow was applied to prevent large negative ungaged flows from destabilizing the HEC-RAS model. This process is repeated until the flow at the endpoint either matches the flow convergence desired or meets the maximum number of iterations specified. Simultaneous was selected as the optimization mode, which means that ungaged calculations for each reach are made independently of others. The input information required to run the internal ungaged flow calculator within RAS for Gavins to Omaha is provided in Appendix F.

To compute ungaged flows with the script, first the unsteady HEC-RAS model is run with observed flow on the Missouri and at all gaged tributaries. Flow hydrographs computed by HEC-RAS are written to the HEC-DSS output file. The HEC-DSS script is manually executed by the modeler and the products are written to a separate HEC-DSS file for viewing, evaluation, and use in the next model run. The script first computes total Missouri River flow by adding the gage location cross section hydrograph with the appropriate storage area connection(s) and/or lateral structure hydrograph(s). Table 4-3 lists the hydrographs that are added together to obtain total bluff to bluff Missouri River flow at the mainstem gage locations.

Table 4-3. Total Flow at the Missouri River Mainstem Gage Locations

Gage Location	USACE Abbreviation	HEC-RAS Cross Section River Mile	HEC-RAS Storage Area Connections (SAC) and Lateral Structures (LS) Added to Cross Section Hydrograph for Total Flow
Omaha, NE	OMA	625.22*	-
Nebraska City, NE	NCNE	562.74	SAC 575B-N
Rulo, NE	RUNE	498.04	SAC rr1 + SAC rr2 + SAC rr3 + SAC rr4 + SAC hwy 5
St Joseph, MO	STJ	448.16	SAC 471b-c
Kansas City, MO	MKC	366.12	LS 370.67 + LS 367.35
Waverly, MO	WVMO	293.22	SAC sug1a-b + SAC blt5-sug2 + SAC blt5-sug3 + SAC blt6-sug3
Boonville, MO	BNMO	196.62	SAC how9a-t + SAC how9a-b
Hermann, MO	HEMO	97.93	SAC lut-tc2

* Due to geometry limitations, the total flow could not be added at the Omaha USGS gage location. XS 625.22, which is upstream of the right and left bank levees was used to approximate the total flow at the gage location.

For each ungaged reach, starting with the most upstream, the HEC-RAS total flow at the downstream gage is compared to the USGS daily average flow hydrograph, and the difference is calculated. The difference is portioned by drainage area ratio, lagged backward in time, and put back into the model between the two gages at user specified locations. A minimum flow was applied to prevent large negative ungaged flows from destabilizing the HEC-RAS model. The model is run again, and the difference and ungaged flows are computed once more before moving to the next downstream gage. Calculations were performed sequentially, which means that the ungaged flow for the next reach takes on any lack of flow convergence in the upstream reaches. Simultaneous computations would have required tackling the challenge of providing an appropriate observed flow boundary condition on the upstream end, which is difficult for the record floods where flow is split between cross sections and storage areas in a varying way. The input information required to run the ungaged DSS script is provided in Appendix F.

Ungaged flows that were computed from the observed POR remain unchanged for the unregulated and regulated simulations. Model stability issues were encountered when negative ungaged flows coincided with times of low flow on the mainstem Missouri River, essentially causing the modeled river flow to run dry. This was an issue mostly with the regulated runs, likely due to a mismatch of timing of low flows compared to the observed POR. Several techniques were used to stabilize the computation. Because properly modeling the annual peak was the focus of this study, and these usually happen in the spring and summer, a filter was used to limit the negative flows during the winter. If a negative flow occurred during 01 Aug to 28 Feb, it was set to zero. This technique was only applied to ungaged flows in the Omaha Model. This solved most the Omaha Model's stability issues. Hand edits were made to the ungaged flows for both the Omaha and Kansas City Models for the remaining instabilities. Typically, the ungaged flows were modified as little as possible, reducing the instances of negative ungaged flow one at a time until the simulation pushed past the zero-flow instability. Annual peaks were assessed after applying these techniques. It is possible that the few August to February annual peaks may have been slightly impacted by the modifications to ungaged, but the hand edits had no impact on the peak flow results.

4.4 Simulation Results

HEC-RAS model output is a continuous instantaneous flow hydrograph, a value once per day rather than daily average, at every model node. Model computation was performed at a timestep of every 20 minutes for the Omaha model and every 10 minutes for the Kansas City model. HEC-RAS hydrograph output timestep was selected as 1 day, a smaller interval was not feasible given the long simulation time period and large number of computation nodes in each model. From this once per day hydrograph, the maximum value in each year was identified and this was considered the HEC-RAS annual peak. Evaluation of results was limited to the annual peaks at the gage cross section locations. Results for the observed, unregulated, and regulated period of record simulations as well as scaled floods are described below. Tabular peak flow results by year for the observed, unregulated, and regulated simulations are included in Appendix G.

4.4.1 Observed

HEC-RAS results for the observed POR simulation tended to be slightly lower than the USGS, by about -2-kcfs or -2% on average overall. Averages by gage are shown in Table 4-4. The ungaged flow computation was made with daily average flow hydrographs, which explains why the RAS peaks tend to be low on average. Refer to Section 3.4 for a discussion of differences between daily average and instantaneous, which are generally between 2–6%, indicating that the HEC-RAS results are in a reasonable range.

Table 4-4. HEC-RAS Instantaneous Annual Peak Flow Compared to USGS Instantaneous Annual Peak Flow for Observed POR

	Difference from USGS Annual Peak for All Years (1930–2019) (cfs)		Percent Difference from USGS Annual Peak for All Years (1930–2019) (%)	
Gage Location	Avg	St Dev	Avg	St Dev
Sioux City, IA	-1,816	7,854	-2%	9%
Omaha, NE	-3,631	9,368	-6%	10%
Nebraska City, NE	-796	10,620	-1%	9%
Rulo, NE	-4,160	10,736	-4%	6%
St Joseph, MO	-2,963	9,548	-3%	7%
Kansas City, MO	-1,958	8,283	-1%	5%
Waverly, MO	-3,016	7,886	-2%	4%
Boonville, MO	-1,882	14,555	-1%	4%
Hermann, MO	1,677	14,316	1%	4%
Overall	-2,061	10,352	-2%	6%

Plots of the HEC-RAS instantaneous annual peak verses USGS instantaneous annual peak for the observed POR, as well as flows for the top 5 events at each gage are provided in Appendix H. Variability of the HEC-RAS results from year to year and gage to gage is moderate, as reflected by the standard deviation of about 10-kcfs or 6%. The largest outliers were 43% too low in the year 1934 (rank #12) at the Omaha gage and 28% too high in the year 1971 (rank #36) at Nebraska City. Despite these outliers, most years at most gages matched well to observed. As seen in the appendix, the more frequent events tend to plot closer to the line of equal agreement, whereas for the less frequent floods there was more scatter in the comparison. The floods of record (1993, 1952) had good agreement to the USGS recorded peak. The deviation at middle floods is likely due to the uncertainty in the modeling parameters of floodplain routing and storage. Historic events pose more of a challenge as the present-day river and floodplain configuration likely routes flow very differently through the system than historically. Modeling errors tend to accumulate in the downstream direction, though this is not necessarily visible in the observed POR statistics, because the uncertainty is hidden in the ungaged flow contribution.

For example, HEC-RAS output hydrographs for the 1952 flood for 3 mainstem gage locations in the Omaha Model, and the upper 2 gages in the Kansas City Model are shown in Figure 4-4. The 1952 flood is the largest in the POR for the Missouri River from Sioux City through St. Joseph. Due to the magnitude being much greater than any other flood, modeling it in HEC-RAS was challenging. Difficulties were encountered with calculating the ungaged flows and routing historic flows through a present-day channel and floodplain configuration, which varies widely from the geometry present in 1952. Results from the HEC-RAS observed simulation compare well with observed USGS record, however, ungaged flows through these reaches have a large positive and large negative swing around the peak to compensate for the difference in timing of the HEC-RAS present day river versus the historic river.

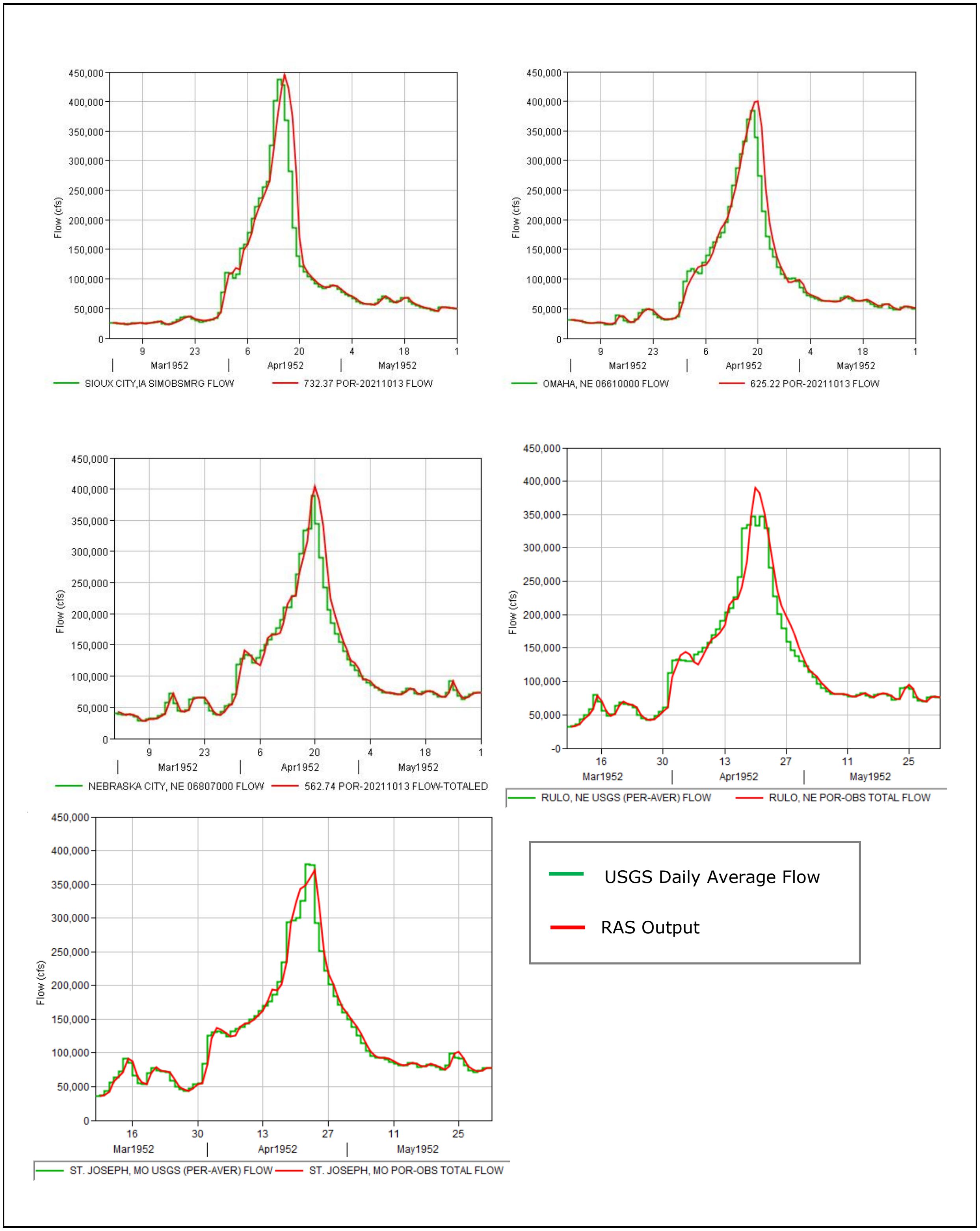


Figure 4-4. 1952 Flood at Sioux City, Omaha, Nebraska City, Rulo and St. Joseph, HEC-RAS Observed Simulation vs. USGS Observed

As another example, HEC-RAS output hydrographs for the 1993 flood for 4 mainstem gage locations below the Kansas River in the Kansas City Model are shown in Figure 4-5. The 1993 flood was the largest in POR at Waverly and downstream, and second largest to the 1951 flood at Kansas City. HEC-RAS results for the peak of the 1993 flood tracks well with observed, though the HEC-RAS peak is slightly too high and slightly too late compared to the daily average USGS flows. Ungaged flows were a large contribution of the total flood volume for this flood. Flow added between Kansas City and Waverly has a large and direct impact on Boonville and Hermann flows.

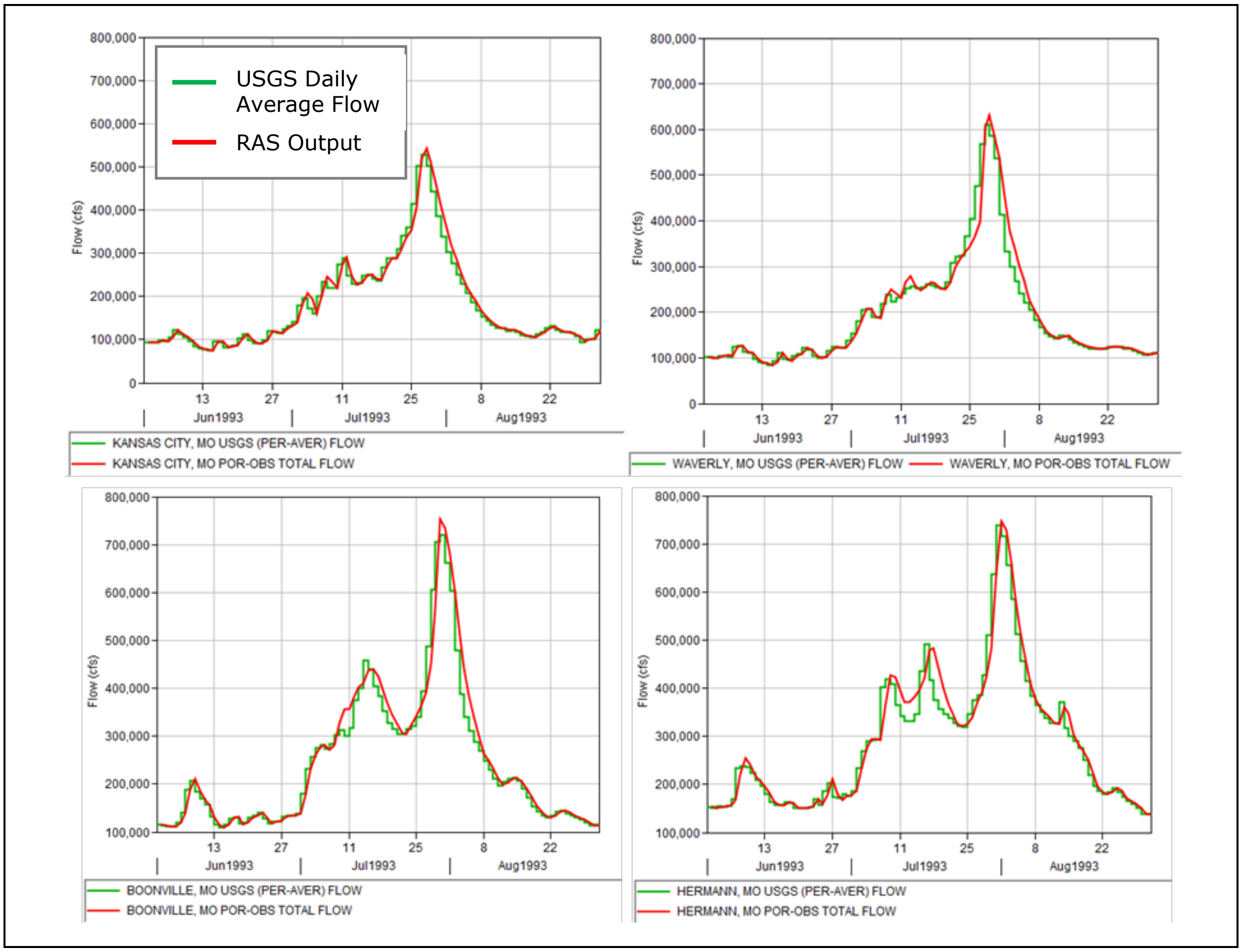


Figure 4-5. 1993 Flood at Kansas City, Waverly, Boonville, and Hermann HEC-RAS Observed Simulation vs. USGS Observed, 1993

Overall, the HEC-RAS observed POR hydrographs match well with USGS. However, use of a present-day channel and floodplain geometry while comparing to historic flows was problematic, and lead to less confidence in ungaged flows. Errors embedded in the ungaged flow hydrographs are present in the unregulated and regulated evaluations. This method is reasonable for assessing flow statistics at the gage locations.

4.4.2 Unregulated and Regulated

HEC-RAS annual peak results for the unregulated POR and regulated POR simulations are shown in Appendix H. Unlike the observed POR, the unregulated and regulated results are fabricated scenarios. There is no benchmark for comparison of unregulated and regulated flows other than evaluating differences between the paired results for each year, and comparison of the HEC-RAS model results to other modeled results. HEC-RAS unregulated peaks are consistently higher and more pronounced than the HEC-RAS regulated peaks. As expected, due to changes in regulation and depletions over time, the unregulated simulation matches more closely to observed data in the early years of the POR, whereas the regulated simulation matches more closely to observed data in the later years of the POR.

For example, the 1952 HEC-RAS regulated and unregulated simulation is shown in Figure 4-6. The unregulated peaks range from 500 kcfs to 600 kcfs while the regulated peaks stay in the 100 kcfs to 200 kcfs range. The large difference between unregulated and regulated is likely because most of the flood volume came from the upper basin, upstream of all the mainstem reservoirs. At the time, only one of the mainstem dams was in place. The 1952 flood, with all dams in place would have looked much lower as reflected by the regulated simulation. The negative swing on the falling limb of the regulated simulation was likely caused by a negative unaged, compensating for the difference in timing of present-day routing versus historic routing.

As another example, the 1993 HEC-RAS regulated and unregulated simulation is shown in Figure 4-7. All unregulated peaks are well above the regulated for the 1993 flood event, peaking above 1 million cfs at Hermann. The 1993 event is relatively late in the POR, thus the regulated simulation is very similar to the observed flows.

Overall, HEC-RAS produces results consistent with what we would expect for unregulated verses regulated flows. Unregulated flows were higher or equal to regulated for every annual peak at every gage. The difference between unregulated and regulated describes how influential lake regulation is on the Missouri River flows.

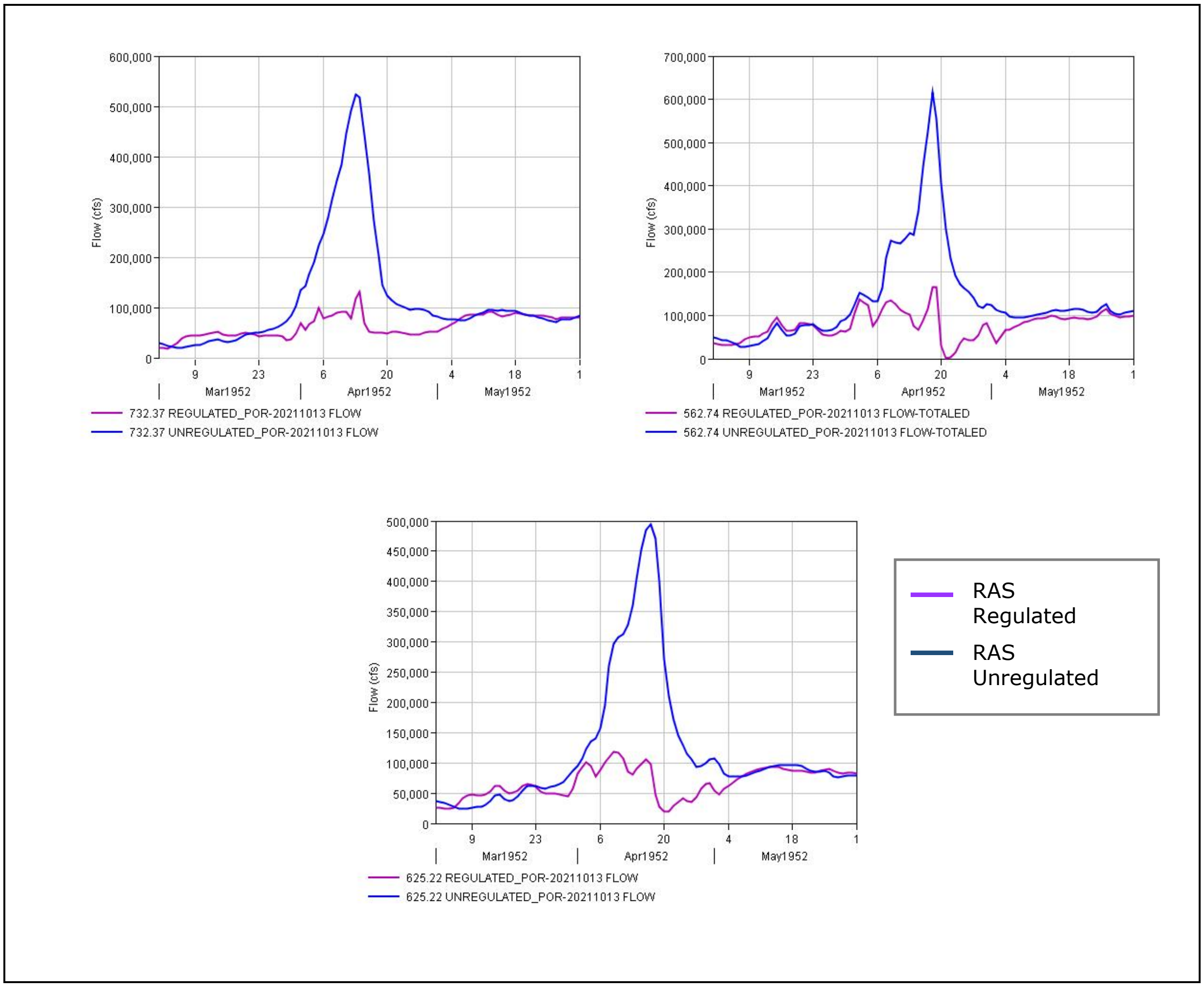


Figure 4-6. 1952 Flood at Sioux City, Omaha, Nebraska City, HEC-RAS Unregulated vs. Regulated

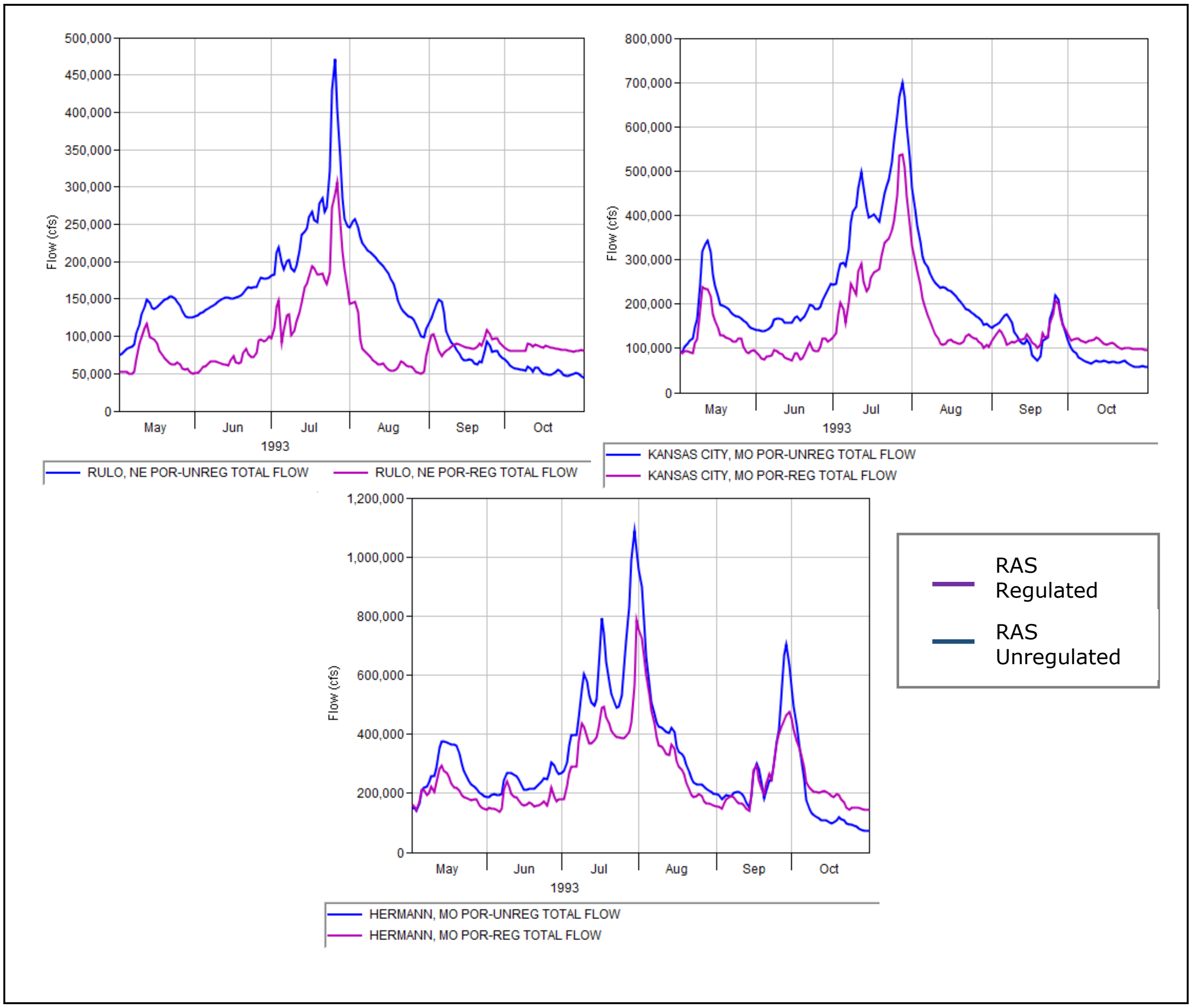


Figure 4-7. 1993 Flood at Rulo, Kansas City, and Hermann, HEC-RAS Unregulated vs. Regulated

4.4.3 Scaled Events

In an attempt to produce unregulated to regulated flow transform curves from the HEC-RAS models, historical events were synthetically scaled and run in HEC-RAS. Two events were run in the Omaha Model:

- 1952 plus 2 standard deviations
- 2011 plus 1 standard deviation

And three events were run in the Kansas City Model:

- 1993 plus 1 standard deviation
- 2008 plus 1.5 standard deviation
- 2019 plus 1 standard deviation

Outputs generated in ResSim were used directly for boundary conditions at Gavins Point Dam, the Kansas River at Desoto, and the Osage River at St. Thomas. All other HEC-RAS gage boundary conditions and ungaged boundary conditions are ResSim local flows from the scaled simulations, distributed by basin area ratio. Depletions were included, unchanged from the unregulated and regulated POR simulations. Each scaled event was run for an entire year, for both the unregulated and regulated scenarios. Simulation of extreme events pushed the 1D HEC-RAS model geometry configuration to the limit. The most extreme events heavily inundate the lateral structures to a level in which the bathtub assumption of storage areas is no longer appropriate, and a full valley cross section may more appropriately represent the transfer of flow down the river. Due to the number of instabilities encountered and the time it took to generate a stable run, it was unfeasible to run the full number of events necessary for the transform curves.

4.5 Model Limitations

HEC-RAS has an important strength that sets it apart from other simpler routing methods for the Missouri River. It is physically based and can capture the complex relationship of channel and floodplain flow, especially the effect of storage and water movement behind and through leveed areas. It requires many data sources: LiDAR data, channel bed data, roughness factors, and precise information on where flow enters the system. Each of these data sources are accompanied by uncertainty and sometimes data gaps. HEC-RAS has the potential to provide a more correct and complete answer than simpler methods, but also has wider uncertainty bounds. HEC-RAS solves complex momentum equations to provide a routed hydrograph, which can be time consuming and is sensitive to instabilities as it is tested with extreme and varied conditions.

4.5.1 Historic River Configuration

The HEC-RAS geometry used for this study represents present-day river conditions for the Missouri River channel bed, navigation structures, floodplain elevations, and levee top elevations. The river and floodplain have changed considerably over the last 90 years, and each of these elements affect travel time and floodplain attenuation. Computing ungaged flows using a present-day river is problematic, as the timing between the HEC-RAS routed peak flow, and gage observed peak flow do not necessarily line up. Timing differences get incorporated into the ungaged flows as large negative and positive swings, and these swings are carried over into the unregulated and regulated simulations.

4.5.2 1D Modeling Assumptions

Nebraska City, Rulo and Waverly have similar wide floodplains with complex levees and high ground obstructions that restrict and direct flow through the overbank during the extreme events. Flow is spread so wide on the floodplains that a small change in stage can mask a large change in flow. At these locations, 1D storage areas and connections is an oversimplification, and it is not clear without extensive 2D modeling and calibration to on the ground observations if 1D modeling strategies are sufficient to represent the routing of water through these locations. Calibration of the 1D model was limited to the high flow events of 2011 and 2013, which did not fully test the 1D storage areas to the level of the most extreme events in the period of record. Additionally, the USGS flow data used for calibration and ungaged flow computations is also subject to uncertainty. Accurate flow measurements at these locations are difficult for the USGS to obtain as safety on the boat during high water events is a concern. Often crews are forced to take measurements further downstream of the actual gage locations and make a correction for tributaries that enter between the gage and measurement locations. Uncertainty in the routing through the Nebraska City, Rulo, and Waverly floodplains have a ripple effect downstream. If the HEC-RAS computations are incorrect in the timing of flow routing, or the effect of storage on the peak through this area, the most pronounced impact will be on the next gage downstream, for Nebraska City flow at Rulo is impacted, for Rulo flow at St. Joseph is impacted, and for Wavery flow at Boonville is impacted.

4.5.3 Ungaged Flow

The calculated ungaged flow is the largest source of uncertainty in the model. Ungaged flow was computed iteratively with the HEC-RAS simulation incorporating uncertainties that may be due to historic geometry differences, timing, 1D assumptions, and/or calibration errors.

4.5.4 Levee Breaches

Breaches were not included in the HEC-RAS POR simulations, though there have been many levee breaches over the lifetime of levee construction on the Missouri River. Some levees in the system have never breached, and some levees have breached numerous times. With the current model configuration of levees as lateral structures, all protected areas are flooded at the onset of levee overtopping only. A tool within HEC-RAS allows lateral structures to simulate a breach, however there is added uncertainty when incorporating the tool in the models. Parameters needed to perform the computations include breach location, time of breach onset, development rate, and weir coefficient. Often this information is hard to obtain during high water events, even for the most recent flood events. Historically, the same levee may have breached in different locations at different relative water surface elevations. Breaches occur due to a number of factors including geotechnical and overtopping. Correlation of breach with stage/flow records show that breaches in subsequent years have occurred at lower stages and shorter duration than prior years that did not breach. Variability over time and space makes breach parameters for HEC-RAS even more difficult to summarize for the POR. Breaches that occurred in the observed record are not relevant to either the regulated or unregulated flows. For these reasons, breaches were not included in any of the simulations for this study.

4.5.5 Daily Data

Due to the availability of historic flow data, daily average flow hydrographs were used for the HEC-RAS model input for upstream boundaries. Daily average flows were also used as the calibration target for ungaged flow calculations. Daily average data is an average of all values reported for that day, while the reported USGS annual peak is the highest value reported for that day. When comparing the USGS instantaneous annual peaks with the maximum value in the USGS daily average flow data, the instantaneous values are always higher than the daily averages. For example, during the 2011 event at Rulo, the instantaneous annual peak was 328,000 cfs whereas the daily average was 302,000 cfs. No adjustment was made to the HEC-RAS results to adjust for the difference between daily average and instantaneous peaks. Additionally, output from the model was on a daily timestep, although the model reports an instantaneous midnight value, not a daily average. No adjustment was made for the HEC-RAS results to adjust the instantaneous midnight flow to a true computed maximum flow for the study. Because the Missouri is a slow rising and slow falling river for most events, 1 day output appears to capture the peak flow fairly well.

4.5.6 Computation Time

Overall, the HEC-RAS analysis took longer than anticipated. Computation timestep of 20- and 10-minutes were used for the Omaha Model and Kansas City Model, respectively. Average run time for the POR was 14 hours for the Omaha Model and 54 hours for the Kansas City Model, longer if the simulation went unstable and ended before the POR could be completed. Computing the ungaged flows for the POR required running the 90- year simulation several iterations per mainstem gage for a total of 12 times for both the Omaha Model and Kansas City Model. Distributed compute strategies were employed for the Kansas City Model, splitting the POR into decades to be run simultaneously on multiple computers and collating results at the end. This was helpful to reduce overall run times but presented additional challenges of organization and version control. Long computation times and troubleshooting ultimately meant that HEC-RAS was a tool that required more resources than were allocated for this project.

4.6 HEC-RAS Model Routing Lessons Learned

While the HEC-RAS results were not selected for the final flow frequency statistics, modeling the observed, unregulated, and regulated POR as well as scaled floods (see Appendix E and Section 5) was an extraordinary accomplishment. The HEC-RAS geometries were stress tested beyond any historic use and are more robust and better prepared for any follow-on stage frequency efforts. Lessons learned include ways to modify the geometry and flow parameters for stability in extreme floods, a need to develop a greater understanding of ungaged flows on the Missouri River, and a need for scripts that can be utilized for post processing. Effort to run as many scaled floods as conducted with HEC-ResSim was deemed impractical, however, of the floods that were computed as documented in Section 5, results were either higher or lower than the ResSim, indicating no clear trend with extreme floods. Differences in the computed flow frequencies is considered in the following Section, and in Section 3.8.2, 3.8.3, 3.8.5, and 3.8.6 for expected probabilities at select gages.

4.7 Comparison of Unregulated Flow Frequency with HEC-RAS vs HEC-ResSim Routing

Analysis of the two methods of routing, which generated two annual peak or seasonal annual peak datasets, was conducted to determine differences in the computed flow frequency results. As previously discussed, the first data set was generated using an HEC-ResSim model (ResSim) and the second using a HEC-RAS model (RAS). The main difference between the two modeling efforts lies in the routing methodology. The ResSim flows are routed using calibrated routing coefficient while the RAS flows are routed using unsteady one-dimensional open channel flow equations that account for dynamic and shear effects on the flow due to channel and overbank geometry.

A secondary difference resides on the modeling time step used. The ResSim flows were computed using a daily timestep while the RAS flow were computed using a 10-minute timestep. Given the need for instantaneous peaks, maximum daily flows obtained from ResSim were factored by a peak-to-daily flow ratio (peak ratio) of 2 to 6% depending on the gage as tabulated in Section 3.4. Since the RAS flows were computed at a 10-20-minute interval, the midnight flow values that were used to populate the annual peak dataset were considered instantaneous, and no ratio was applied. In summary, these datasets are not “true” peak flows; however, since daily average flows and actual peak flows are relatively close on the middle- to-lower Missouri River, the HEC-ResSim peak to daily ratio factored flows and the RAS midnight flow values are considered acceptable for this effort. Potential error with this approach may be similar to the 2-6% peaking factors applied to the ResSim.

4.7.1 Period of Record and Historical Events

As summarized in Section 3, the systematic period of record spans from 1930–2019, whereas the historical period of the final flow frequencies extends back in time to 1843. Estimates of historic peak flows were available from several sources as summarized in Section 2.4, Section 3, and Appendix A. The systematic period of record data is summarized in Appendix A for the ResSim routings.

4.7.2 Analysis Procedure

Bulletin 17C flow frequency analysis was conducted with the two main datasets. Additionally, supplemental historic data was used to extend the effective period of record (POR) using perception thresholds. Full frequency analyses were conducted with the extended POR datasets using perception thresholds. Although not identical to the final chronology and historical period utilized in the adopted unregulated flow frequency results, the same set of historical flows were used to supplement ResSim and RAS datasets for the comparison analysis. The Sioux City, Omaha, Nebraska City, Rulo, and St. Joseph stations were analyzed with a mixed population analysis as described in Section 3.3, while the Kansas City, Waverly, Boonville, and Hermann stations were analyzed with a single annual maximum series. The extended datasets used for the routing comparison analyses are identified and described in Table 4-5. Computed probability unregulated flow frequency curves comparing the HEC-ResSim and HEC-RAS routing methods are shown in Table 4-6, Table 4-7, and Table 4-8. For expected probability impacts, results comparing the 1930 to 2019 period are also included for four gages in Sections 3.8.2, 3.8.3, 3.8.5, and 3.8.6. Overall, little difference was found in the results for either routing method, especially considering differences in how peaking factors were applied.

Table 4-5. Mixed Datasets Used for Analyses with Period of Record and Brief Description

Data Set	Period of Record	Description
RS	1930–2019	The HEC-ResSim Flows were computed at a daily timestep using calibrated routing coefficients. The maximum daily flows were factored by a peak to daily flow ratio on the order of 2–4% based on its location as documented in Section 3.4.
HR	1930–2019	The HEC-RAS flows were routed using the unsteady one-dimensional open channel equations. This methodology considers the effects of the channel and overbank geometry on the flow characteristics. The flows were computed using 10-20-minute timesteps which were considered instantaneous values for this effort.
RS+U	1898–2019	Basis is HEC-ResSim dataset from 1930–2019 extended using the 2003 UMRSFFS data from 1989–1929.
HR+U	1898–2019	Basis is HEC-RAS dataset from 1930–2019 extended using the 2003 UMRSFFS data from 1898–1930.
RS+H*	Varies–2019	Basis is HEC-ResSim dataset from 1930–2019 extended using available historic events and perception threshold. Beginning of dataset will vary depending on availability of historic events.
HR+H*	Varies–2019	Basis is HEC-RAS dataset from 1930–2019 extended using available historic events and perception thresholds. Beginning of dataset will vary depending on availability of historic events.

*While different than the final adopted historic period chronology documented in Section 3.6 and 3.7, identical historical chronology was used for this sensitivity analysis.

Table 4-6. Comparison of Unregulated Flow Frequency based on HEC-RAS and HEC-ResSim Routed Flows at Sioux City, Omaha, and Nebraska City, Computed probability (Without the Expected Probability Adjustment), 1930–2019

Sioux City				Omaha				Nebraska City			
% ACE	Flow (cfs) HEC-ResSim	Flow (cfs) HEC-RAS	% Difference	% ACE	Flow (cfs) HEC-ResSim	Flow (cfs) HEC-RAS	% Difference	% ACE	Flow (cfs) HEC-ResSim	Flow (cfs) HEC-RAS	% Difference
0.2	727,333	712,000	-2.1	0.2	692,892	713,000	2.9	0.2	715,232	735,000	2.8
0.5	573,091	562,000	-1.9	0.5	549,107	561,000	2.2	0.5	582,711	593,000	1.8
1	474,470	465,000	-2.0	1	457,410	465,000	1.7	1	498,411	503,000	0.9
2	391,406	384,000	-1.9	2	380,648	384,000	0.9	2	426,974	428,000	0.2
5	304,890	299,000	-1.9	5	301,074	299,000	-0.7	5	348,774	347,000	-0.5
10	253,500	249,000	-1.8	10	253,404	249,000	-1.7	10	298,214	295,000	-1.1
20	209,219	205,000	-2.0	20	211,672	205,000	-3.2	20	251,595	248,000	-1.4
50	152,554	150,000	-1.7	50	157,114	150,000	-4.5	50	188,686	185,000	-2.0
80	115,147	113,000	-1.9	80	120,347	114,000	-5.3	80	146,035	143,000	-2.1
90	100,246	99,000	-1.2	90	105,525	100,000	-5.2	90	128,907	127,000	-1.5
95	89,718	88,000	-1.9	95	94,976	89,000	-6.3	95	116,772	115,000	-1.5
99	73,383	72,000	-1.9	99	78,494	75,000	-4.5	99	97,890	97,000	-0.9

Note: Annual peak data for ResSim increased daily flows by 2-6% using peaking factors in Section 3.4; whereas HEC-RAS used a 10-20-minute time step with flows pulled at midnight each day, which may or may not correspond to the peak.

Table 4-7. Comparison of Unregulated Flow Frequency Based on HEC-RAS and HEC-ResSim Routed Flows at Rulo, St. Joseph, and Kansas City, Computed probability (Without the Expected Probability Adjustment), 1930–2019

Rulo				St. Joseph				Kansas City			
% ACE	Flow (cfs) HEC-ResSim	Flow (cfs) HEC-RAS	% Difference	% ACE	Flow (cfs) HEC-ResSim	Flow (cfs) HEC-RAS	% Difference	% ACE	Flow (cfs) HEC-ResSim	Flow (cfs) HEC-RAS	% Difference
0.2	751,000	731,000	-2.7%	0.2	636,000	622,000	-2.2%	0.2	800,000	754,000	-5.8%
0.5	619,000	588,000	-5.0%	0.5	546,000	523,000	-4.2%	0.5	694,000	654,000	-5.8%
1	533,000	497,000	-6.8%	1	485,000	458,000	-5.6%	1	620,000	583,000	-6.0%
2	457,000	420,000	-8.1%	2	429,000	399,000	-7.0%	2	552,000	515,000	-6.7%
5	371,000	333,000	-10.2%	5	362,000	332,000	-8.3%	5	465,000	430,000	-7.5%
10	313,000	278,000	-11.2%	10	315,000	286,000	-9.2%	10	401,000	369,000	-8.0%
20	259,000	228,000	-12.0%	20	268,000	242,000	-9.7%	20	336,000	307,000	-8.6%
50	189,000	167,000	-11.6%	50	204,000	183,000	-10.3%	50	241,000	221,000	-8.3%
80	144,000	131,000	-9.0%	80	159,000	145,000	-8.8%	80	175,000	162,000	-7.4%
90	128,000	119,000	-7.0%	90	141,000	130,000	-7.8%	90	148,000	139,000	-6.1%
95	116,200	111,000	-4.5%	95	128,000	119,000	-7.0%	95	130,000	123,000	-5.4%
99	99,100	100,000	0.9%	99	108,000	103,000	-4.6%	99	101,000	99,000	-2.0%

Note: Annual peak data for ResSim increased daily flows by 2-6% using peaking factors in Section 3.4; whereas HEC-RAS used a 10-20-minute time step with flows pulled at midnight each day, which may or may not correspond to the peak.

Table 4-8. Comparison of Unregulated Flow Frequency based on HEC-RAS and HEC-ResSim Routed Flows at Waverly, Boonville, and Hermann, Computed Probability (Without the Expected Probability Adjustment), 1930–2019

Waverly				Boonville				Hermann			
% ACE	Flow (cfs) HEC-ResSim	Flow (cfs) HEC-RAS	% Difference	% ACE	Flow (cfs) HEC-ResSim	Flow (cfs) HEC-RAS	% Difference	% ACE	Flow (cfs) HEC-ResSim	Flow (cfs) HEC-RAS	% Difference
0.2	849,000	784,000	-7.7%	0.2	896,000	824,000	-8.0%	0.2	1,160,000	1,126,000	-2.9%
0.5	739,000	679,000	-8.1%	0.5	793,000	730,000	-7.9%	0.5	1,020,000	988,000	-3.1%
1	663,000	605,000	-8.7%	1	720,000	660,000	-8.3%	1	921,000	887,000	-3.7%
2	591,000	534,000	-9.6%	2	649,000	592,000	-8.8%	2	824,000	789,000	-4.2%
5	500,000	445,000	-11.0%	5	556,000	503,000	-9.5%	5	699,000	662,000	-5.3%
10	432,000	381,000	-11.8%	10	484,000	435,000	-10.1%	10	604,000	566,000	-6.3%
20	363,000	317,000	-12.7%	20	408,000	366,000	-10.3%	20	504,000	469,000	-6.9%
50	259,000	228,000	-12.0%	50	290,000	263,000	-9.3%	50	351,000	328,000	-6.6%
80	184,000	167,000	-9.2%	80	203,000	190,000	-6.4%	80	241,000	229,000	-5.0%
90	154,000	144,000	-6.5%	90	167,000	160,000	-4.2%	90	196,000	190,000	-3.1%
95	133,000	127,000	-4.5%	95	141,000	139,000	-1.4%	95	165,000	163,000	-1.2%
99	101,000	103,000	2.0%	99	103,000	107,000	3.9%	99	118,100	122,000	3.3%

NOTE: Annual peak data for ResSim increased daily flows by 2-6% using peaking factors in Section 3.4; whereas HEC-RAS used a 10-20-minute time step with flows pulled at midnight each day, which may or may not correspond to the peak.

4.7.3 Conclusions of Routing Method on Flow Frequency

Peak flow frequencies estimated using HEC-RAS routed flows were overall very similar to peak flow frequencies estimated using HEC-ResSim routed flows, especially considering differences in that HEC-RAS flows used are not true annual peak values. Improvements to post-processing of results would better facilitate pulling the true peak flows from the model results. HEC-RAS based flow frequencies were lower by about 2–8% at all locations except Omaha and Nebraska City, where the HEC-RAS based flow frequencies for the smallest or least frequent AEP’s were about 2–3% higher. Assuming HEC-RAS results converted to instantaneous peaks would require somewhere between 0% and the 2-6% increase depending on location as in Section 3.4, differences in computed flow frequencies would decrease overall. The HEC-RAS models for the lower Missouri River are computationally intensive necessitating long run times. This difficulty is confounded when attempting to route synthetic scaled floods which have flows greater in magnitude than the HEC-RAS models were built to handle, making it infeasible to build unregulated to regulated transforms using HEC-RAS routed flows. Effort to run as many scaled floods as conducted with HEC-ResSim was deemed impractical, however, of the floods that were computed as documented in Section 5, results were either higher or lower than the ResSim, indicating no clear trend with extreme floods.

Therefore, the flow frequency analysis was continued with HEC-ResSim routed flows. It was not feasible to overcome the limitations of HEC-ResSim with regards to modeling overbank flow and leveed areas. While not employed for the final unregulated flow frequency analysis, future analysis of potential changes to levee alignments or heights for potential downstream effects may still need to utilize HEC-RAS unsteady flow analysis. However, this potential future analysis that would be done as part of levee improvement studies can likely focus on hydrographs derived from regulated flow datasets. Regardless, design of a future system of levees that must rely on levee overtopping or breaching upstream to pass a particular flow is not advisable. Sensitivity analysis of routing flows with levees infinitely high, or using only cross sections modeling only areas between levees and bluffs is also recommended to determine the maximum downstream impact of cumulative potential future levee raises over time.

5. Regulated Flow Frequency, Transform Method

Flow frequency cannot be estimated with analytical methods such as Bulletin 17C directly on regulated streams. To estimate the regulated flow annual probabilities at each gage, two methods were utilized in this study, the "transform" method which seeks to determine the most likely regulated flow for a given unregulated flow, and a Monte Carlo approach calculated in HEC-WAT. The transform method is described in this section, whereas HEC-WAT in presented in Section 6. In this section, unregulated to regulated transform relationships were developed for each gage then applied to the Bulletin 17C analyses to estimate the regulated flow frequencies. While ultimately not adopted for the final regulated flow frequencies, the transform method was important to compute as it mimics the process developed in the 2003 Upper Mississippi River System Flow Frequency Study (UMRSFFS) and is outlined in EM 1110-2-1415, Hydrologic Frequency Analysis. The general transform process is best described in EM 1110-2-1415 as follows where the term "natural" may be thought of as "unregulated" or no depletions, no dams, for this study:

> *"One approach to determining a frequency curve of regulated or modified runoff consists of routing all of the observed flood events under conditions of proposed or anticipated development. Then a relationship is developed between the modified and the natural flows, deriving an average or dependable relationship. A frequency curve of modified flows is derived from this relationship and the frequency curve of natural flows. In order to determine frequencies of runoff for extreme floods, routings of multiples of the largest floods of record or multiples of a large hypothetical flood can be used." - EM 1110-2-1415, page 2–8*

While the process mimics the 2003 study, several improvements to the analysis were made to expand the data used to develop the relationships. These include incorporating the new flow records with several large floods, and expanded analysis of synthetic, or scaled floods, not only on the Missouri Mainstem Dams as in 2003, but also the Kansas and Osage Basin reservoirs. Rain/runoff based model runs for the Kansas City gage that emphasized the Kansas River Basin, and as available for spillway sizing at Gavins Point Dam and the other five upstream dams were also plotted for comparison. The following sections present how the regulated flow data was developed for both districts, and the specific analysis for each gage as conducted by the Omaha District and Kansas City District, respectively.

5.1 Regulated Flow Data and Transform Process

As in the 2003 UMRSFFS, the data required for the development of unregulated to regulated flow transform relationships consists of two primary parts as described above from EM 1110-2-1415, the period of record data and extreme events beyond the period of record based on multiples of large floods. As encountered in the 2003 UMRSFFS, the plotting of these data sets yields a wide spread of regulated flow results for a given unregulated flow, resulting in a need to carefully consider how best to fit the best a transform relationship to the data. The data sorting method used during the 2003 UMRSFFS to help draw a relationship through data with wide scatter was reproduced and expanded upon in this study as part of developing the transform relationships. Methods detailed in RMC TR 2021-02, Estimating Flood Hazard for Dams with Upstream Regulation (USACE 2021, RMC), were also referenced for additional guidance on estimating the transform.

Period of record daily flow data were adjusted to instantaneous peak flow using the multipliers summarized in Section 3.4. As in the 2003 UMRSFFS, the POR annual peak flows were plotted on a scatter plot with unregulated peak annual flow as the independent variable (abscissa), and the regulated annual peak flow values were plotted on the ordinate axis as the dependent variable. Annual peak flow pairs were plotted for each year of the period of record. To aid the development of a relationship through the regulated-unregulated points, rank order pairing was used, which was the method employed during the 2003 UMRSFFS to plot the data with minimal scatter. Each set of regulated and unregulated peak annual flows from the POR were independently ranked, and data pairs were created between the ranked events. For example, the largest unregulated peak flow was paired with the largest regulated peak flow, then the second largest unregulated peak flow was paired with the second largest regulated peak flow, etc. The final transform relationships are a combination of the transform through the POR data, and an extrapolated transform based on synthetic scaled floods.

A problem encountered in developing a relationship through the scatter produced by the period of record is that the scale of the basin and the dispersed nature of the dams make each flood unique. Some floods that the Mainstem Reservoirs are highly effective at regulating may produce very high unregulated peak flows, with overall smaller volumes, whereas other floods may produce very high volumes with lower unregulated peaks, thus generating much variability in the relationship. Additionally, the scale of the basin makes it possible that some storms could almost entirely miss the reservoir drainage areas while producing extreme runoff downstream. In Hydrometeorological Report Number 52 (HMR 52), which is designed to distribute probable maximum precipitation (PMP) from HMR 51 across a watershed to aid in determining probable maximum floods (PMF), storm ellipses have been developed for areas of 10 to 60,000 square miles. In comparison, the Missouri River Drainage area is 279,480 square miles above Gavins Point, increasing to 528,200 square miles at Hermann, MO, with 146,683 square miles of that downstream of the dams, each of these areas being several times larger than a typical PMP storm. However, also due to the dispersed nature of the dams, for large storms or extended wet weather patterns, it is rare for the storms to miss all the dams. This variability in volume, given the large flood control storage space often supplemented by the larger multiple use storage of the Mainstem Dams, coupled with the variability of where storms center and the sequence of the storms, limits the ability to predict transition points of where the regulated flows will transition to unregulated flows. To better predict this transition, multiple runs of probable maximum storms across the basin with and without dams may be required, which is beyond the scope of the current study which has a stated goal of estimating regulated floods only extreme as 0.2% AEP. However, the dams are designed to pass very large extreme storms, and the largest projects of the Mainstem Dams, Tuttle Creek in the Kansas Basin, and Truman in the Osage Basin, have very large pools with gated spillways. Routings for these projects during a PMF often still show reduced outflow compared to inflow. Therefore, a full transition to the unregulated flows may not be physically possible, unless an upstream dam breach were to occur, in which case flooding could be worse than unregulated.

As described in Section 2.2, the normal flood risk reduction operations of the dams generally involve reducing outflows from the dams when downstream flow target points are above criteria, and evacuating flood waters from the reservoirs when the risk has subsided. Larger floods which fill the flood storage space and begin to enter surcharge storage must then be managed to pass the event without risking the safety of the dams. Further, for downstream locations, it is possible that maximum annual flooding at the dam site may not coincide with a higher flow derived from below the dams at a different point in the year due to flooding from tributaries. These regulation activities, combined with the meteorological reality of the large basin, make the tendency for regulated flows for any given event to be at least somewhat smaller than the unregulated flows, to significantly smaller than the unregulated flows. A common concern with the approach from the 2003 UMRSFFS and repeated and expanded upon in this document of rank storing the data is that it disassociates the site's unregulated to regulated response for a given event. Given this concern, a list of considerations, given guidance from RMC TR 2021-02, and how they are addressed by the current study analysis are provided below:

- <u>Study transform methodology</u>. The methodology to fit a relationship to the data was adopted after careful deliberation with internal and external reviewers across the nation during the 2003 UMRSFFS, and again with the Technical Review Group (TRG) for the current study. Methodology in RMC TR 2021-02 provides several example ways to develop regulated flows. However, the guidance document also states that it "is not intended to be a textbook. It is by no means comprehensive, as each project is unique and will potentially require additional analysis. Nor is this document a substitute for critical thinking and good engineering judgment." Rank sorting the data was established as a method to look for trends in the data in the 2003 study. Methods in RMC TR 2021-02 also encourages users of the guidance to look for trends in the data, and the same-event or same year data were also retained on the plots to show how the relationship looks in relation to this unsorted data.
- <u>Convergence threshold</u>. The convergence threshold, which has not been estimated in this study, is defined in RMC TR 2021-02 as "the initial flood magnitude at which the difference between regulated and unregulated flows is negligible." While flows are expected to trend towards unregulated at very extreme events, information summarized above suggests a full transition back to the unregulated flows is unlikely for the 10 Missouri River gages. Developing a transition threshold, given the large number of upstream dams and geographic scale, was deemed beyond the scope of

analysis as it would require multiple iterations of hypothetical storms produced through rain-runoff modeling with and without dams, varying the storm location and orientation. To reduce concerns, analysis of HMR 51/52 storms made for the Kansas City Levees Project and other design floods were included for the Kansas City gage for comparison, and spillway design flood information from publicly available water control manuals was also plotted at Gavins Point Dam.

- Graphical techniques. According to RMC TR 2021-02, "When the observed data set does not provide a large enough flow from which to estimate the convergence threshold, graphical techniques could be used." By nature, the graphical approach requires the sorting of rank-order data into a probability scale, in a similar format as the plots included in Section 5.4, adding data points used to inform the transition. In probability scale, the results of the transform method shown in Section 5.4 begin to trend back towards the unregulated scale at most of the gages by the 0.1% AEP but are still significantly lower than the unregulated flows. If sorting the data in probability scale is considered a reasonable method, similarly sorting the data as a means to help inform a relationship through the scatter plots is also valid.
- Weight more important years to inform the relationship. A suggestion was made to review data for the period of record that puts the most weight on the data from the years with the most modern regulation and withdrawals, or to see if there are seasonal differences. As discussed in Section 3.2, all period of record data has been adjusted for consistency and is all valid for current operations to the 2018 Master Manual and current manuals of the Kansas and Osage Basin Projects. Supplemental graphs for Gavins Point Dam which retain the same-year flows, and group similar behaving floods, were added to the report using all 18 scaled flood events. Also plotted were the design floods for projects at and upstream of Gavins Point, which did consider both early spring and late spring meteorology when developing maximum possible flood estimates. No improvement to the adopted transform relationship could be determined and is assumed similar at other gages.
- Unique projects require additional analysis. As suggested in RMC TR 2021-02, some basins are unique and require additional analysis. For this reason, and given difficulty establishing these relationships, scope for Monte Carlo Analysis was included in this study, as summarized in Section 6. A limitation of the scaled floods is that each starts at multi-purpose pool elevation. In the Monte Carlo Analysis, the starting pool can be varied by running 50-year simulations, thus better accounting for the ability of the System to further mitigate flood risk using multiple use zone storage.
- Range of analysis. Should additional extension of the hydrology beyond 0.2% AEP be required, for either method, supplemental modeling of synthetic floods, such as with rain-runoff modeling, may be needed to help define the transition towards the unregulated flows. For the current study, the analysis is considered adequate.

5.1.1 Period of Record Transform

To define the relationship between unregulated and regulated flow frequency curves in the range of flow captured in the POR, trendlines were fit through the rank-ordered pair points using polynomials. The use of a polynomial is an efficient way to create smooth transform relationships. For some gages, peak annual flows with values much higher than the rest of the POR were removed from the period of record trend line to improve the fit of the trendline. These points were included with the scaled flood events when removed from the POR.

5.1.2 Extrapolation of Transform using Scaled Floods

To extend the unregulated-regulated relationship, as documented in Appendix E, scaled flood events were modeled using the combined ResSim model that included the six mainstem Missouri River reservoirs, the lower seven Kansas River Basin reservoirs (Waconda, Wilson, Kanopolis, Milford, Tuttle Creek, Perry, and Clinton), and the six Osage River Basin reservoirs. Figure 5-1 depicts the HEC-ResSim model set up used to compute the scaled floods. Additionally, a few scaled floods were also routed using HEC-RAS for comparison purposes as documented for some of the gages in Section 5.3. As presented in Section 2.2, these three reservoir systems represent almost all of the pertinent flood storage available for flood risk reduction in the Missouri River Basin. Other dams not included in the scaled flood analysis include Rathbun Dam on the Chariton River in southern Iowa, and the non-federal Kingsley Dam in southwestern Nebraska as they have been determined to insignificantly impact the Missouri River as summarized in Section 2.2. Simulations for the scaled floods consisted of model runs beginning on March first of the respective year with a look back period to January. Model time windows continue through February of the following year. Flood events were scaled up using factors developed to preserve relative volumes from four different regions of the basin in alignment with the Monte Carlo analysis as shown in Section 6.

All Kansas City District gages and reservoirs used the same scaling factors for the respective simulations. Depletions were applied in accord with the process for the period of record flows (add historic depletions to observed data to obtain unregulated, remove present level incremental depletions to observed to obtain present level depleted regulated flows). In the 2003 UMRSFFS, five events, as in full years of data when floods occurred, were scaled to help generate the relationship. For this study, the same five years were used along with 13 others, for a total of 18 years, or events, to extend the data. These events reflect generally the largest events within the watershed and as needed to test extreme flows for each basin. For example, the 1986 flood was important for the Osage Basin, but was much more minimal in the Kansas River Basin. Events modeled were 1943, 1944, 1947, 1951, 1952, 1960, 1967, 1973, 1978, 1984, 1986, 1987, 1993, 1995, 1997, 2007, 2008, 2010, 2011, 2013, 2015, 2017 and 2019. Flows were increased in each region by 0.5, 1.0, 1.5, and 2.0 standard deviations. This scaling resulted in lower multiples used for the area above the mainstem Dams than for downstream reaches. At 2.0 standard deviations, factors were 1.60, 2.91, 2.12, and 2.98 times the observed flows for the Mountain, Northern Plains, Southern Plains, and Missouri Hills Regions, respectively (see Appendix E), which is within the maximum scaling of 3 suggested in EM 1110-2-1415.

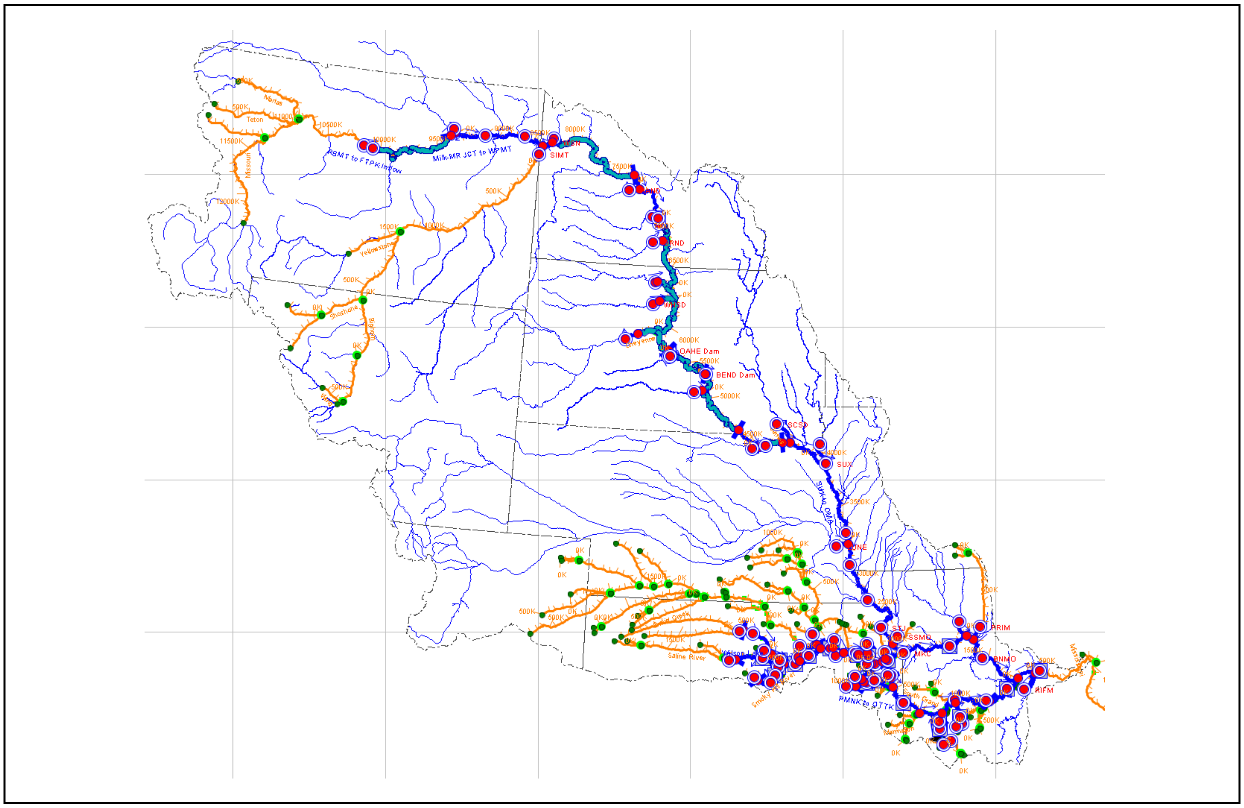


Figure 5-1. Combined Missouri River Basin HEC-ResSim Model Schematic

Maximum daily regulated and unregulated flows from each scaled flood event were multiplied by the same peaking factor to convert maximum 1-day flows to instantaneous peak flow in Section 3.4. The data pairs of regulated and unregulated flows were then plotted with the period of record data on the scatter plots and transforms were drawn through the scatter plots. Next, the scaled flood regulated and unregulated peak flows were also independently ranked and paired by rank. For some gages, resulting flows of some scaled events were extremely large and removed from further analysis to prevent their influence on polynomials fit through the ranked data pairs.

5.2 Omaha District Unregulated to Regulated Flow Transforms

A variety of methods involving linear and polynomial trendlines and piece-wise functions through year-ordered and pair ordered data were used to estimate the regulated flow for a given unregulated flow. While relationships were developed using trendline equations, the transform functions are ultimately still graphical in nature. Trendlines were used merely to facilitate the drawing of smooth curves which appropriately fit the POR and scaled flood data. Transform plots for all four Omaha District Missouri River flow frequency stations are shown in Figure 5-2 through Figure 5-5. While multiple iterations of different ways to draw the transform curves were tested and discussed, including several methods similar to the analysis documented in Section 5.3, the Omaha District plots reflect only the final transform relationships. Generally, the analysis shows that even with the wide scatter, regulated flows plot noticeably lower than unregulated flows, well below the line of equal agreement, but getting closer as drainage area increases as at Nebraska City due to the Platte River. *Error! Reference source not found.* at the end of Section 5 shows the resultant regulated flow frequencies.

5.2.1 Transforms for the Four Omaha District Flow Frequency Stations

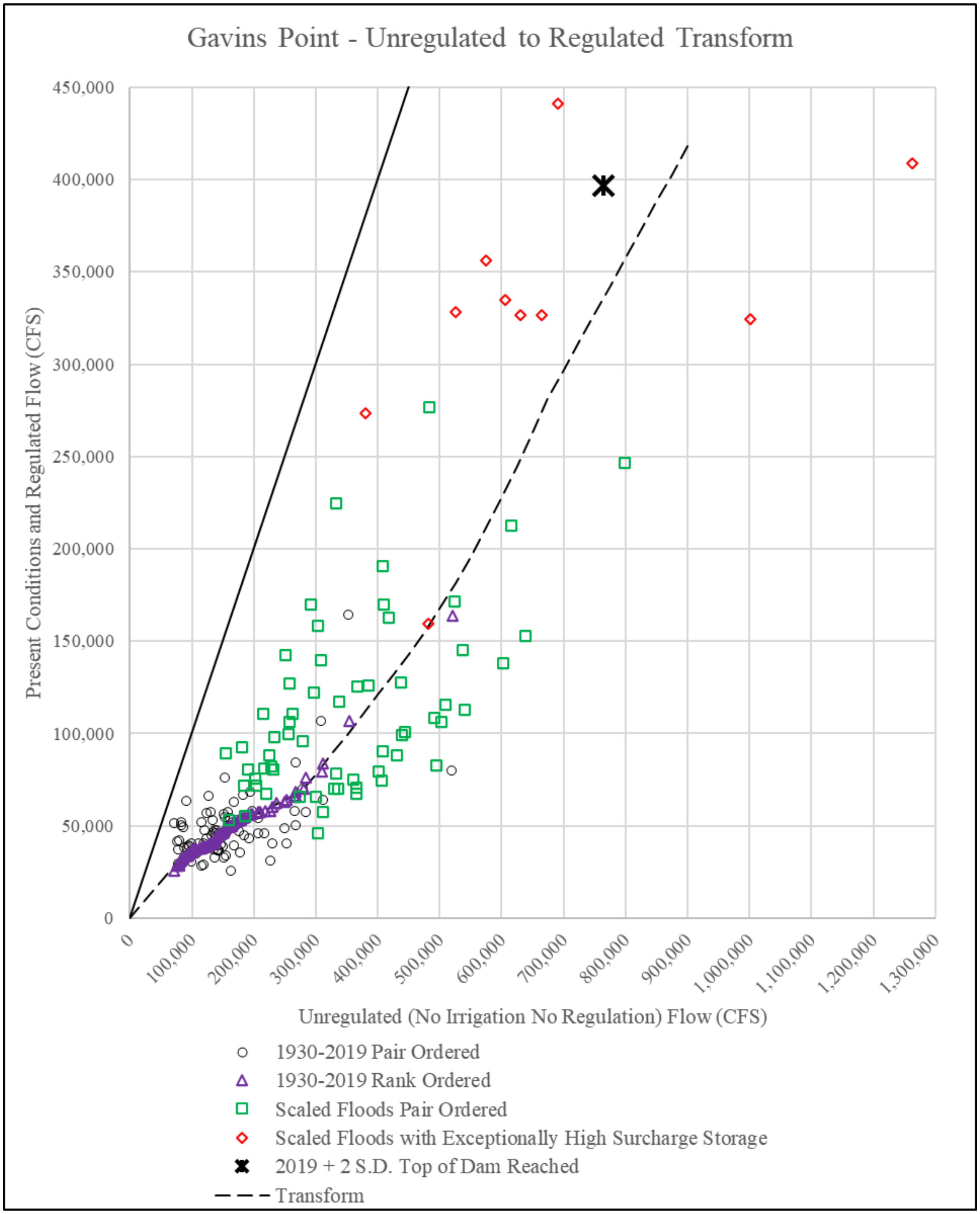


Figure 5-2. Gavins Point / Yankton, SD Unregulated to Regulated Transform

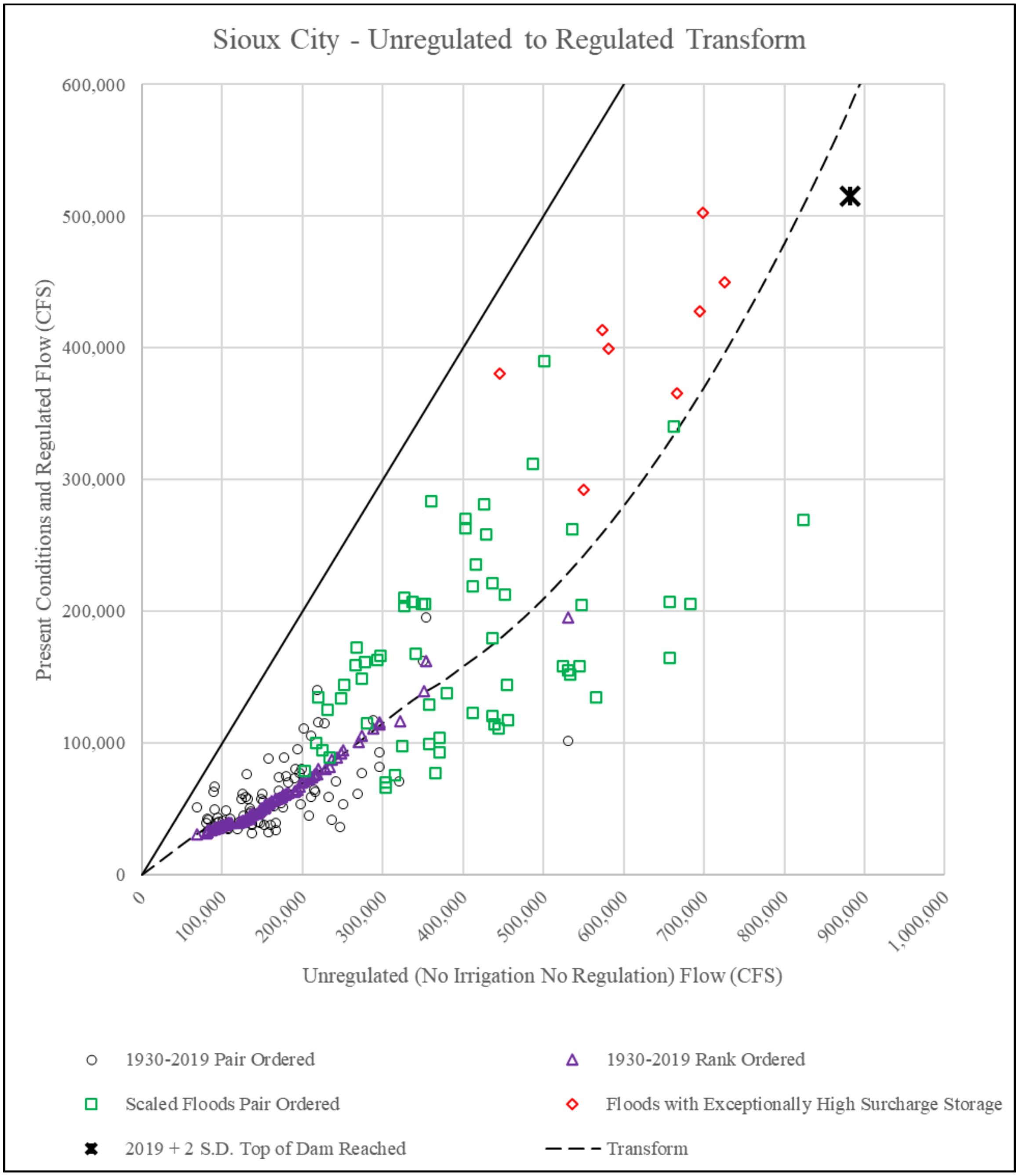


Figure 5-3. Sioux City, IA Unregulated to Regulated Transform

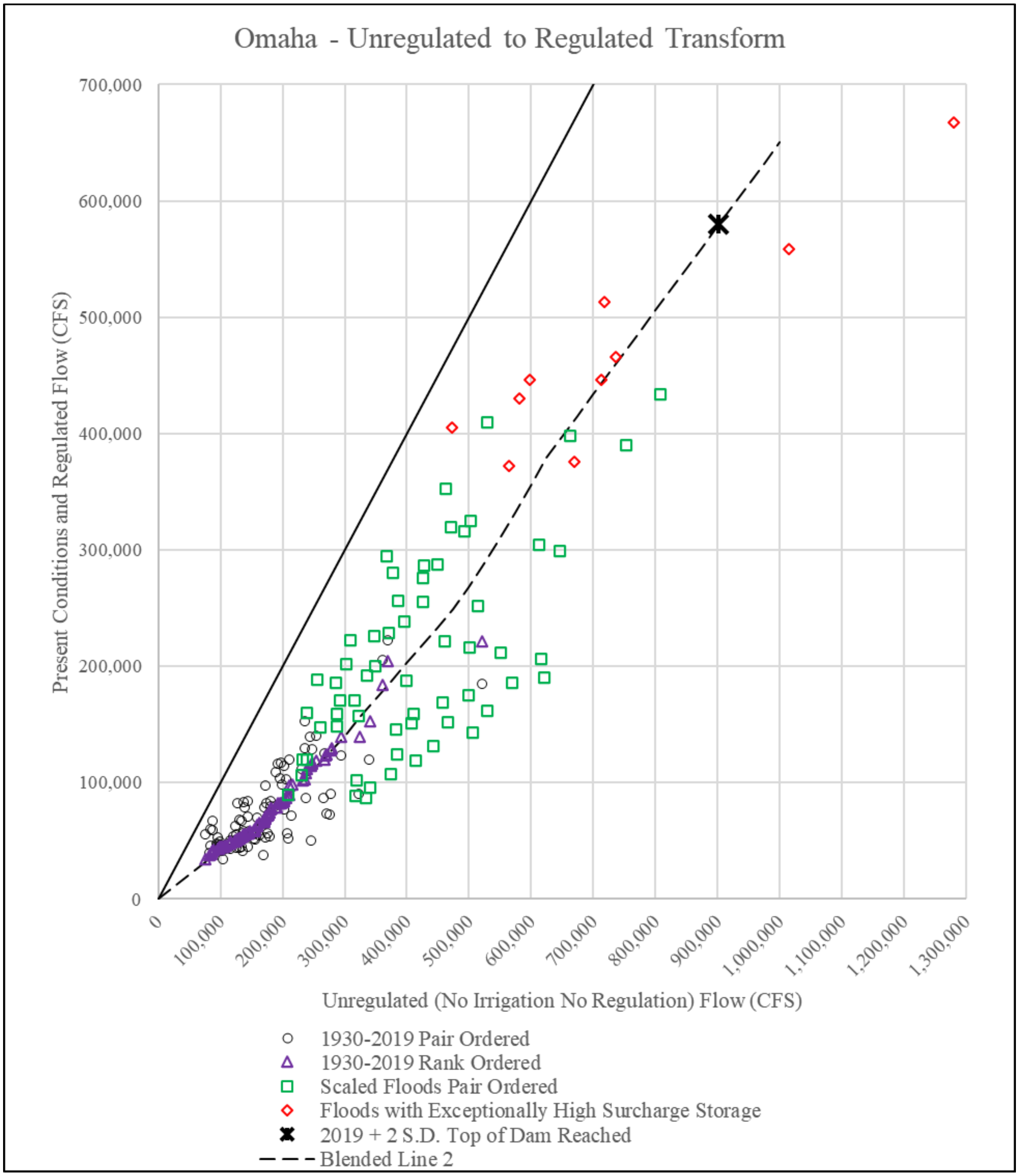


Figure 5-4. Omaha, NE Unregulated to Regulated Transform

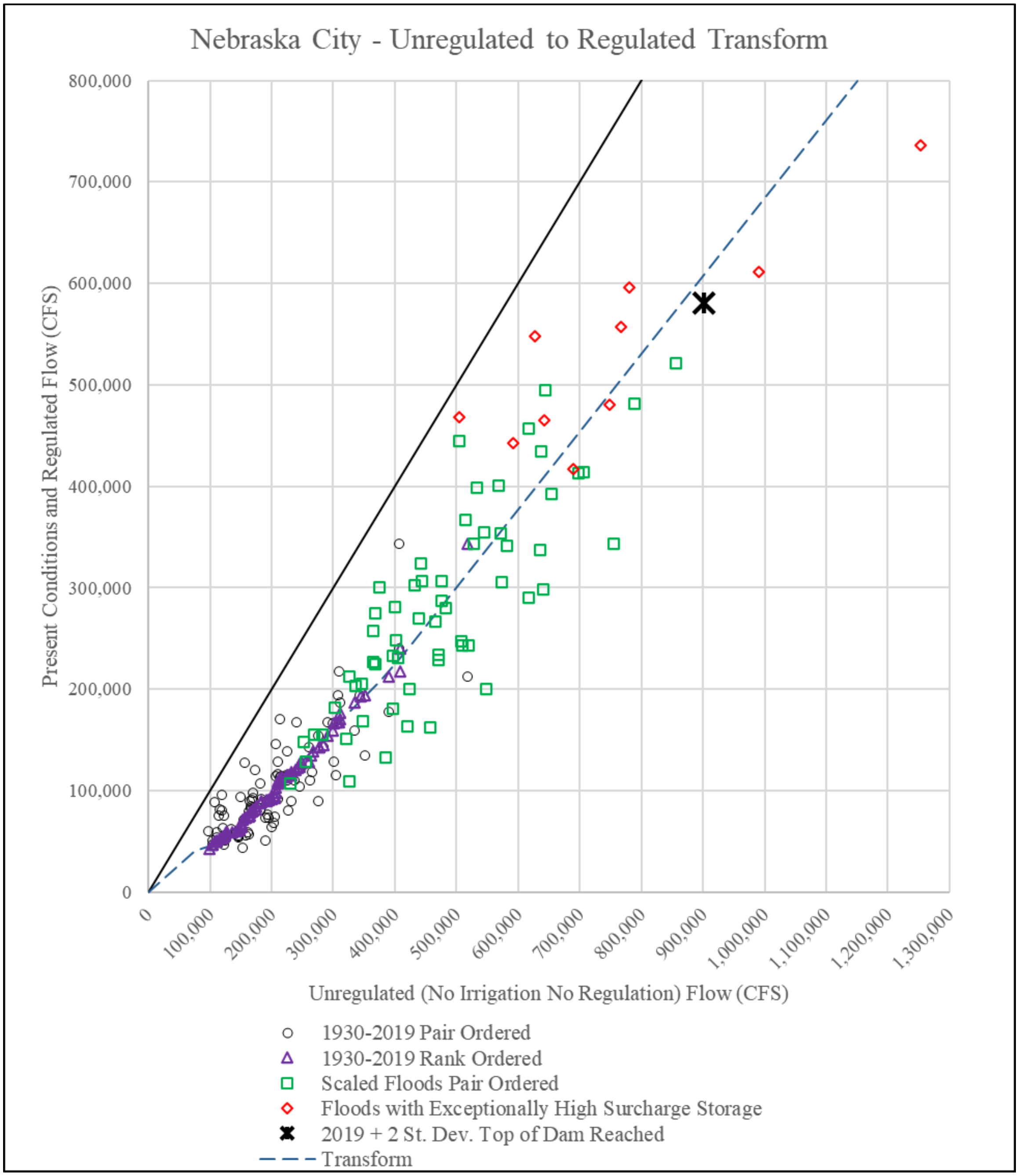


Figure 5-5. Nebraska City, NE Unregulated to Regulated Transform

After receipt of ATR comments, additional investigation at Gavins Point was conducted to see if the shape of the regulated flow frequency curve determined using the Monte Carlo method in Section 6 could be better predicted by looking at specific years that may be representative of operations. Figure 5-6 presents a plot showing the 18 scaled floods developed for Gavins Point Dam, which were grouped with floods of similar performance when routed through the dams. All published spillway design floods (SDF) or maximum possible floods (MPF) from Section 7-24 of the individual water control manuals are also plotted using inflow as unregulated and outflow as regulated as an indication of potential attenuation for each dam. However, considering upstream or downstream dams, actual unregulated flows would likely be higher and regulated flows lower than plotted. Generally, SDF computations assumed wet antecedent conditions with high outflows from upstream projects, coupled with probable maximum precipitation centered to maximize runoff between dams. Scaled floods showing the most significant reduction of stream flows in a class with 1952 include 1943, 1944, 1960, 1967, 1972, and 2008, all plotting similarly to the Oahe spillway design floods. Though variable, scaled floods of 1993, 1995, and 1997, 2010 and 2011, 2018 and 2019, 1986, and 1975, 1978, and 1984, plot similarly to the Lake Sharpe and Fort Randall SDF's. A plateau in the relationship is only shown for smaller scaled floods of 2018-2019, and 1978-1984. As the adopted transform curve follows the routings of this plateau, and is between these hypothetical flood routings, all of which are considered valid, no improvement to the adopted transform could be determined. Monte-Carlo analysis presented in Section 6 ultimately shows the impacts of management for Oahe's spillway on the outflows of the Mainstem Reservoir System.

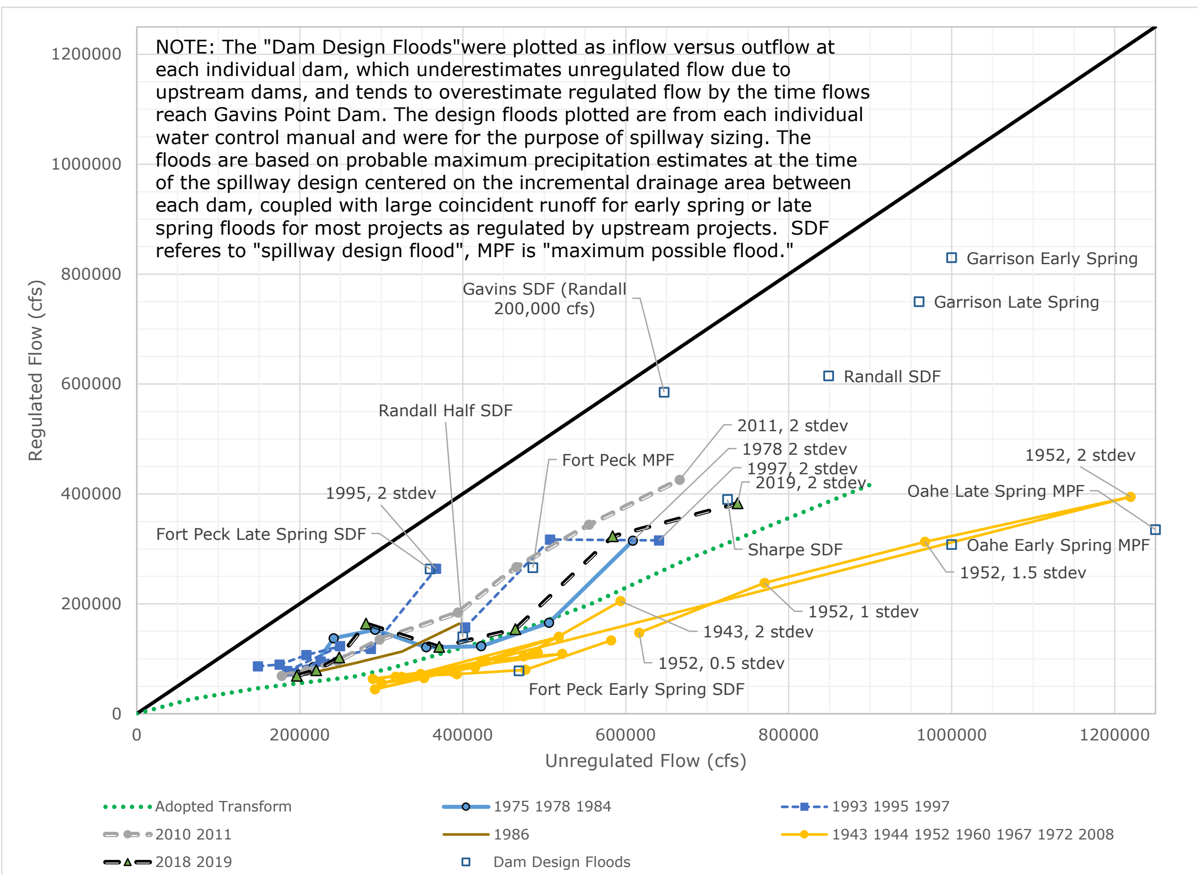


Figure 5-6. Gavins Point Dam, Unregulated to Regulated Transform Compared to Scaled Floods

5.3 Kansas City District Unregulated-Regulated Flow Transforms

Methodology discussed in Section 5.1 was applied to estimate the regulated flow annual probabilities at each Kansas City District gage. In the analysis, which is considered graphical in nature, trendlines were first fit through both the unsorted points and the rank ordered pair points using second order polynomials for a mix of the period of record data and extended data for hypothetical scaled flood events. Generally, the trendlines fit through the rank ordered pairs resulted in slightly higher regulated flow estimates than fitting through the unsorted points. For some gages, peak annual flows with values much higher than the rest of the POR were removed from the period of record trend line. These points were included with the scaled flood events when removed from the POR.

Two main options for defining the regulated-unregulated function based on the available data were explored. The first was to independently fit second order polynomials to both the rank paired period of record peaks, and the rank paired scaled flood peaks. The intersection or closest approach of the two independently fit polynomials was determined and set as the unregulated discharge to transition between the two, resulting in a piecewise function. The second main approach to creating a transform function was by combining the period of record and scaled flood event peaks into one dataset, then independently ranking the regulated and unregulated flows and pairing the ranked data. This removed the challenge of determining the transition point between the period of record and scaled flood curves and smoothed the overlap. A second order polynomial was also used as the resultant function for the combined dataset. Ultimately, the piecewise functions were selected as the preferred transform function due to better fit to the plotting positions of the regulated annual peak flow datasets. *Error! Reference source not found.* at the end of Section 5 shows the resultant regulated flow frequencies. Details of the analysis are presented in the following sections for each gage. Generally, the figures in the following sections show a wide scatter of performance for the dams depending on the event, with regulated flows shifting closer to the line of equal agreement with the unregulated flows with distance downstream from the dams. This includes shifts away from the line of equal agreement visible at Kansas City and Hermann as result of the Kansas and Osage River Basin Reservoir Systems.

5.3.1 Rulo, NE

Period of Record data for Rulo, Nebraska were plotted using the year paired data as well as rank order paired data and are shown in Figure 5-7. Rank ordered data with a polynomial fit is shown in Figure 5-8. Figure 5-9 shows the HEC-RAS routed POR data including a polynomial fit through the rank ordered data. Figure 5-10 shows a comparison between the HEC-ResSim routed and HEC-RAS routed rank ordered annual peak flows. As seen in the figure, the differences between HEC-RAS routings and the HEC-ResSim routings were the most apparent in the middle portion of the period of record data, with the analysis converging at unregulated flows lower than approximately 125,000 cfs and above approximately 500,000 cfs. When plotted, the largest difference between the routing methods were near unregulated flows of approximately 300,000 cfs where the HEC-RAS data plotted approximately 17 percent higher than the HEC-ResSim routings. Due to overall similar results, interest in the extreme part of the curve beyond the observed data, and difficulty running larger floods through HEC-RAS, the remainder of the analysis at Rulo focused on the HEC-ResSim based routings as discussed in the following sub-section. A portion of the difference may be attributed to differences in how results were pulled from HEC-RAS as opposed to ResSim as discussed in Section 4.7. Had HEC-RAS routings been used universally, the overall regulated flow frequency results would very comparable, as the unregulated flow frequencies were generally lower for HEC-RAS than HEC-ResSim routings.

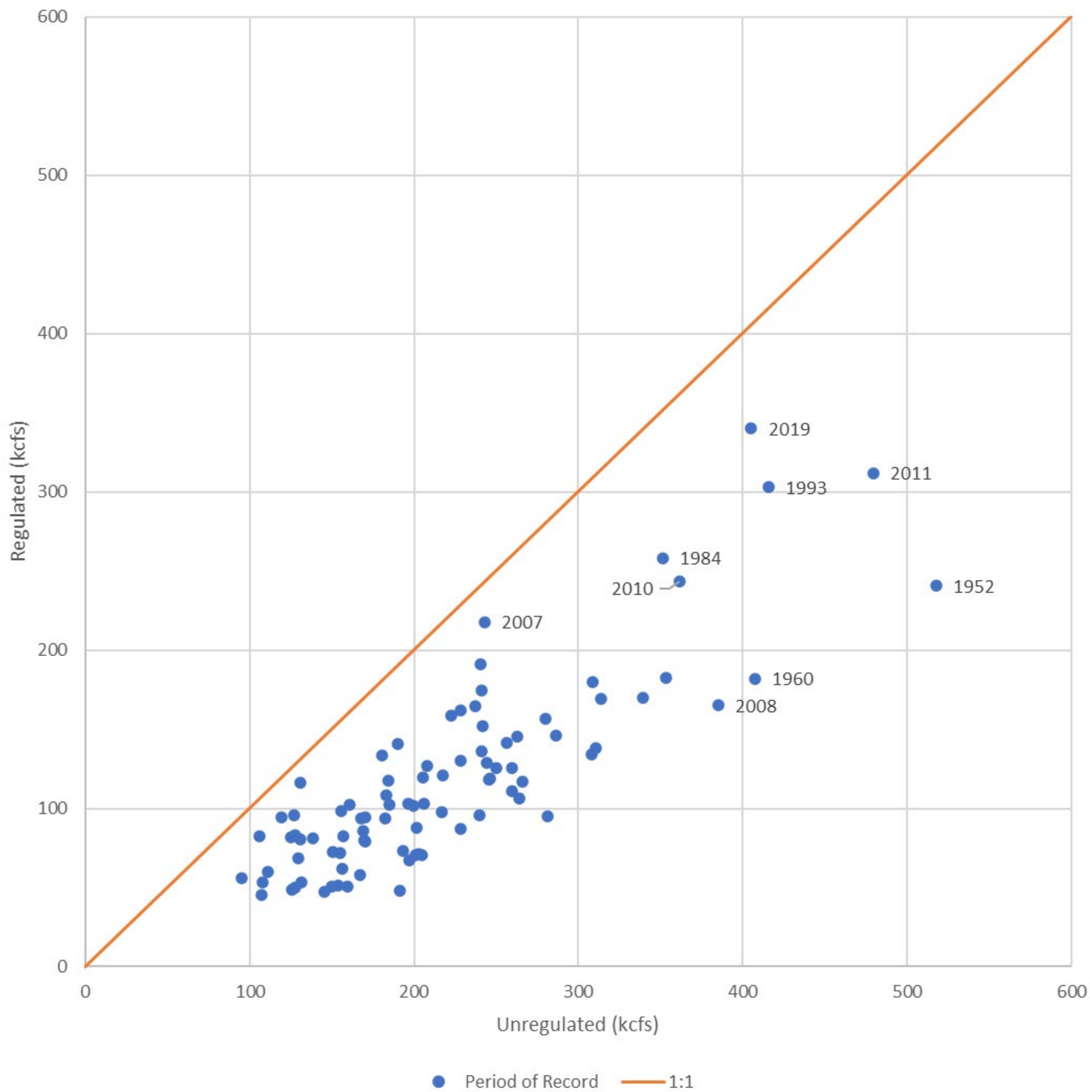


Figure 5-7. Rulo, Nebraska Regulated vs. Unregulated Period of Record Annual Flow Peaks

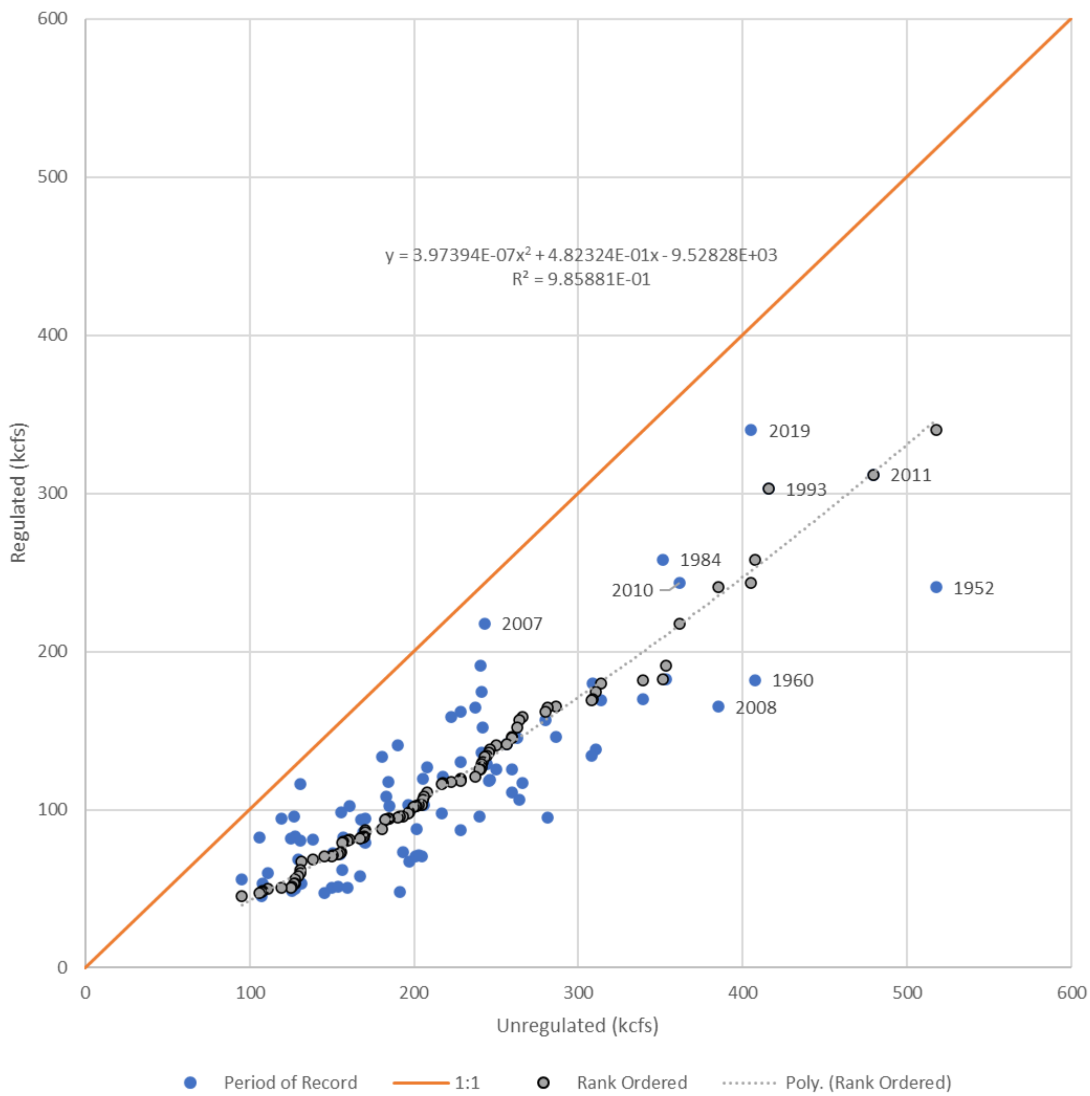


Figure 5-8. Rulo, Nebraska Rank Ordered Annual Flow Peaks with Trendline

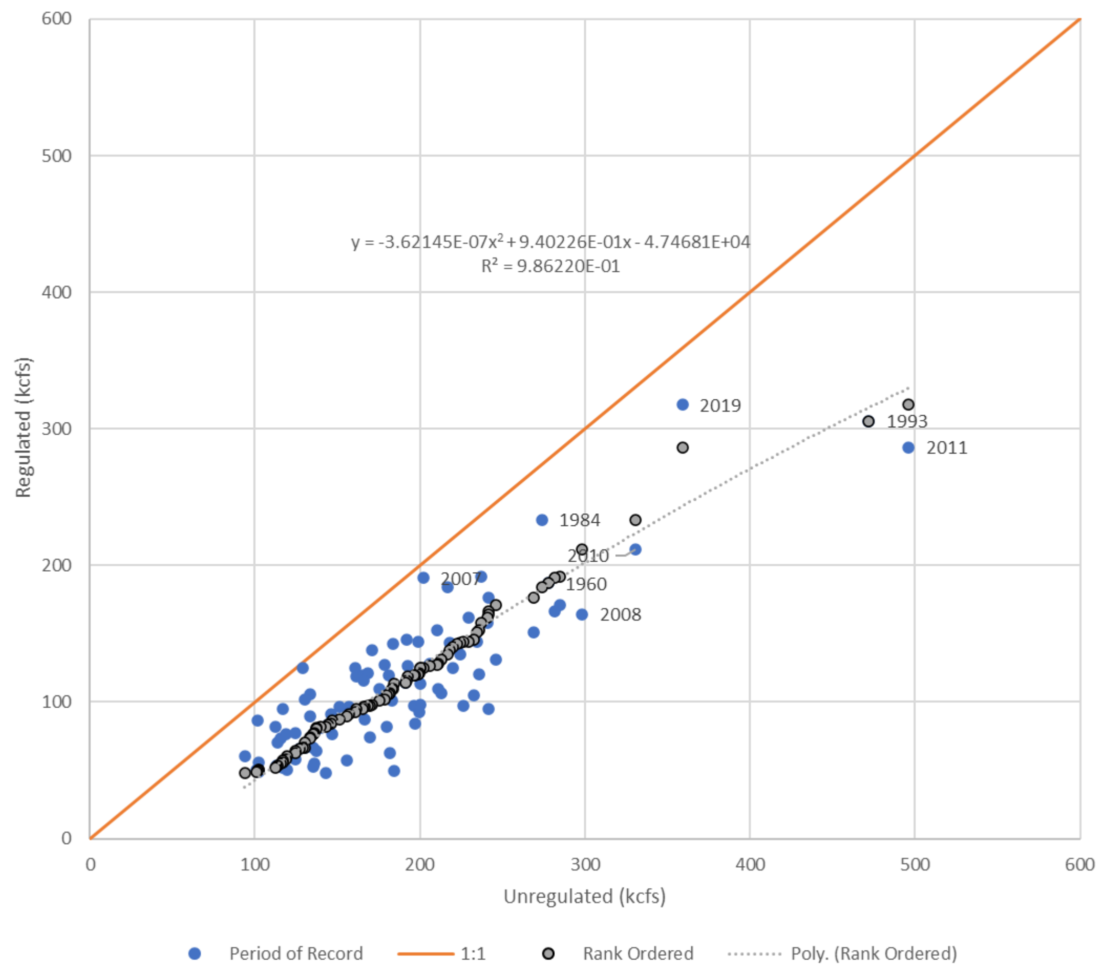


Figure 5-9. Rulo, NE HEC-RAS Routed Period of Record and Rank Ordered Annual Peak Flows

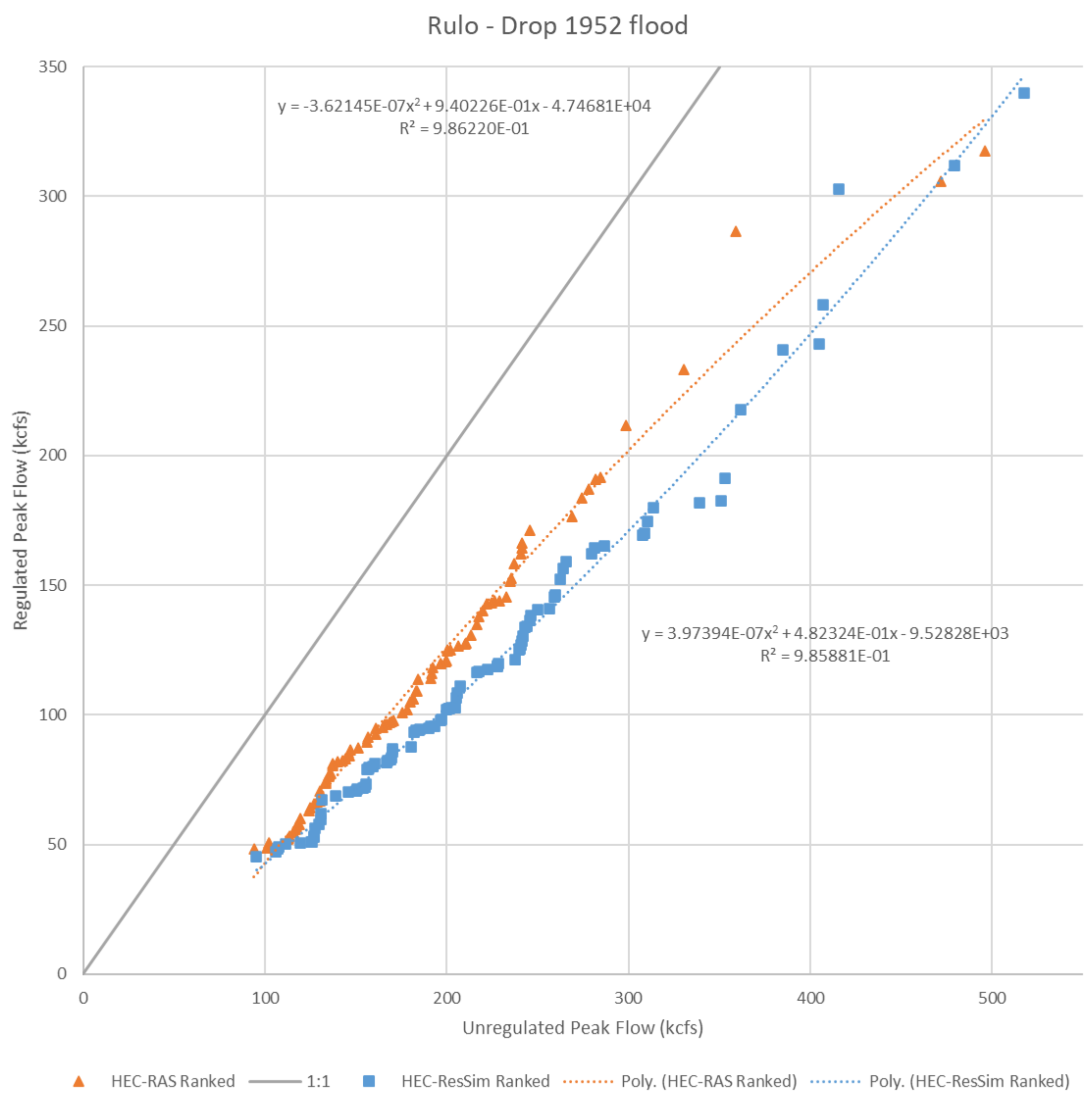


Figure 5-10. Rulo, NE Comparison of HEC-ResSim and HEC-RAS routed POR Ranked Flows

5.3.1.1 Addition of Scaled Floods, Rulo, NE

HEC-ResSim peak flows for the scaled flood events were added to the plot with the period of record data from HEC-ResSim. Peak flows for the scaled flood events extend out to beyond an unregulated flow of 1 million cfs, however the largest flood (1952 plus 2 standard deviations) was removed from the analysis because of its influence to decrease the regulated flows on the transform compared to all other floods. The intersection between the polynomials was computed as approximately 397,000 cfs unregulated flow and used as the transition point between the two curves. Figure 5-11 depicts the results of this analysis.

A combined dataset using the period of record data and the scaled floods was also produced and rank ordered, and then a polynomial was fit through the rank ordered data. Results for this analysis are shown in Figure 5-12. Figure 5-13 shows the final selected transform using the piecewise function as a solid line with the relationship based on the combined dataset as a dashed line. Neither of the analyses used the point that plots farthest to the right, thus the relationships are shown out to only 1 million cfs unregulated flow.

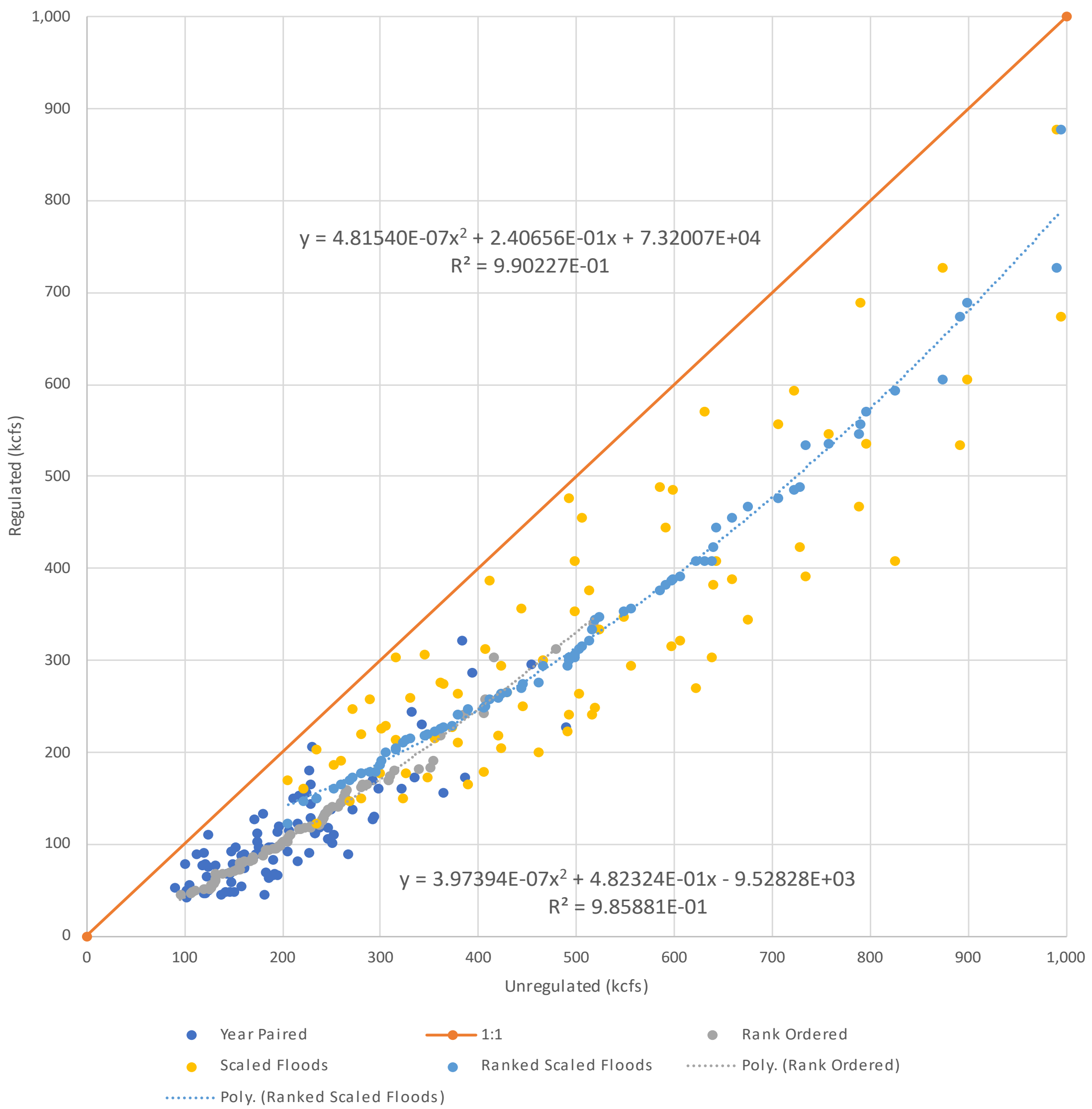


Figure 5-11. Rulo, NE Period of Record and Scaled Flood Events with Best Fit Polynomials

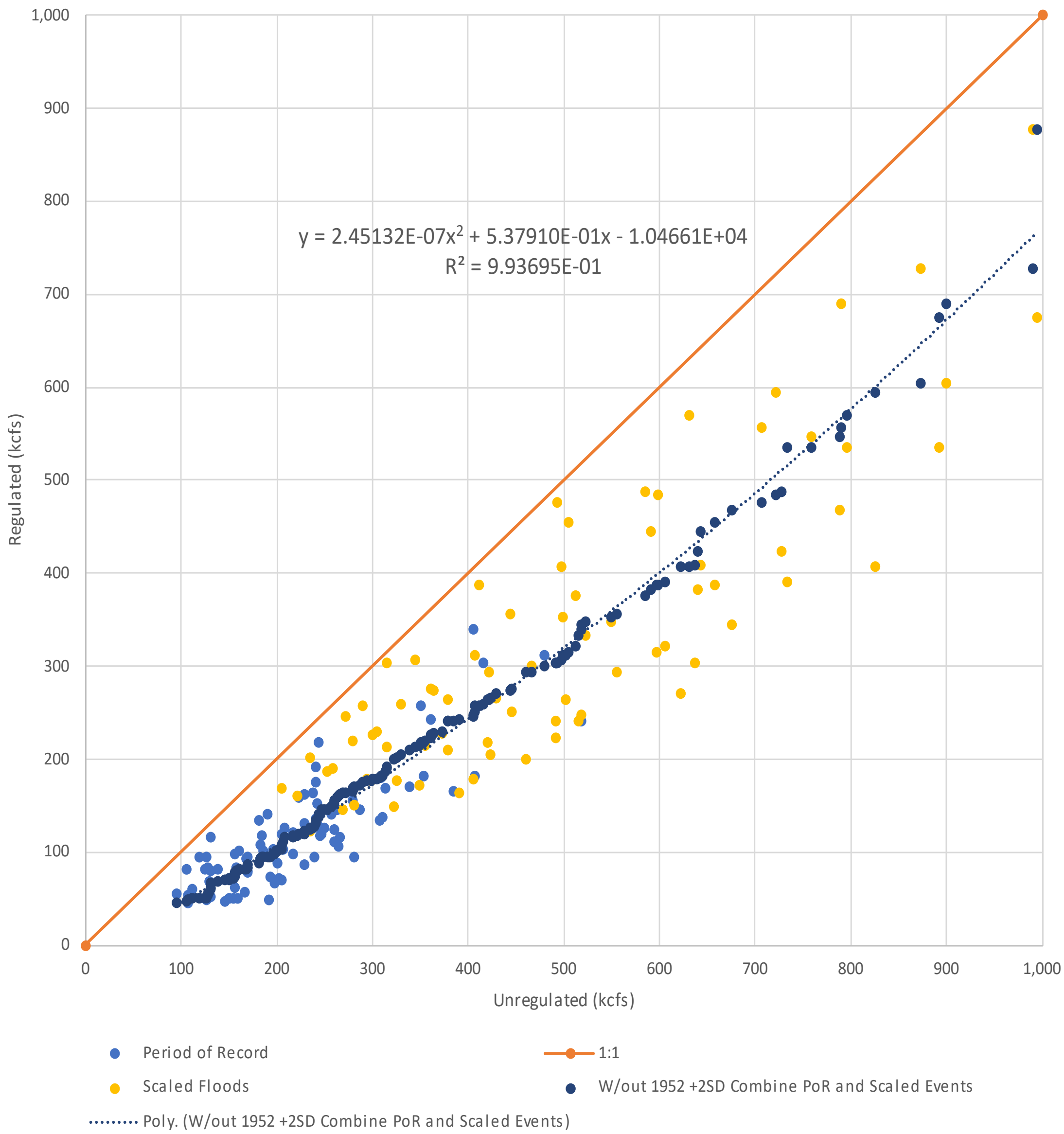


Figure 5-12. Polynomial Fit to Combined Period of Record and Scaled Floods for Rulo, NE

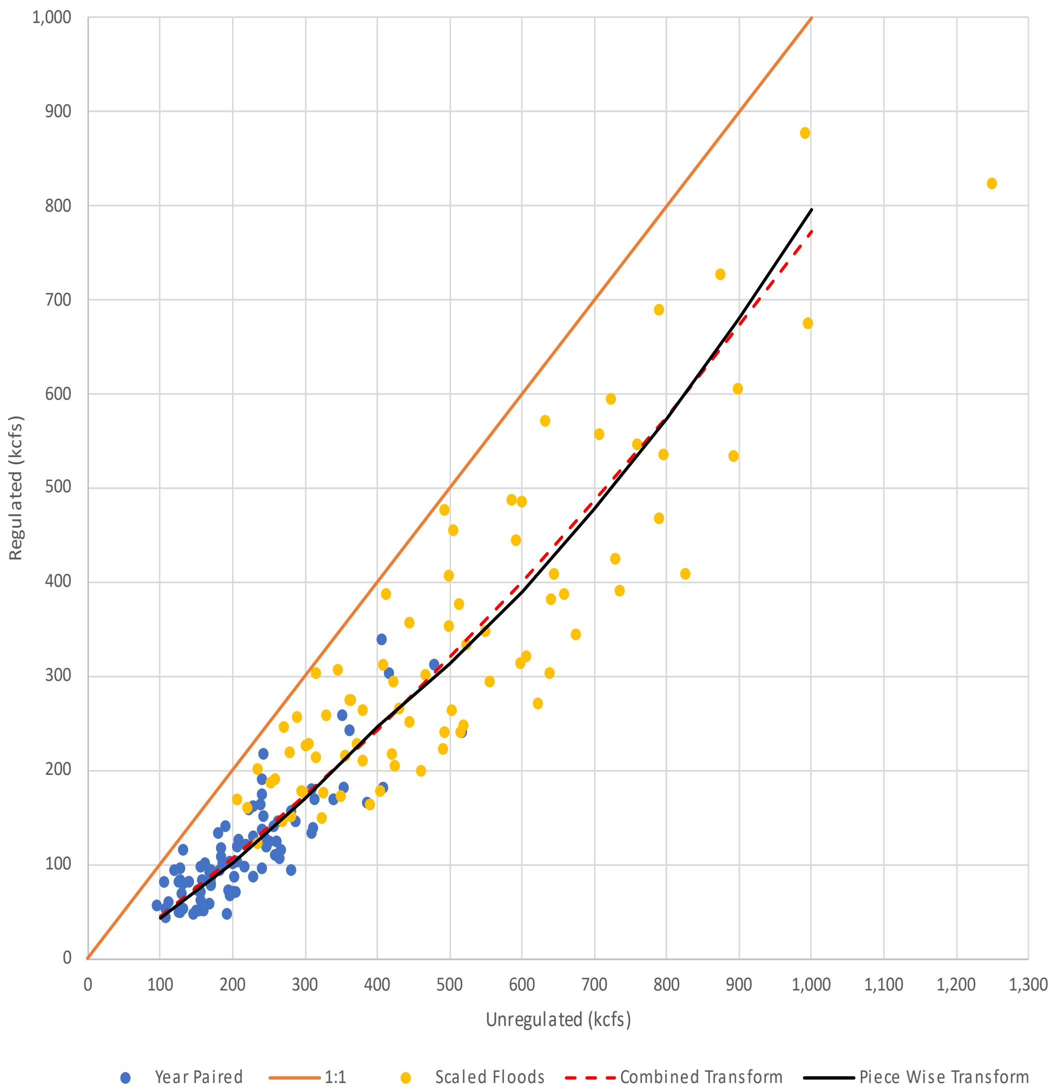


Figure 5-13. Final Unregulated-Regulated Transform for Rulo, NE

5.3.2 *St. Joseph, MO*

Period of Record data for the Missouri River at St. Joseph, Missouri were plotted using the year paired annual peak flow data (Figure 5-14). The polynomial fit through the rank ordered data is shown in Figure 5-15. Interestingly, the 1973 peak flows from the period of record plotted slightly above the unity line, indicating slightly higher regulated flow compared with the unregulated value. Also, with the HEC-ResSim data at the St. Joseph gage, fitting the trend line through the rank ordered period of record pairs results in a negative curvature for the second order polynomial. This indicates an increasing effect of the reservoir system on the peak flows for larger flood events. Figure 5-16 presents the HEC-RAS routed regulated and unregulated peak flows as year paired and rank-ordered pairs with a polynomial fit through the rank-ordered pairs. The 1952 flood was dropped from the HEC-RAS dataset due to the unreasonably large unregulated flow computed by the HEC-RAS model. Figure 5-17 compares the rank ordered datasets from HEC-ResSim and HEC-RAS with their respective polynomials. Similar to the Rulo gage, the two routing methods converge at flows below approximately 125,000 cfs. However, for higher flows in the period of record, the HEC-RAS routings tend to produce approximately 15% higher regulated flows for a given unregulated flow than the HEC-ResSim routings. Still, for the largest events, either routing method results in similar flows for unregulated flows of approximately 500,000 cfs. Due to difficulties routing scaled floods through the HEC-RAS model, the remainder of the analysis focuses on the HEC-ResSim routing method. A portion of the difference may be attributed to differences in how results were pulled from HEC-RAS as opposed to ResSim as discussed in Section 4.7. Had HEC-RAS routings been adopted, differences between the two analyses would be further reduced in that HEC-RAS generally produced lower unregulated flow frequencies as presented in Section 3.8.2 and Section 4.7.

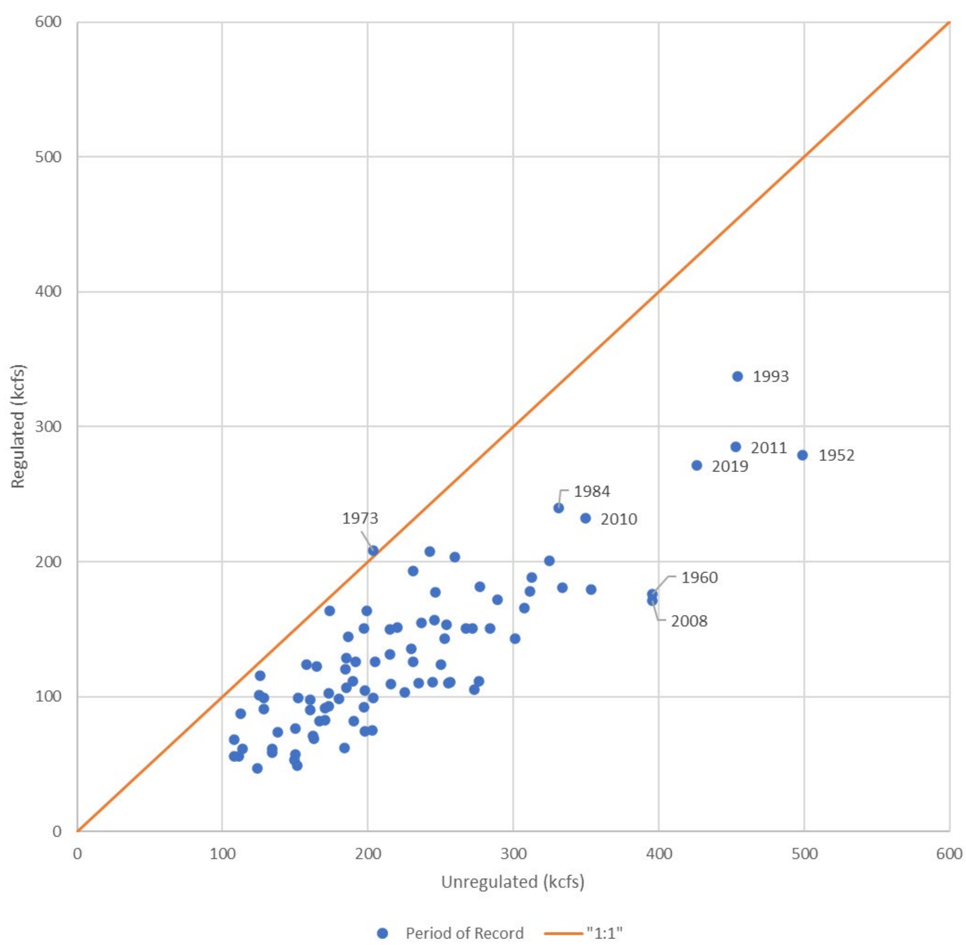


Figure 5-14. St. Joseph, MO HEC-ResSim Regulated vs. Unregulated Period of Record Annual Flow Peaks

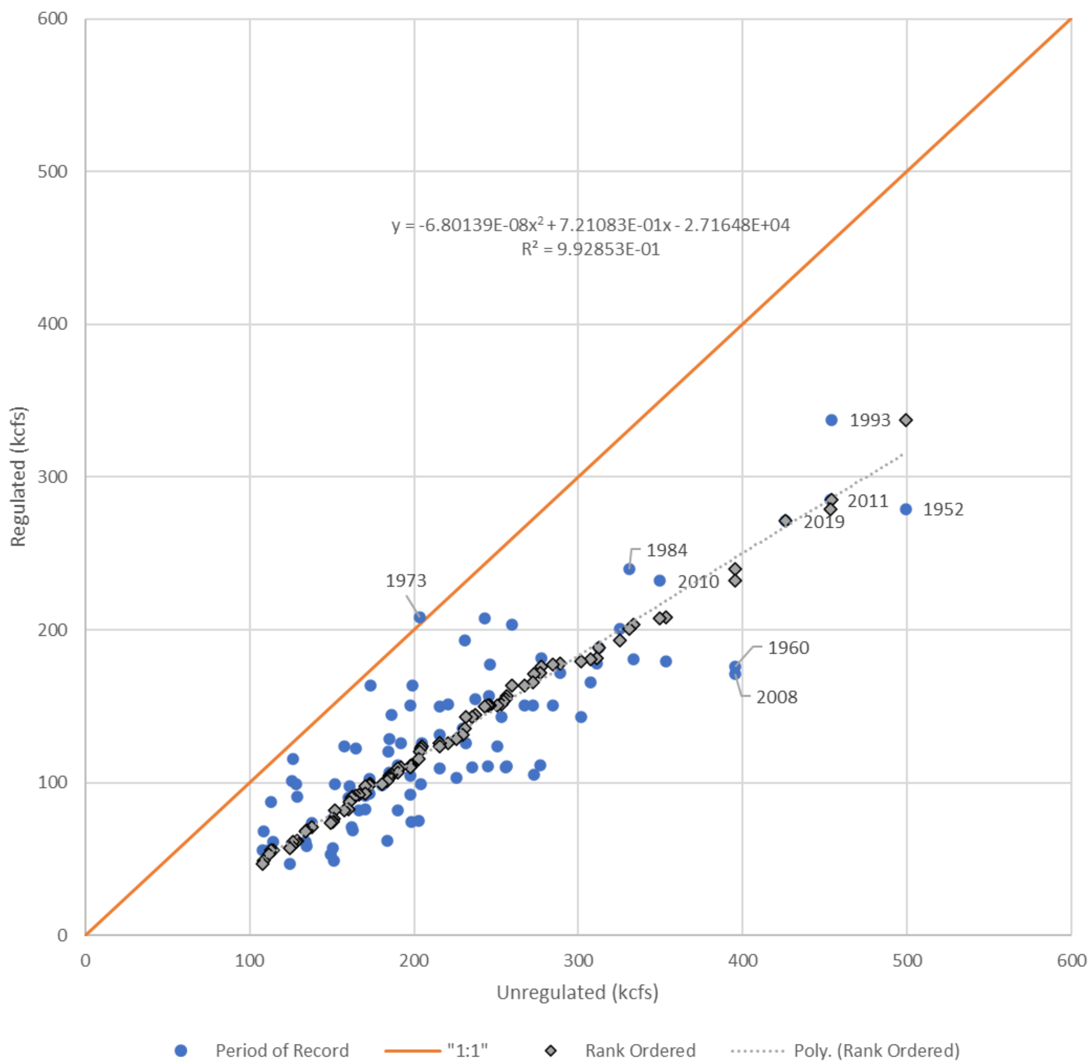


Figure 5-15. St. Joseph, MO Rank Ordered Annual Flow Peaks with Trendline

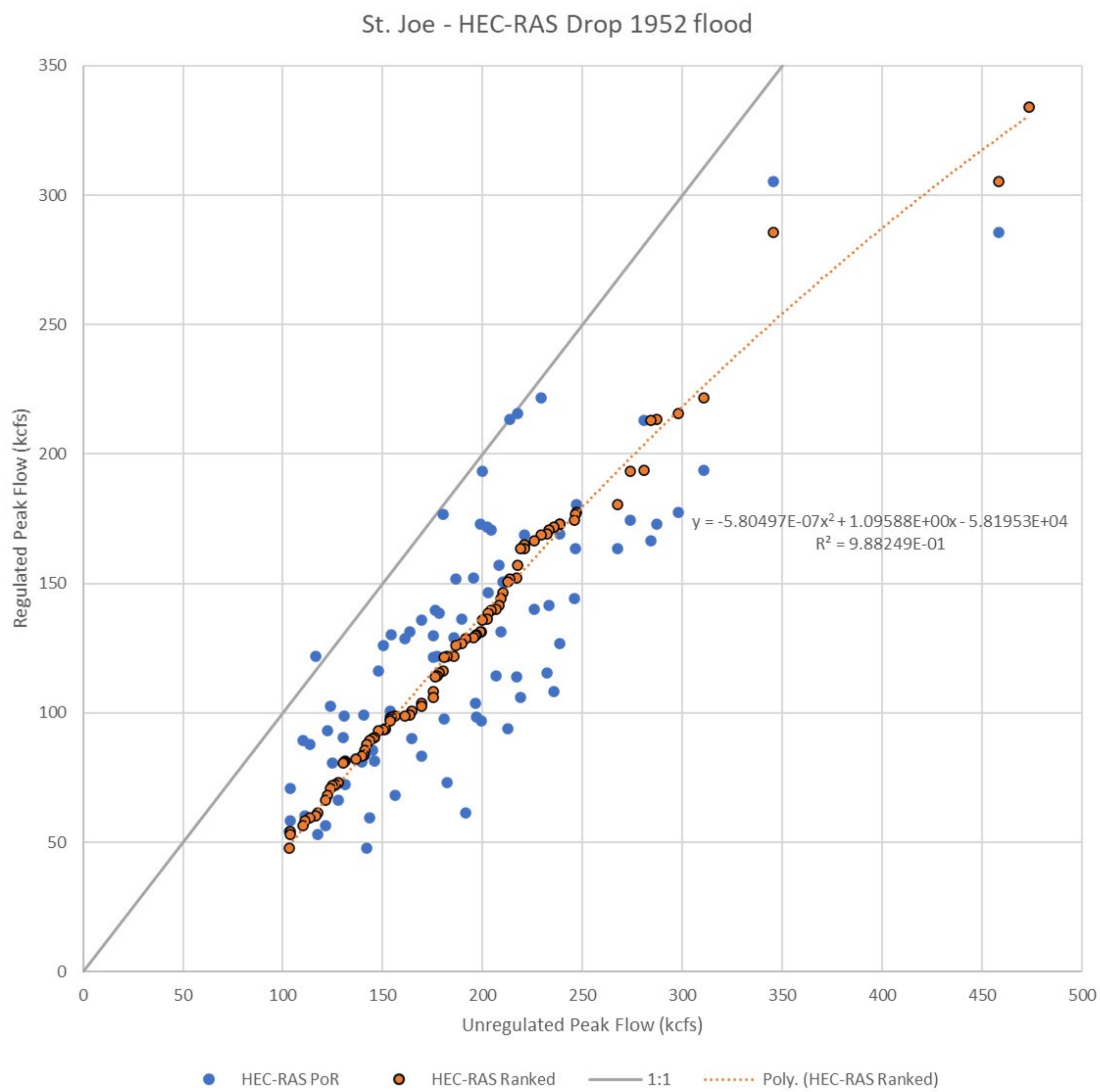


Figure 5-16. St. Joseph, MO HEC-RAS Routed Period of Record and Rank Ordered Annual Peak Flows with Trendline

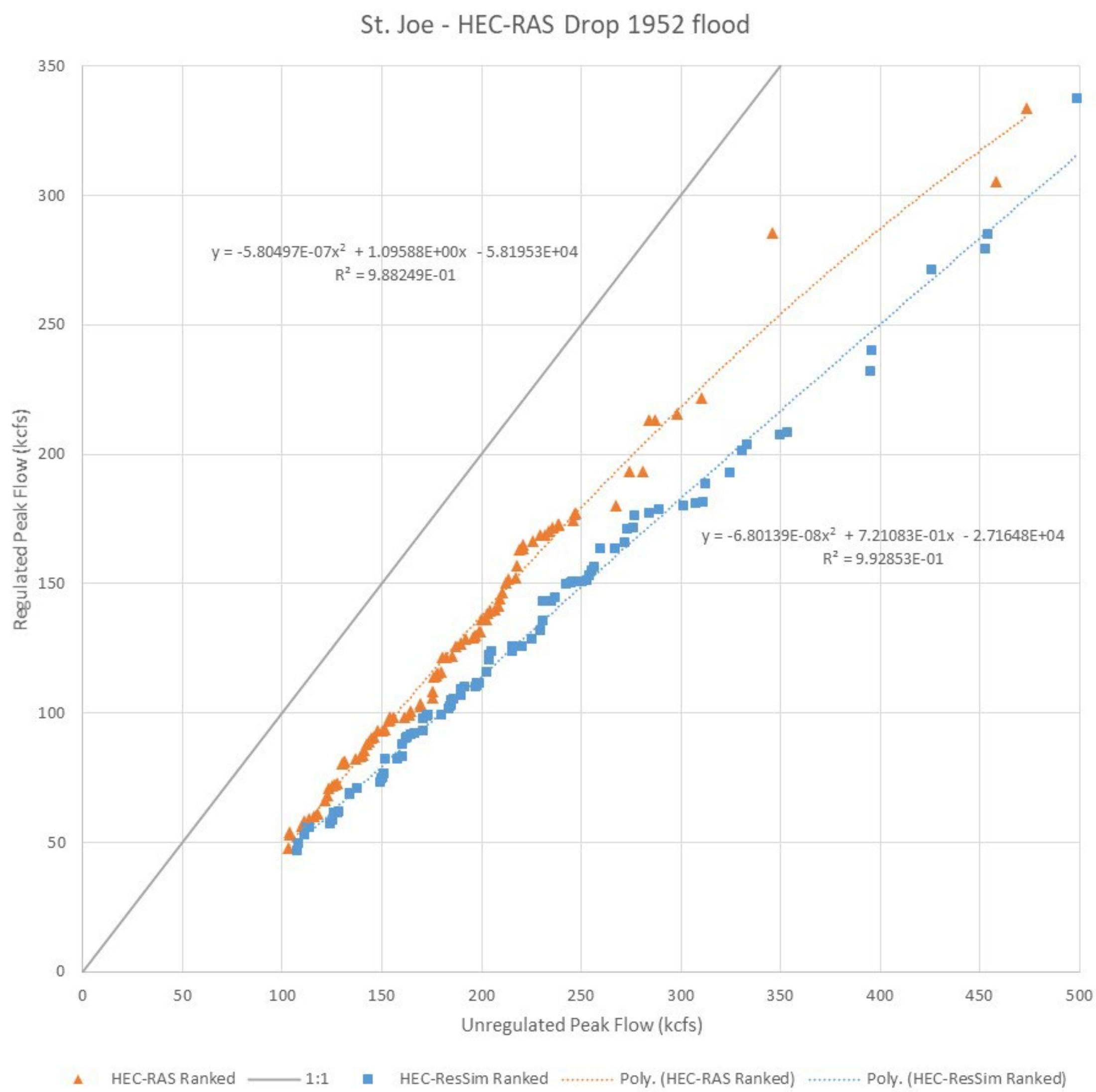


Figure 5-17. St. Joseph, MO Comparison of HEC-ResSim and HEC-RAS routed POR Ranked Flows

5.3.2.1 Addition of Scaled Floods, St. Joseph, MO

HEC-ResSim routed scaled floods were added to the regulated-unregulated plot to extend the relationship beyond the flows experienced in the period of record. Scaled flood peaks based on the 1973 flood were removed from the analysis since the regulated flows were greater than the unregulated. This resulted in a polynomial fit through the rank ordered data that more closely approached the polynomial fit to the period of record data. Figure 5-18 show the polynomial fit to the rank ordered scaled floods. Figure 5-19 shows the polynomial fit to the combined dataset of the period of record and scaled floods. Figure 5-20 shows the final selected transform relationship in black with the polynomial fit to the combined rank ordered data as a dashed red line.

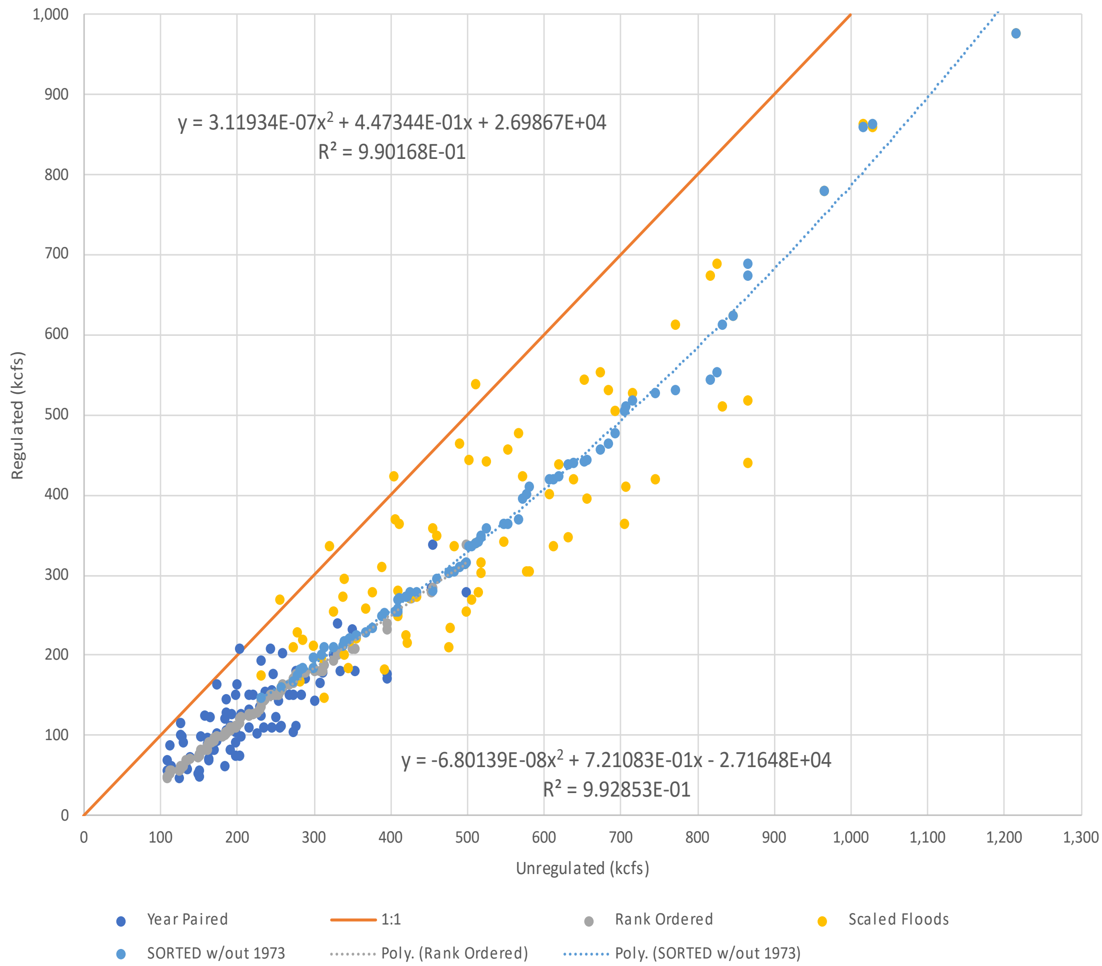


Figure 5-18. St. Joseph, MO Period of Record and Scaled Flood Events with Best Fit Polynomials

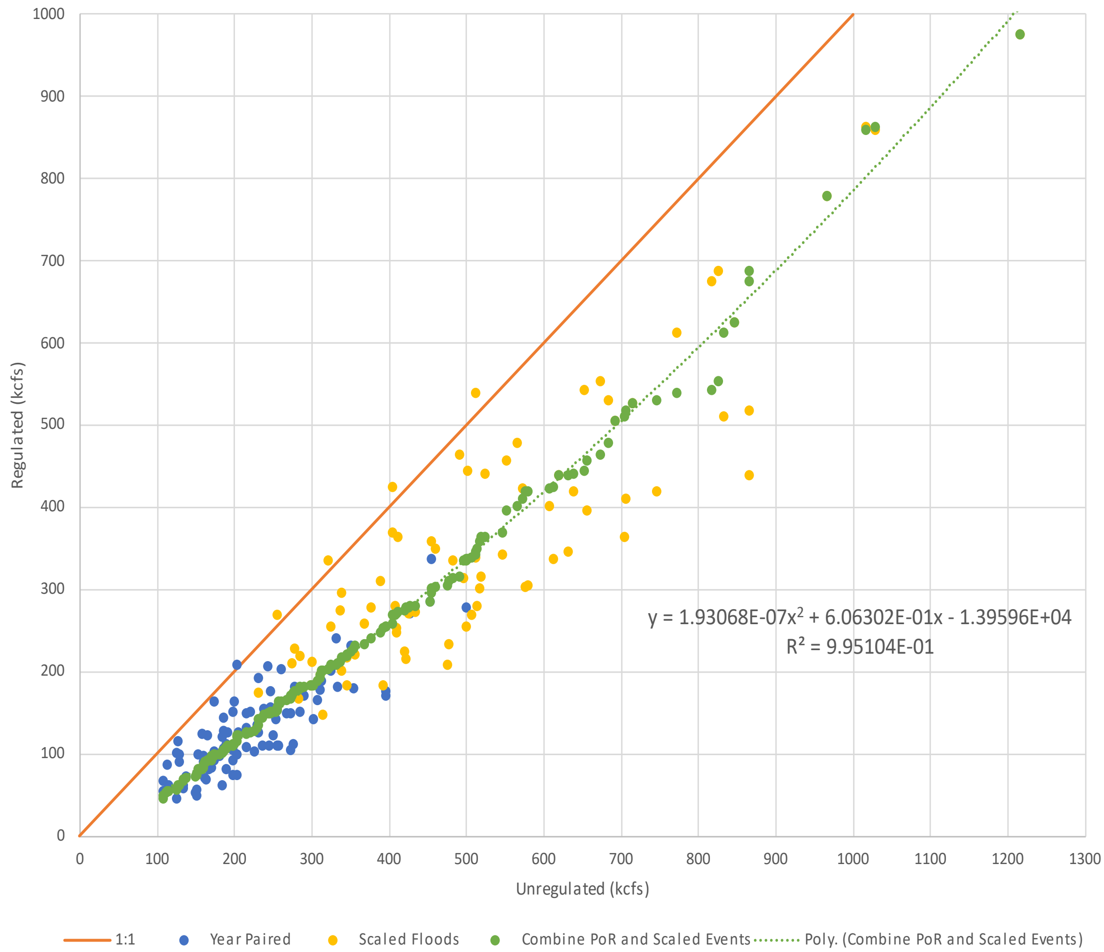


Figure 5-19. Polynomial Fit to Combined Period of Record and Scaled Floods for St. Joseph, MO

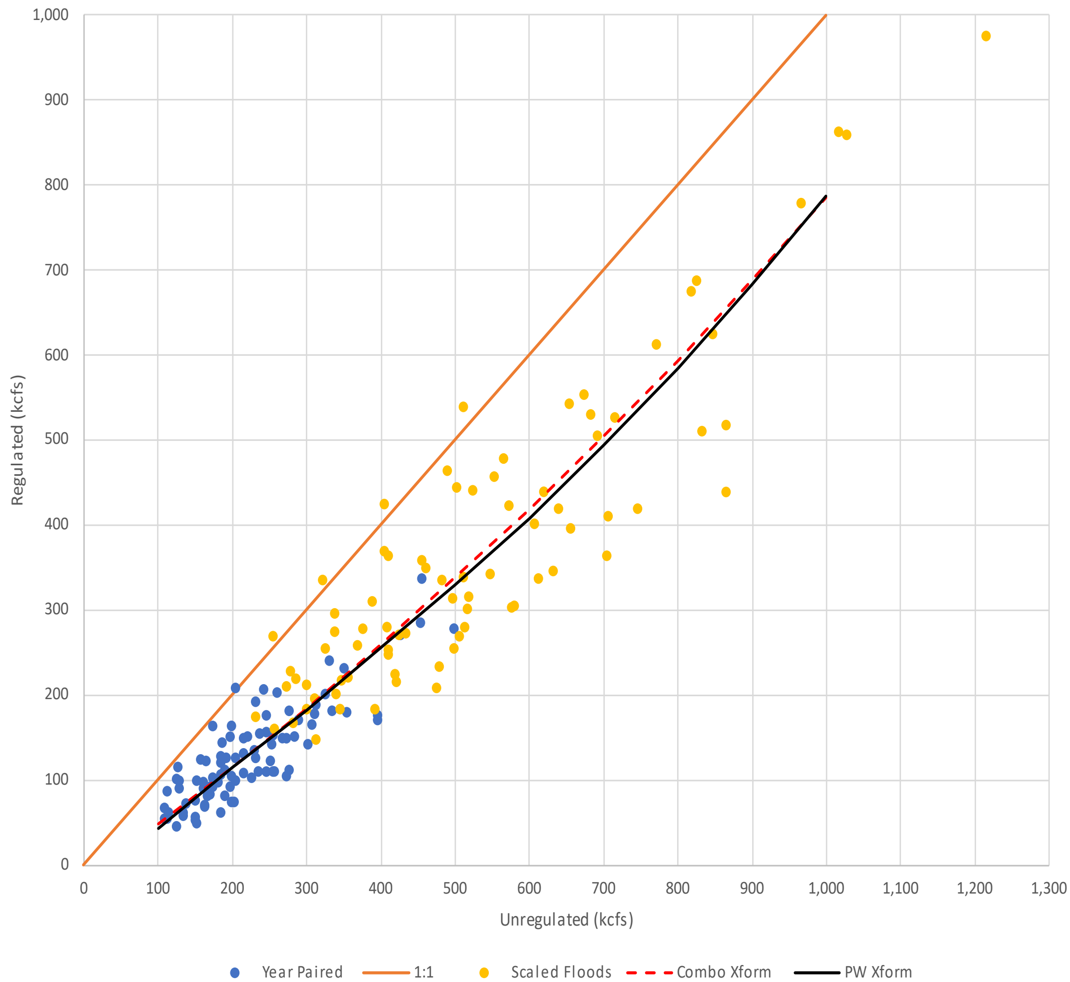


Figure 5-20. Final Unregulated-Regulated Transform for St. Joseph, MO

5.3.3 Kansas City, MO

Period of record data for the Missouri River at Kansas City, MO gage are plotted in Figure 5-21. The three largest floods in the period of record at Kansas City are 2019, 1951, and 1993. Several other floods approached the 2019 unregulated flood magnitude. Figure 5-22 shows the rank ordered period of record data with a second order polynomial fit through the data. Figure 5-23 depicts the HEC-RAS routed period of record data with rank ordered pairs and a polynomial best fit line. The 1952 flood was removed from the HEC-RAS routed data when rank ordering due to its anomalous flows. Figure 5-24 compares the rank ordered data and polynomials for the HEC-ResSim and HEC-RAS routed data. The HEC-RAS data plots distinctly to the left of the HEC-ResSim data; that is the unregulated discharges of the HEC-RAS data are less than for the HEC-ResSim data. This is notable at the lower flows, but the data points for the 1951 and 1993 floods plot much closer together. A portion of the difference may be attributed to differences in how results were pulled from HEC-RAS as opposed to ResSim as discussed in Section 4.7. For similar reasons as the Rulo and St. Joseph gages, given overall minor differences in results for the full analysis using HEC-RAS routings as opposed to HEC-ResSim routings, the remainder of the analysis focuses on the HEC-ResSim routings.

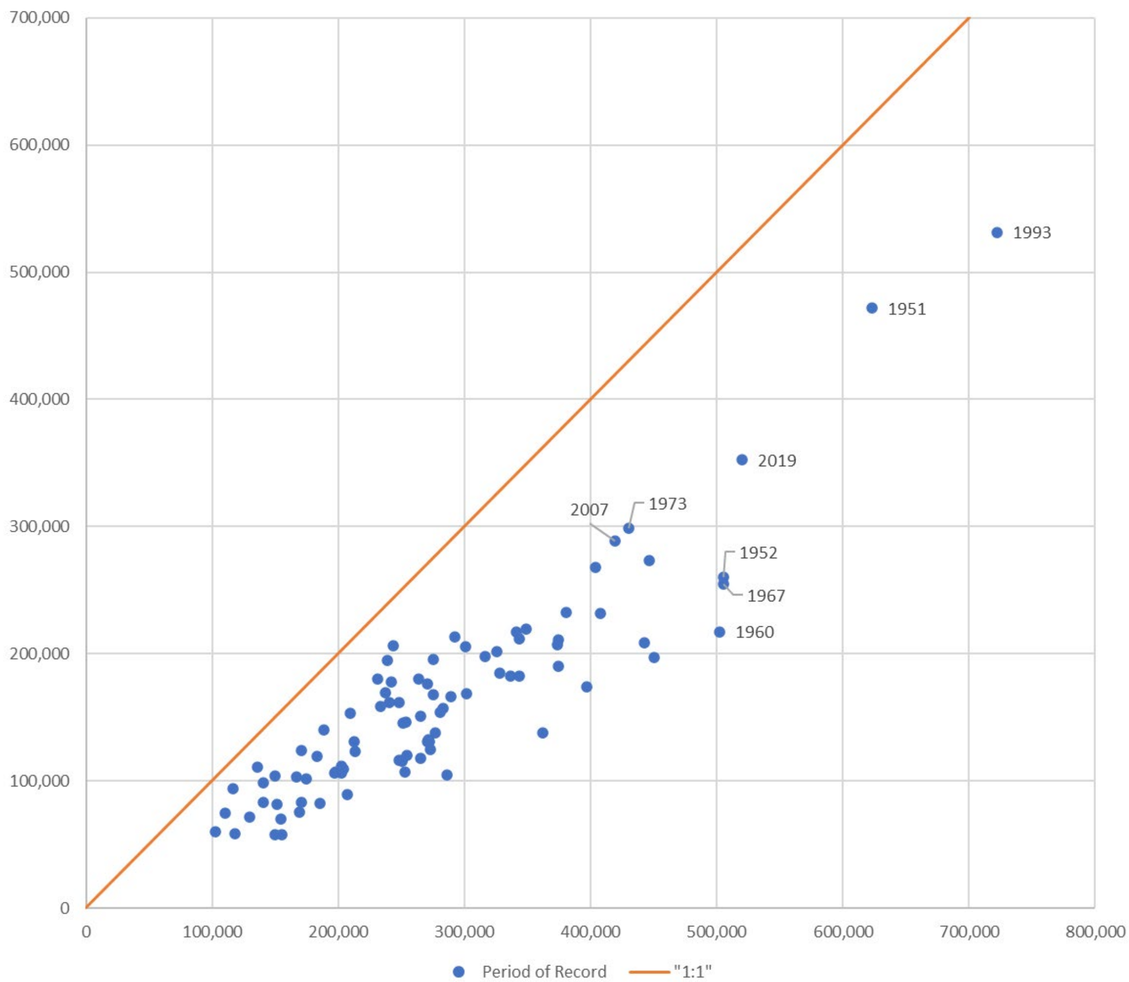


Figure 5-21. Kansas City, MO HEC-ResSim Regulated vs. Unregulated Period of Record Annual Flow Peaks

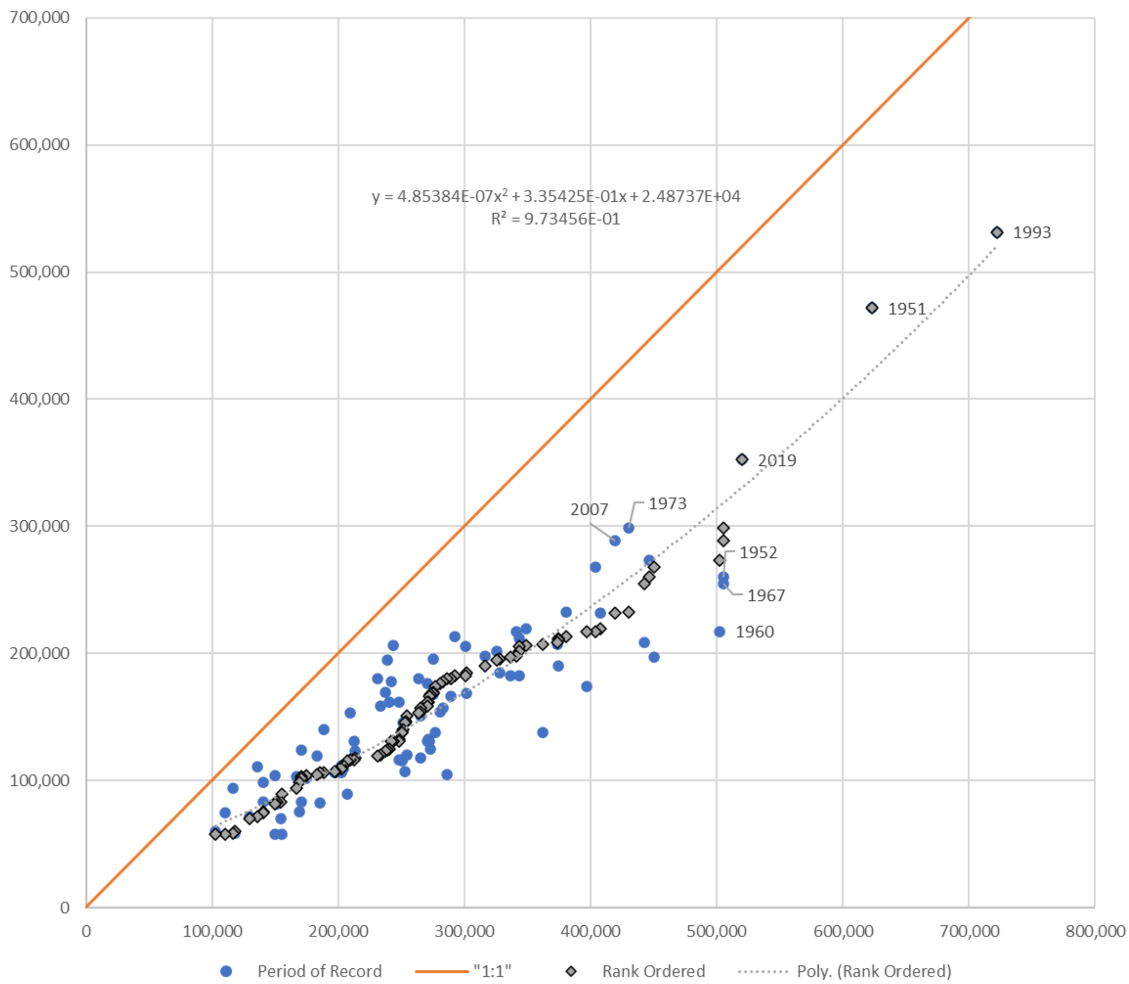


Figure 5-22. Kansas City, MO HEC-ResSim Rank Ordered Annual Flow Peaks with Trendline

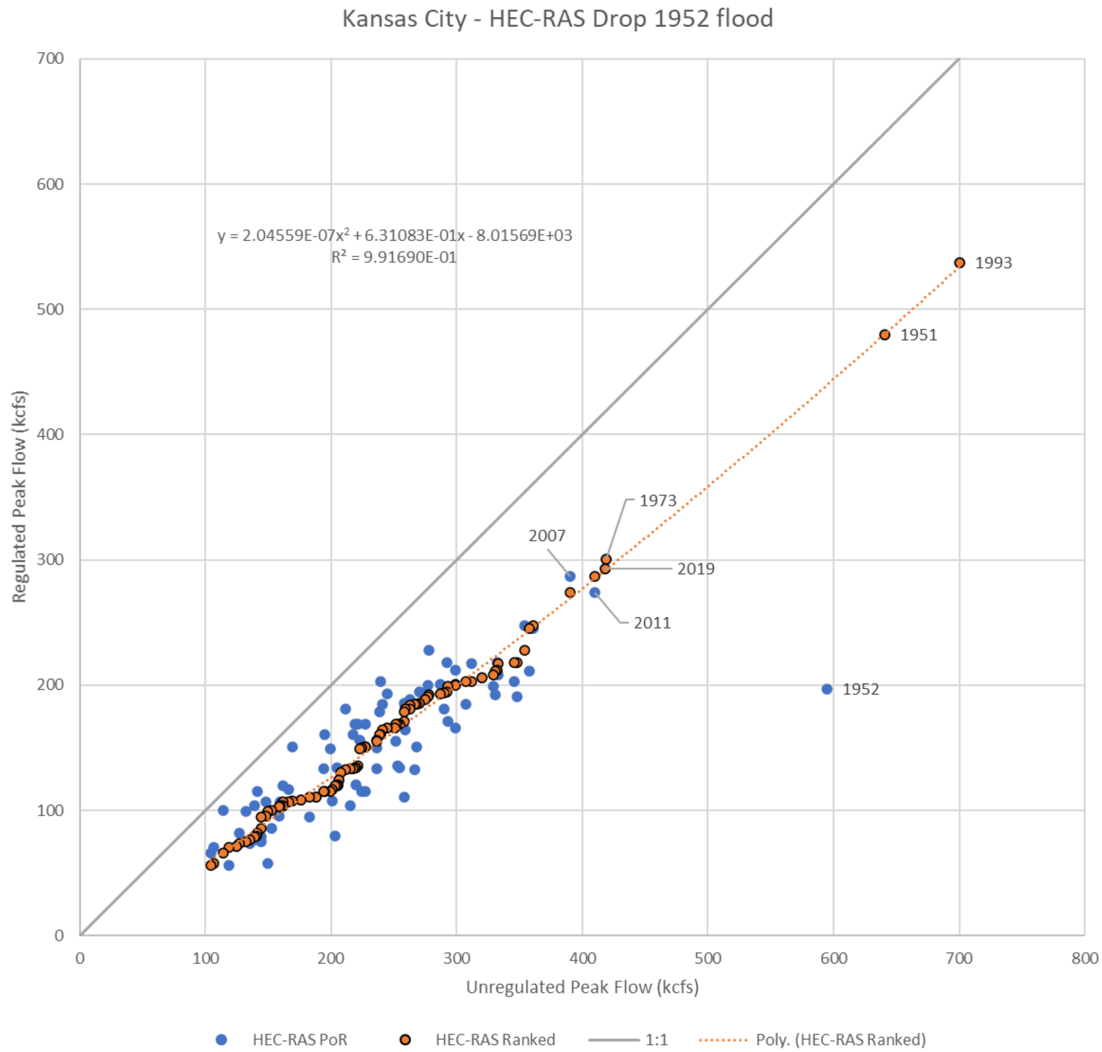


Figure 5-23. Kansas City, MO HEC-RAS Routed Period of Record and Rank Ordered Annual Peak Flows with Trendline

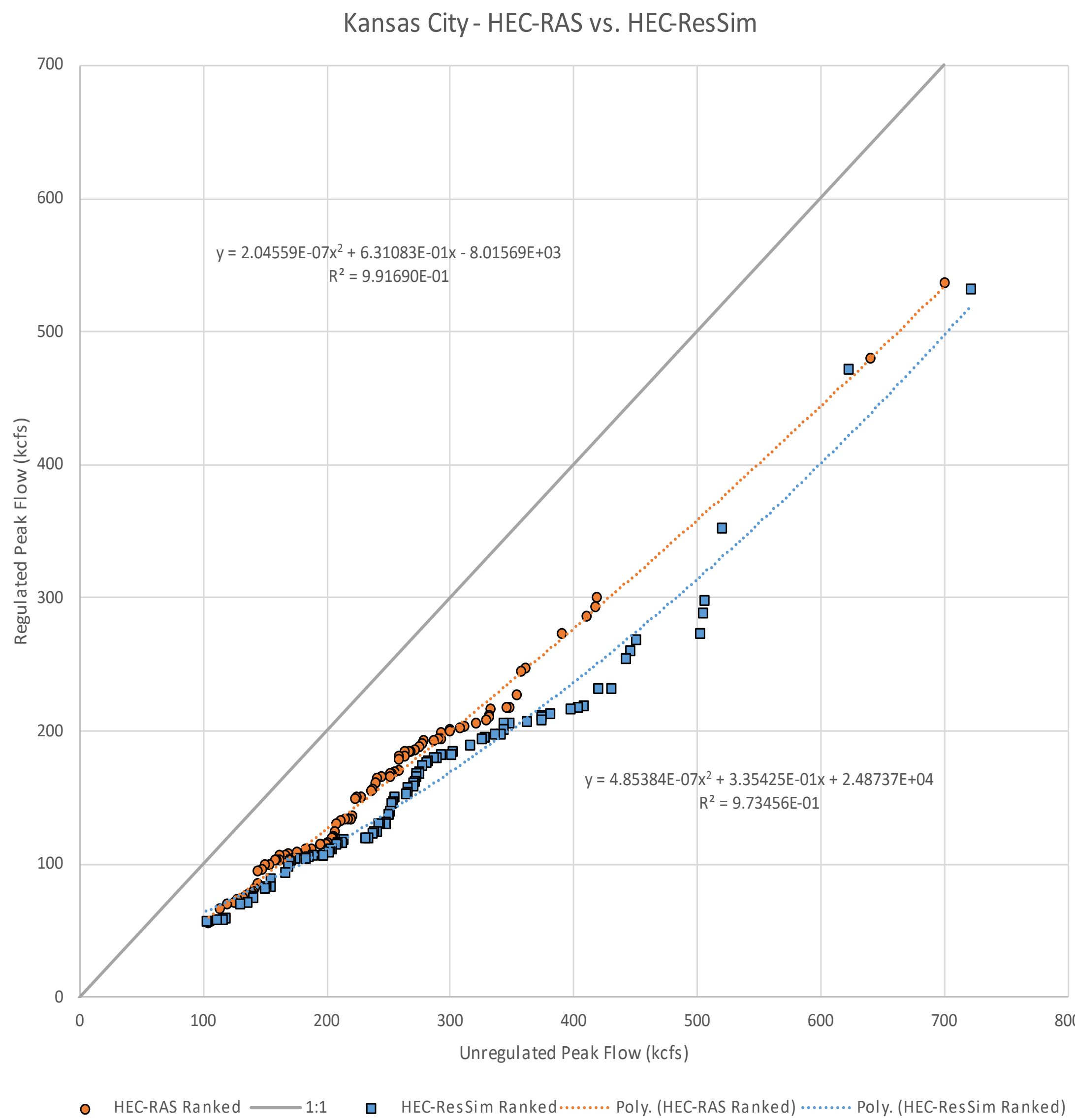


Figure 5-24. Kansas City, MO Comparison of HEC-ResSim and HEC-RAS routed POR Ranked Flows

5.3.3.1 Addition of Scaled Floods, Kansas City, MO

Scaled floods were added to the regulated-unregulated plot and rank ordered and fit with a second order polynomial. The extended plot is shown in Figure 5-25. The two largest scaled floods (1951 and 1993 plus 2.0 standard deviations) were removed when fitting the polynomial to the rank ordered data due to their effect on the upper end of the curve, and the lack of a need to define the transform to these extreme flows. Figure 5-26 shows a polynomial fit through the combined period of record and scaled flood peak flow pairs after rank ordering. Additionally, the 2003 UMRSFFS transform and hypothetical levee design floods and HMR51/52 storms from the Kansas City's Levees Supplemental H&H analysis

(USACE 2021, KC Levees) are plotted in Figure 5-27 for comparison to the data for the current analysis. Figure 5-28 shows the final selected transform in black from the piecewise function based on polynomial fits to the period of record data and scaled floods. The trendline from the combined dataset is shown as a dashed red line for comparison. While the 2021 KC levees transform was similar to the 2003 UMRSFFS, the KC levees transform (Regulated flow = 3.0145431 x 10E-7 x UnregFlow^2 + 0.55090959 x UnregFlow – 21065.358, made for events larger than 50% AEP) produces approximately 16-17% higher flows at the 1% to 0.2% AEP than the current study transform.

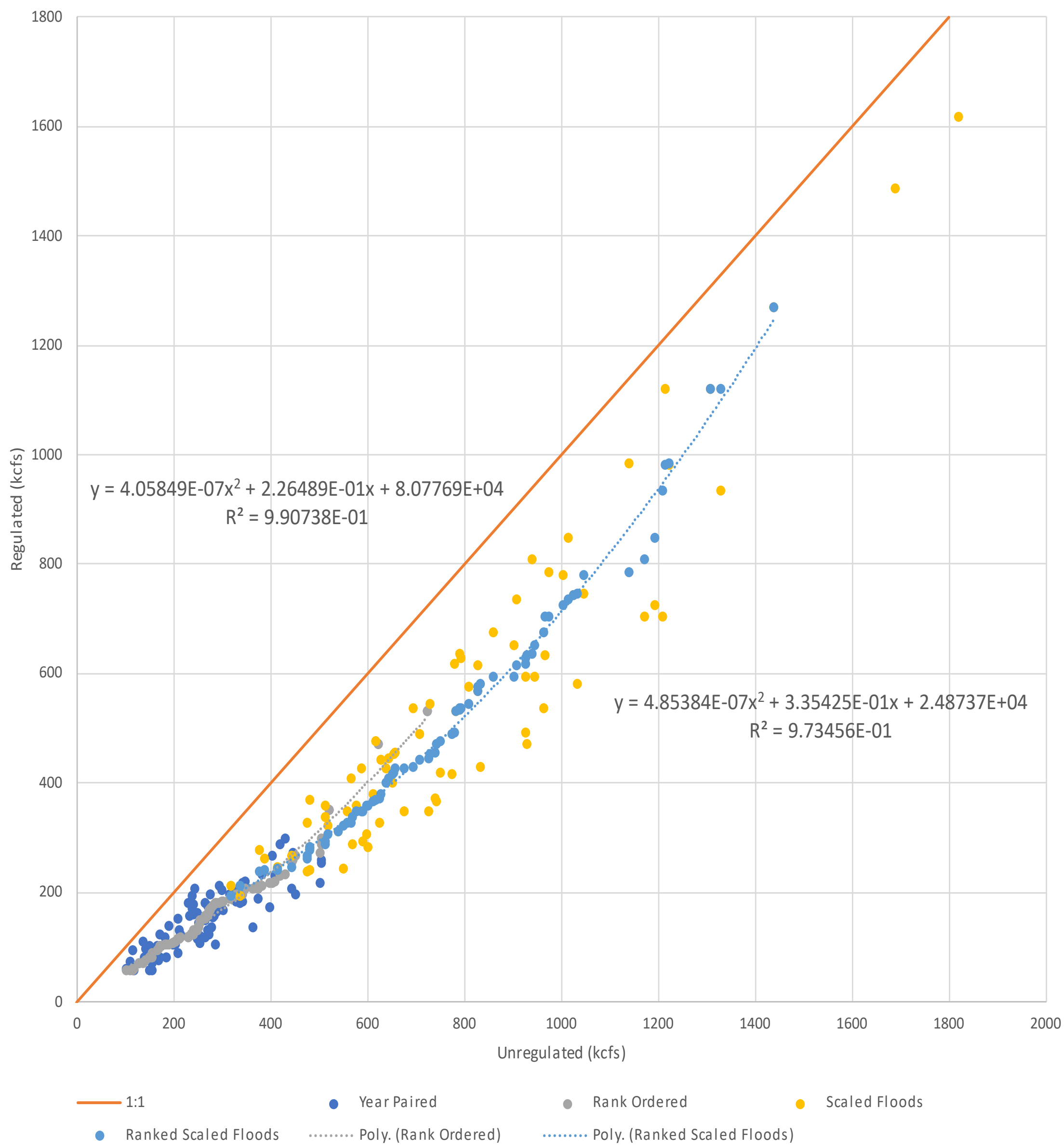


Figure 5-25. Kansas City, MO Period of Record and Scaled Flood Events with Best Fit Polynomials

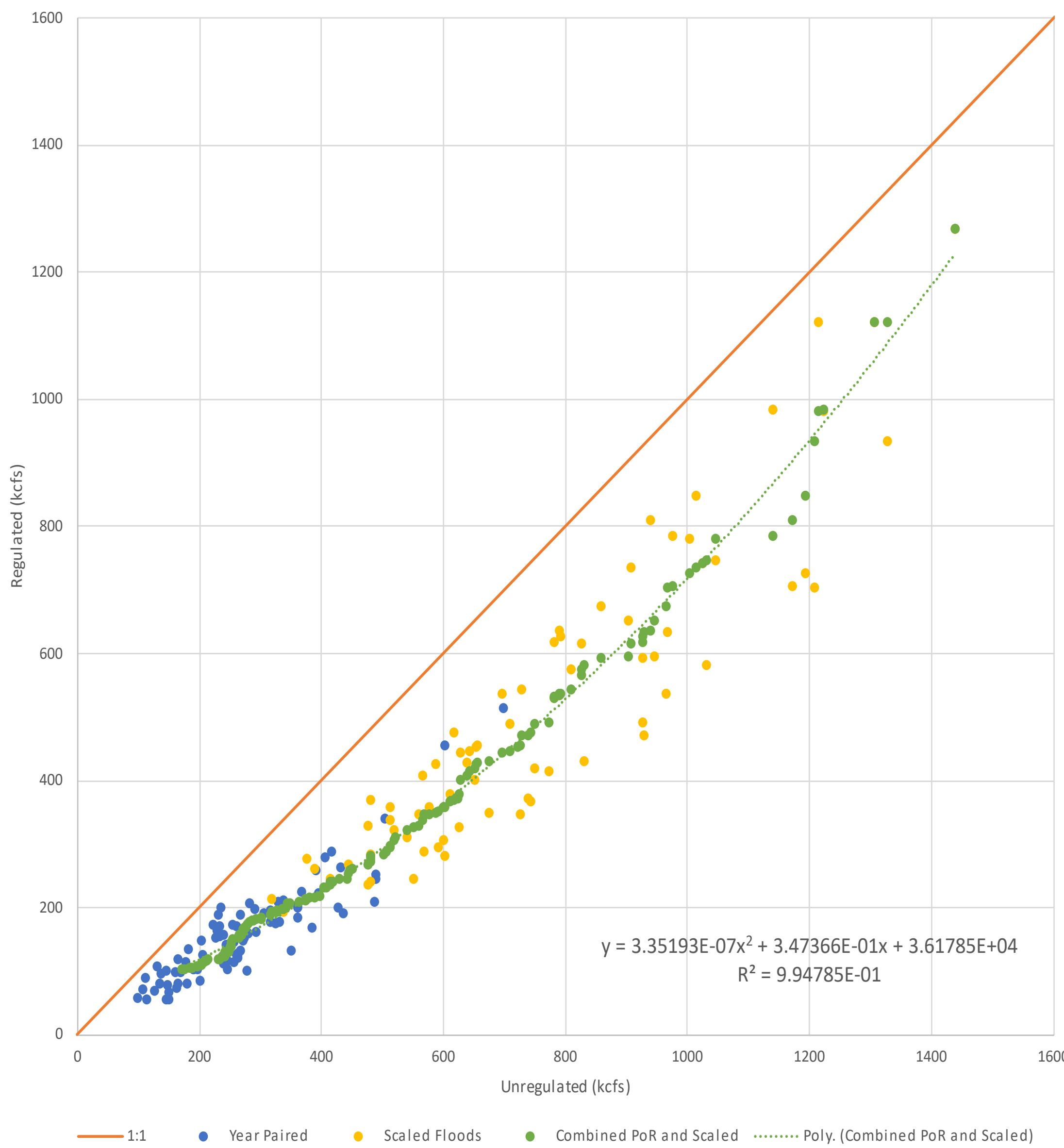


Figure 5-26. Polynomial Fit to Combined Period of Record and Scaled Floods for Kansas City, MO

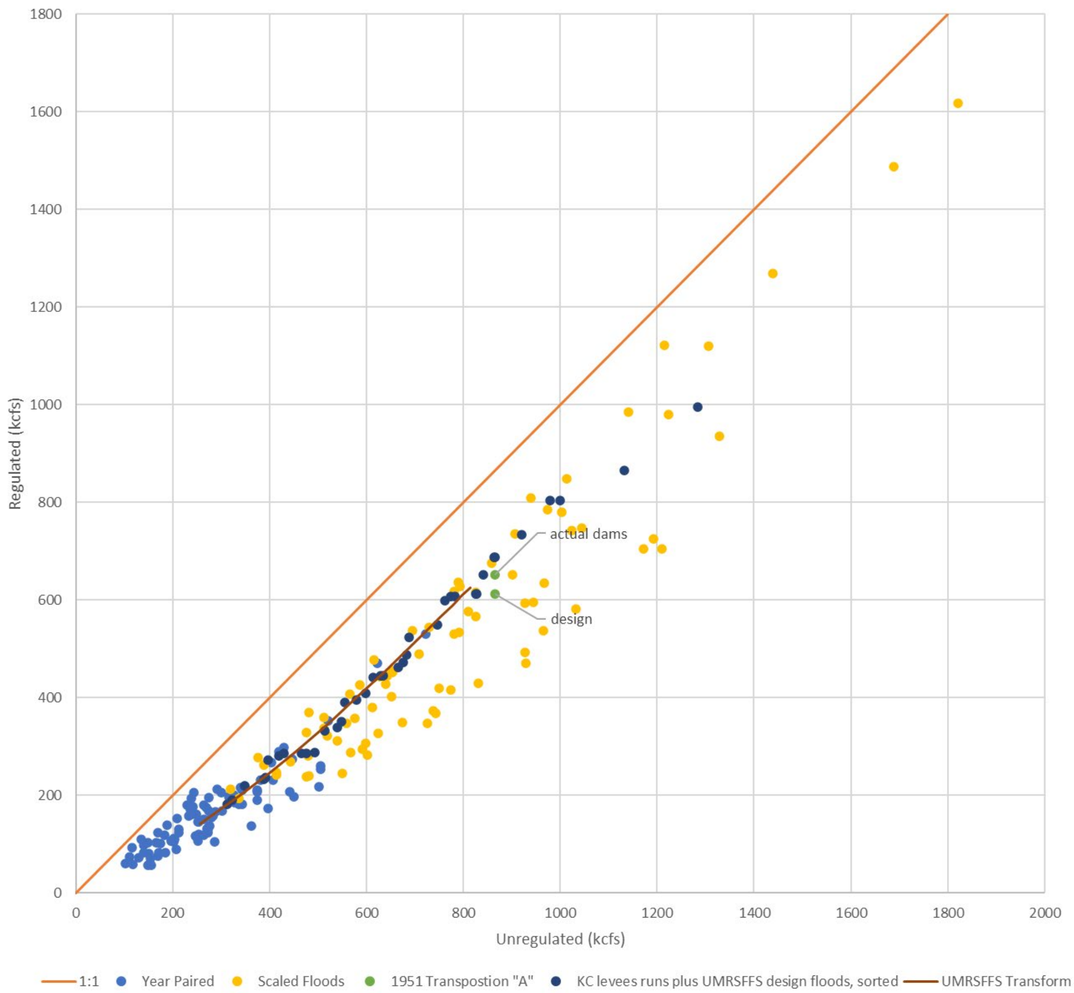


Figure 5-27. Kansas City Period of Record and Scaled Floods with 2003 UMRSFFS Design Floods and KC Levees Hypothetical Floods

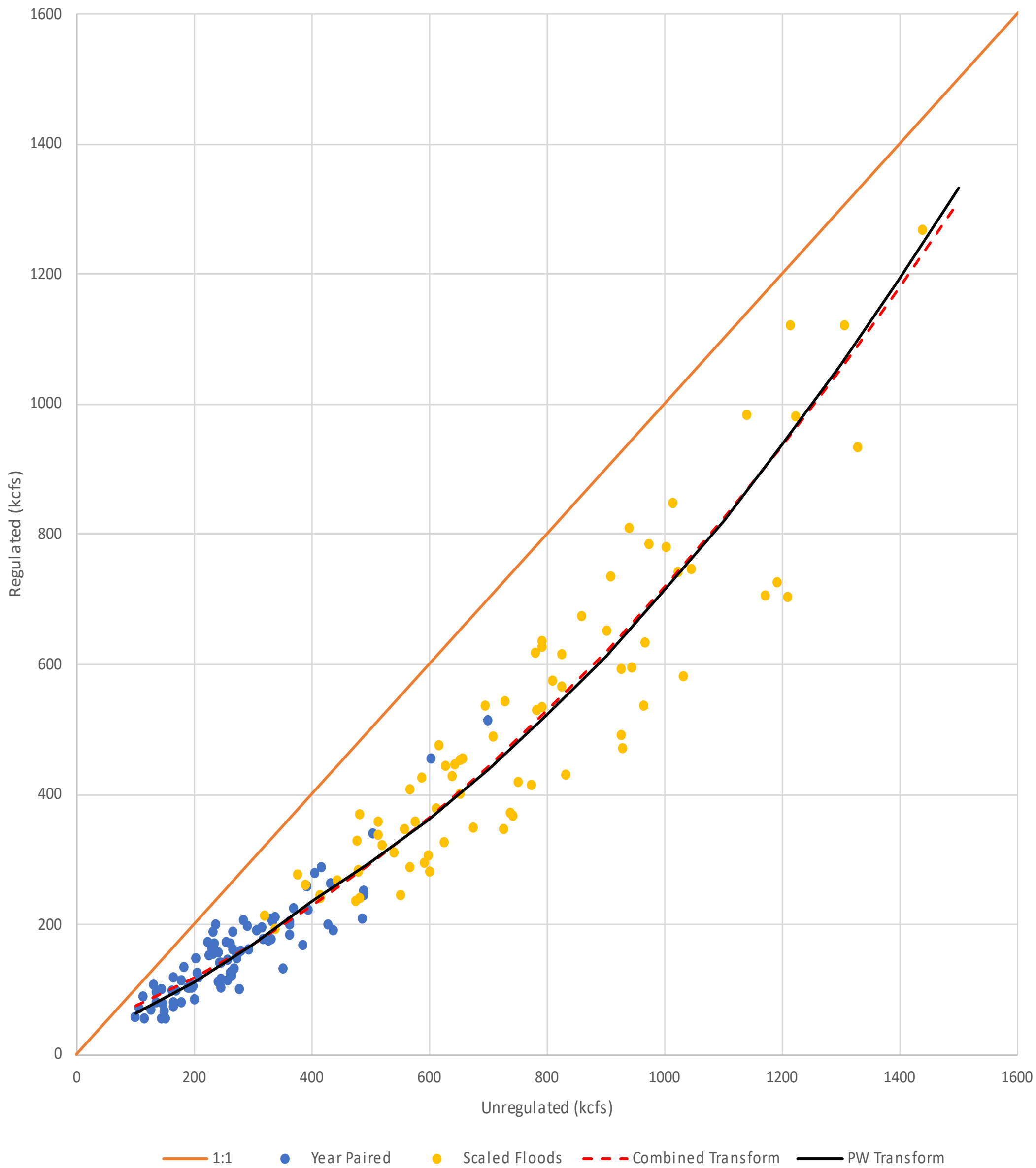


Figure 5-28. Final Unregulated-Regulated Transform for Kansas City, MO

5.3.4 Waverly, MO

Period of record regulated and unregulated peak annual flows for Waverly, Missouri are plotted in Figure 5-29. Figure 5-30 presents the rank ordered data with a second order polynomial fit through the data. To better represent the trend of the period of record data, the 1951 and 1993 flood points were removed from the analysis. The result is shown in Figure 5-31. When these points are removed from the analysis, the curvature on the best fit polynomial becomes negative, indicating an increase in reservoir regulation effectiveness at higher flows. Figure 5-32 depicts the HEC-RAS routed peak annual flows. The 1952 flood was removed from the HEC-RAS analysis since it plots far outside the trend of the other data. Figure 5-33 compares the period of record data for the HEC-ResSim and HEC-RAS data. As for other gages, the HEC-RAS data plots to the left of the HEC-ResSim data, reflecting smaller unregulated peak flows from the HEC-RAS routing. For similar reasons as the other gages, given overall minor differences in results for the full analysis using HEC-RAS routings as opposed to HEC-ResSim routings, the remainder of the analysis focuses on the HEC-ResSim routings.

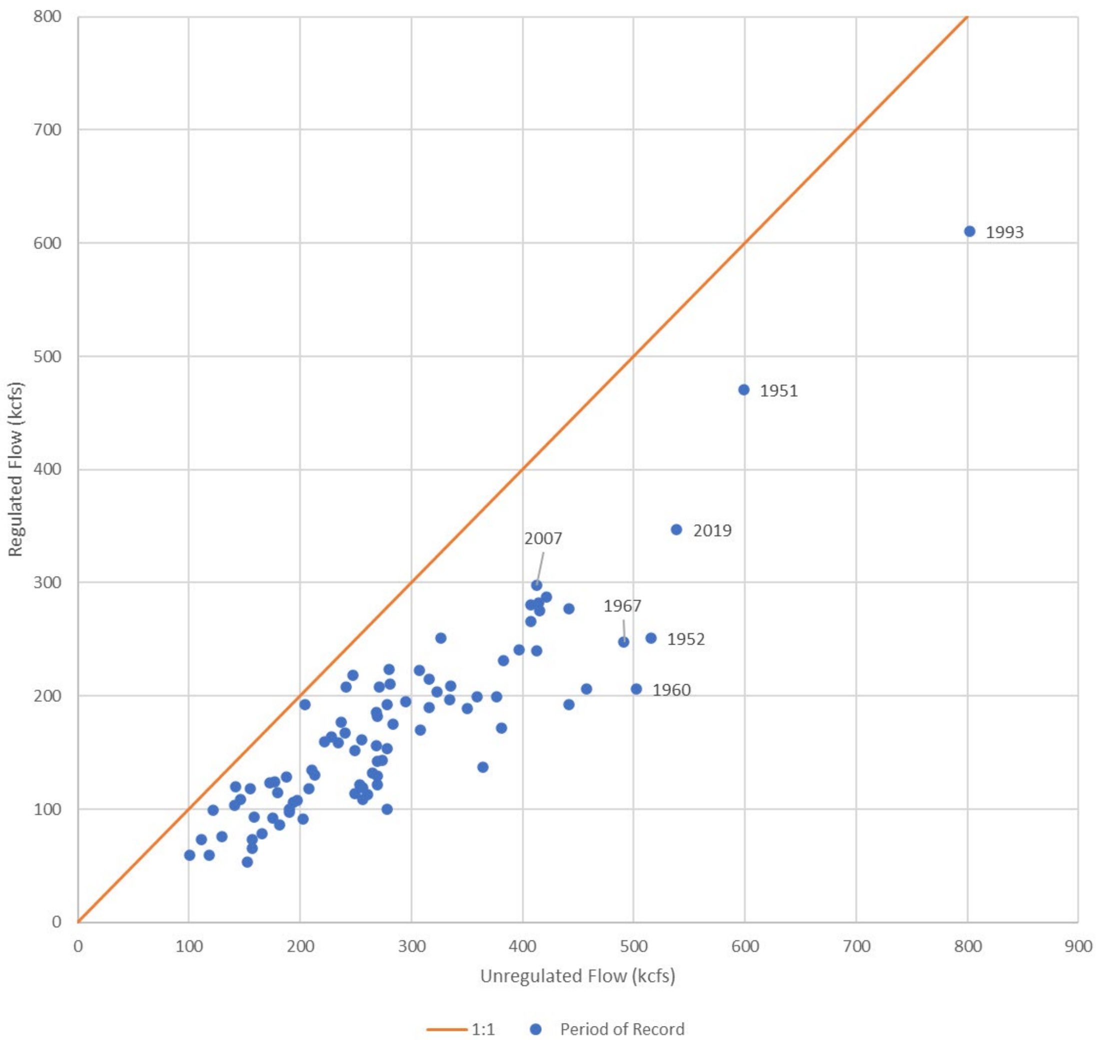


Figure 5-29. Waverly, MO Regulated vs. Unregulated Period of Record Annual Flow Peaks

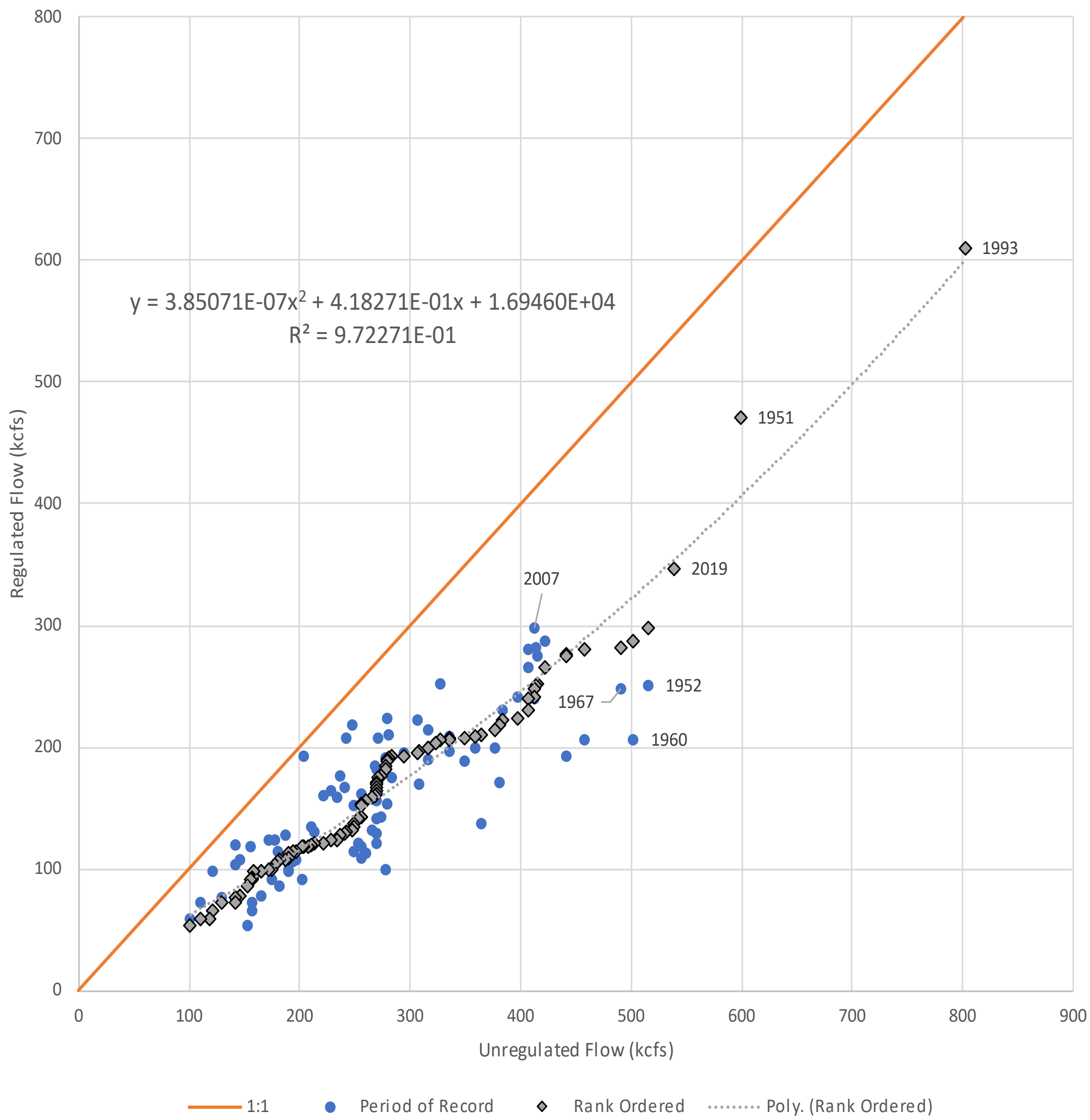


Figure 5-30. Waverly, MO Rank Ordered Annual Flow Peaks with Trendline

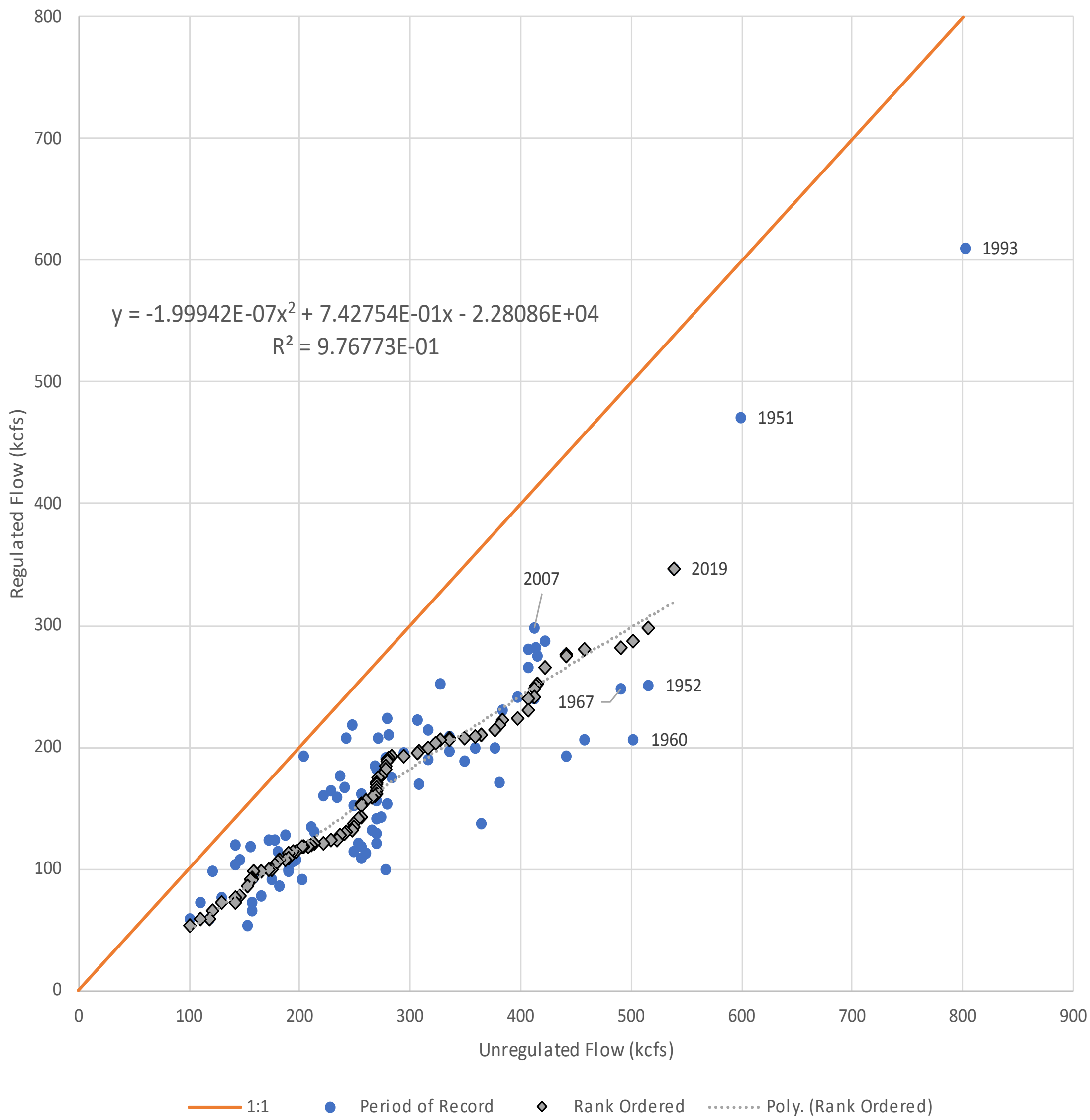


Figure 5-31. Waverly, MO Rank Ordered Annual Flow Peaks with Trendline Excluding 1993 and 1951

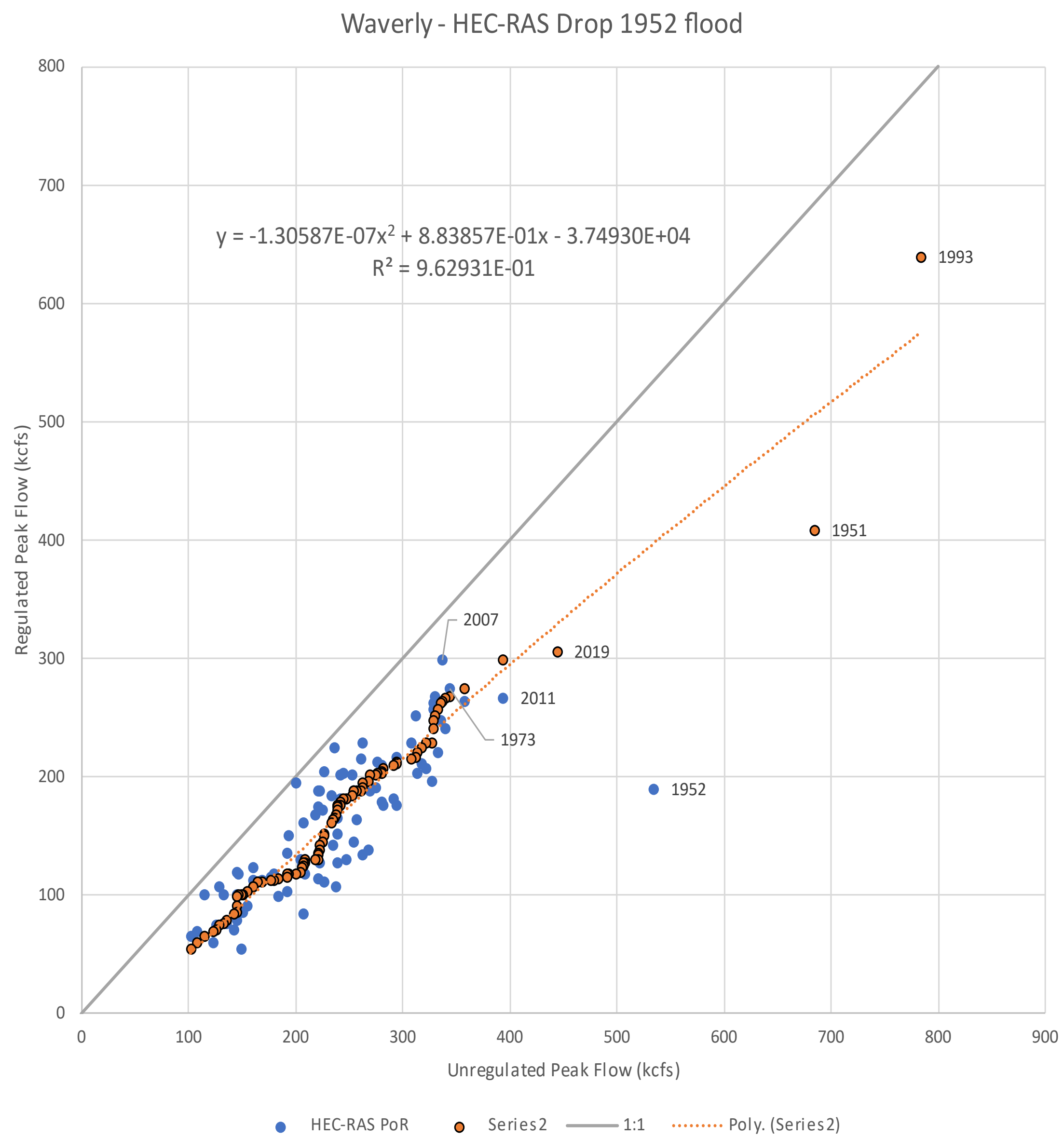


Figure 5-32. Waverly, MO HEC-RAS Routed Period of Record and Rank Ordered Annual Peak Flows with Trendline

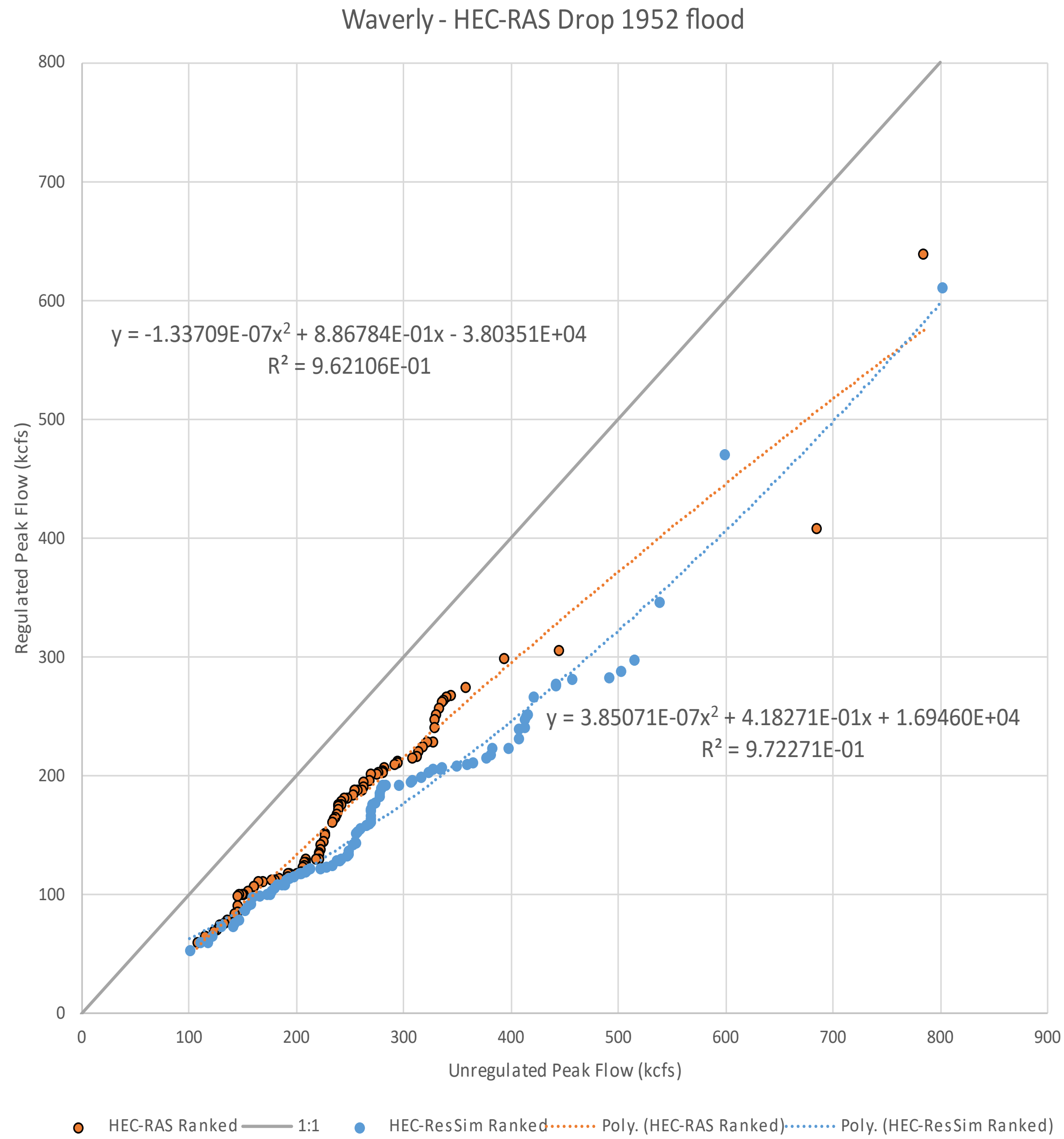


Figure 5-33. Waverly, MO Comparison of HEC-ResSim and HEC-RAS Routed POR Ranked Flows

5.3.4.1 Addition of Scaled Floods, Waverly, MO

HEC-ResSim routed scaled floods were added to the regulated-unregulated plot to extend the relationship beyond the flows experienced in the period of record. Figure 5-34 shows the polynomial fit to the rank ordered scaled floods. The three largest scaled floods (1951 plus 2.0 standard deviations and 1993 plus 1.5 and 2.0 standard deviations) were removed when fitting the polynomial to the rank ordered data due to their effect on the upper end of the curve, and the lack of a need to define the transform to these extreme flows.

Figure 5-35 shows the polynomial fit to the combined dataset of the period of record and scaled floods. Figure 5-36 shows the final selected transform relationship in black with the polynomial fit to the combined rank ordered data as a dashed red line.

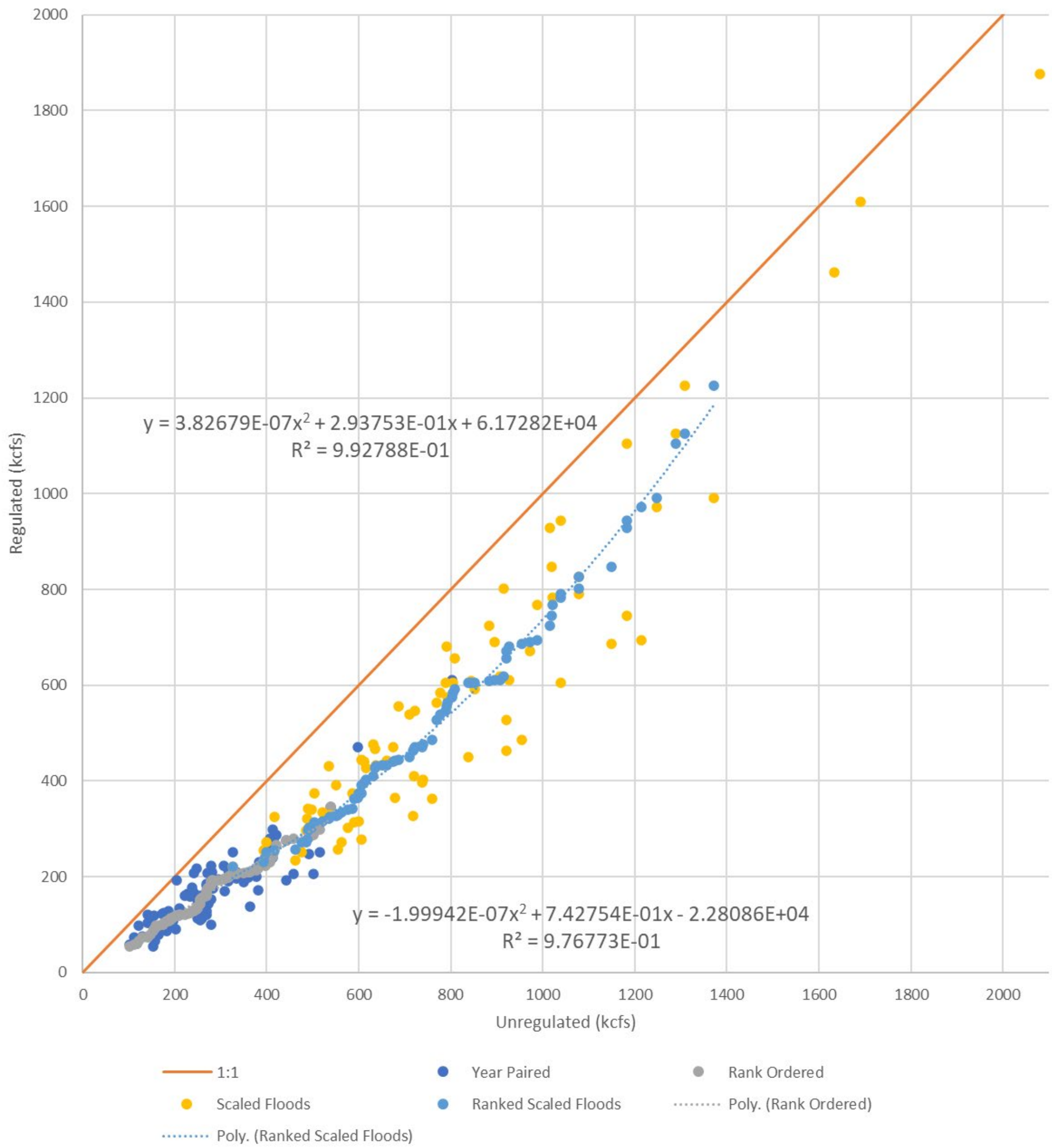


Figure 5-34. Waverly, MO HEC-ResSim Period of Record and Scaled Flood Events with Best Fit Polynomials

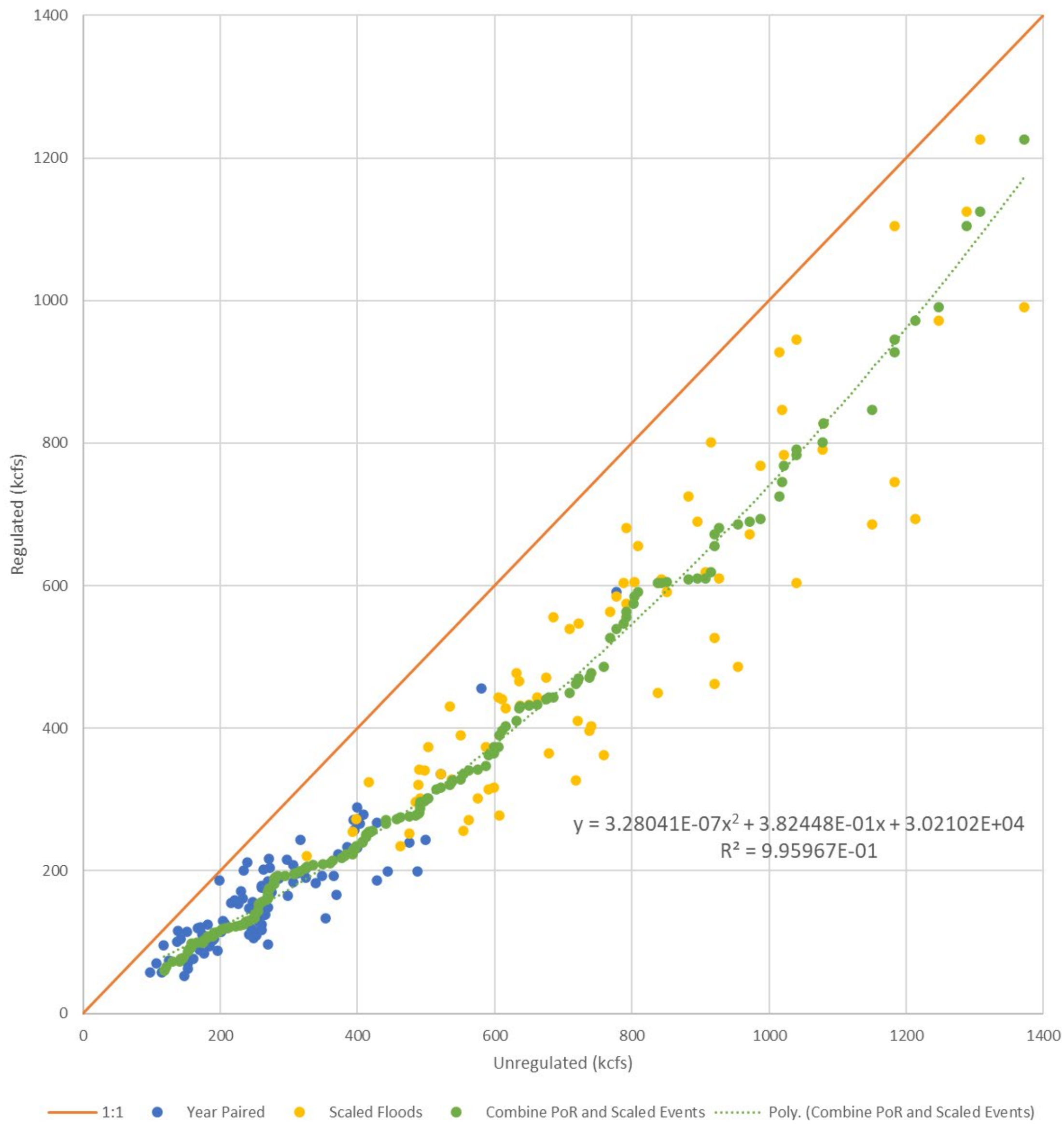


Figure 5-35. Polynomial Fit to Combined Period of Record and Scaled Floods for Waverly, MO

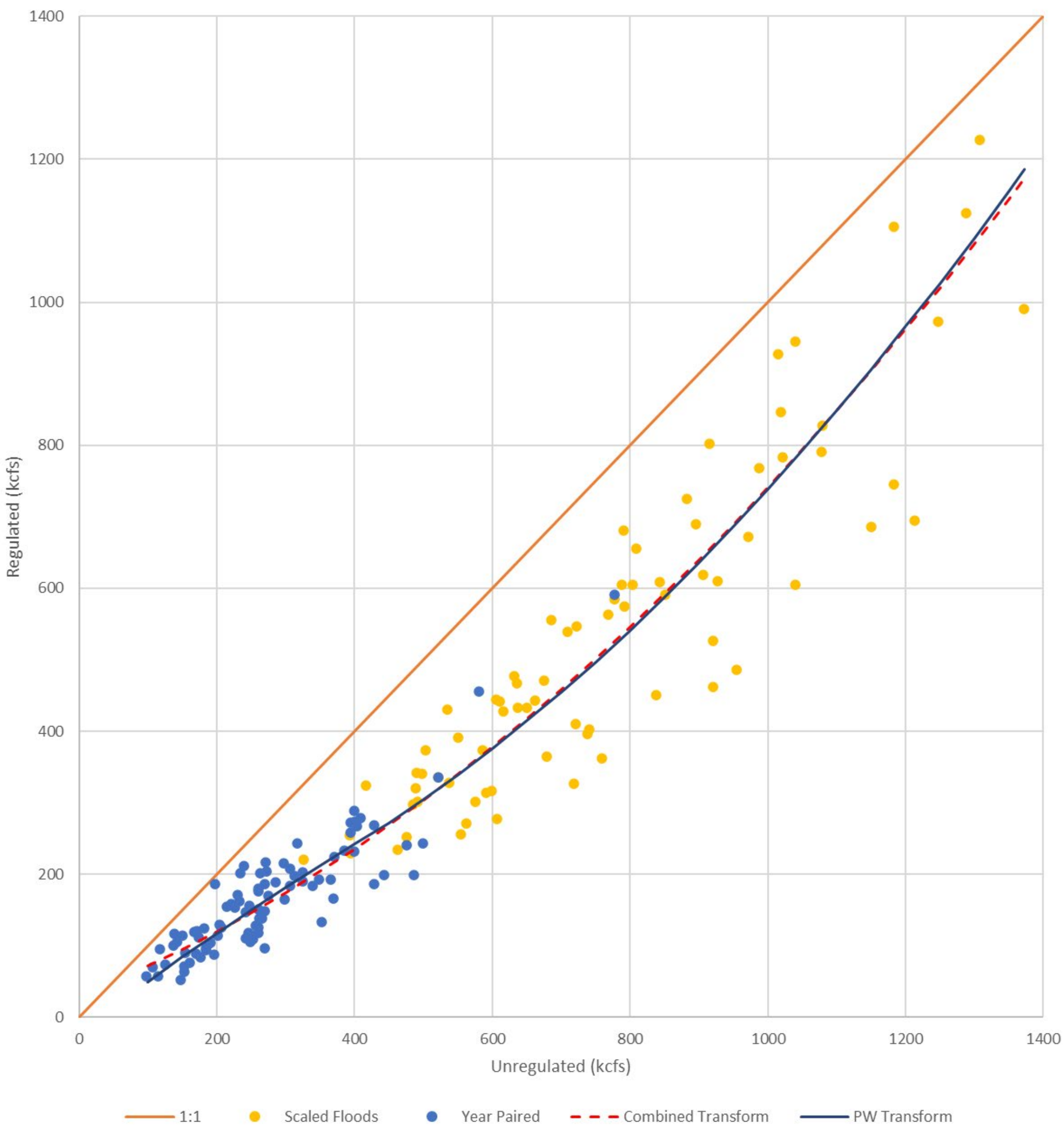


Figure 5-36. Final Unregulated-Regulated Transform for Waverly, MO

5.3.5 Boonville, MO

Period of record regulated and unregulated peak annual flows for Boonville, Missouri are plotted in Figure 5-37. Figure 5-38 presents the rank ordered data with a second order polynomial fit through the data. Because of its large magnitude, the 1993 flood was excluded from the period of record analysis and included with the scaled floods. When the 1993 flood is removed from the period of record ranked floods, the curvature on the best fit polynomial becomes negative, indicating an increase in reservoir regulation effectiveness at higher flows. Figure 5-39 depicts the HEC-RAS routed peak annual flows. The 1952 flood was removed from the HEC-RAS analysis since it plots far outside the trend of the other data. Figure 5-40 compares the period of record data for the HEC-ResSim and HEC-RAS data. As for other gages, the HEC-RAS data plots to the left of the HEC-ResSim data, reflecting smaller unregulated peak flows from the HEC-RAS routing. For similar reasons as the other gages, given overall minor differences in results for the full analysis using HEC-RAS routings as opposed to HEC-ResSim routings, the remainder of the analysis focuses on the HEC-ResSim routings.

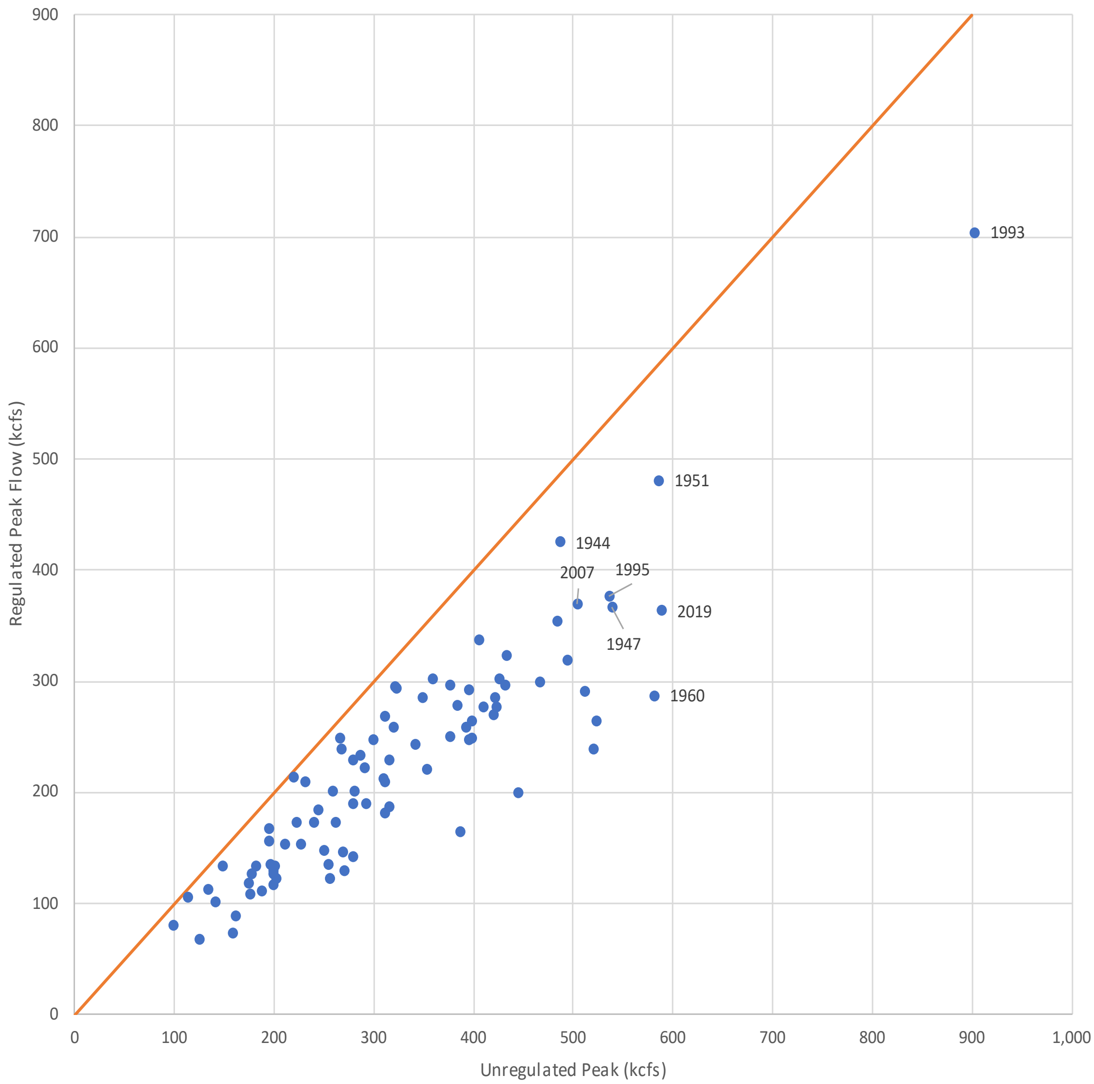


Figure 5-37. Boonville, MO Regulated vs. Unregulated Period of Record Annual Flow Peaks

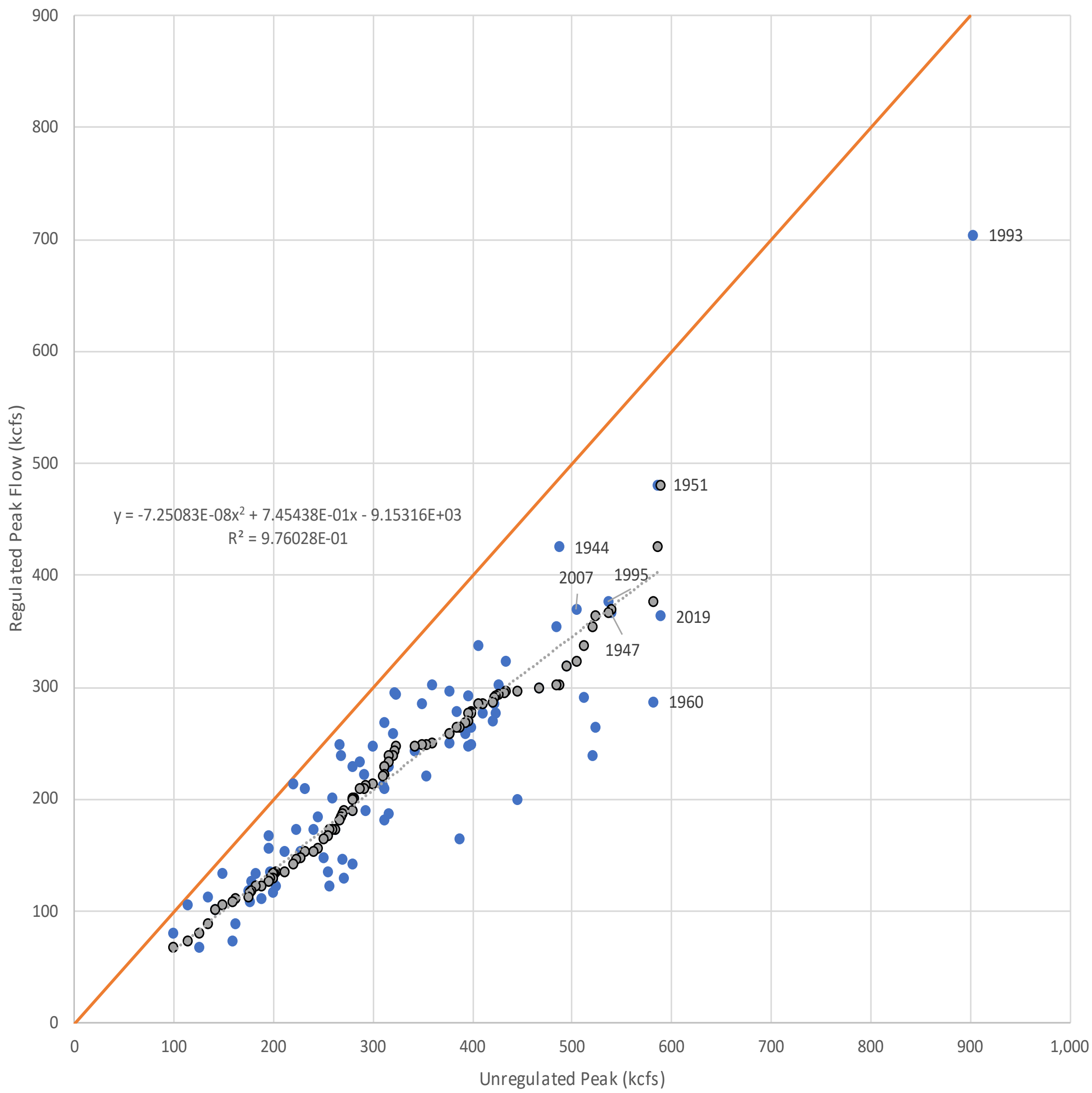


Figure 5-38. Boonville, MO Rank Ordered Annual Flow Peaks with Trendline

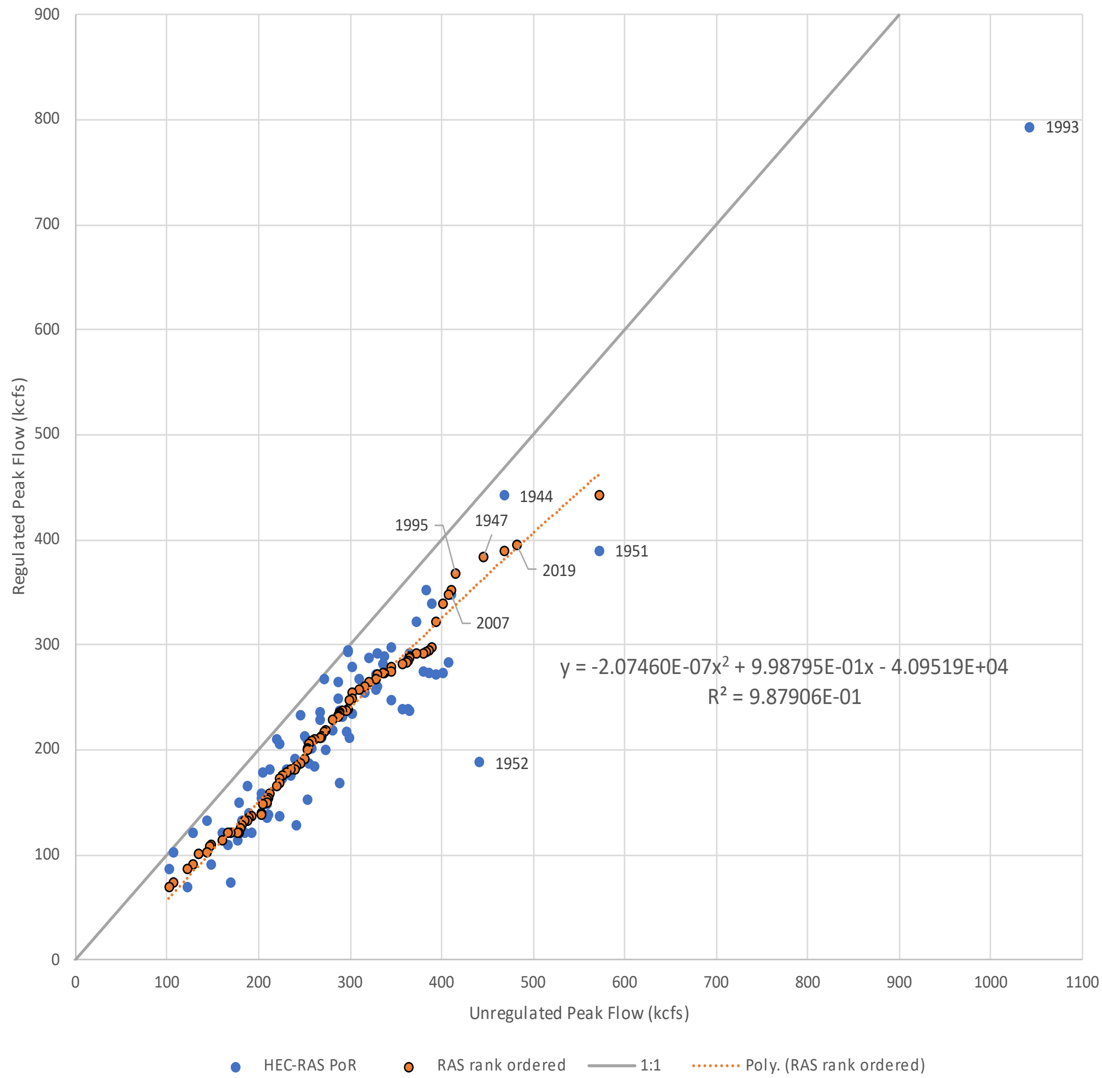


Figure 5-39. Boonville, MO HEC-RAS Routed Period of Record and Rank Ordered Annual Peak Flows without 1952 and 1993 with Trendline

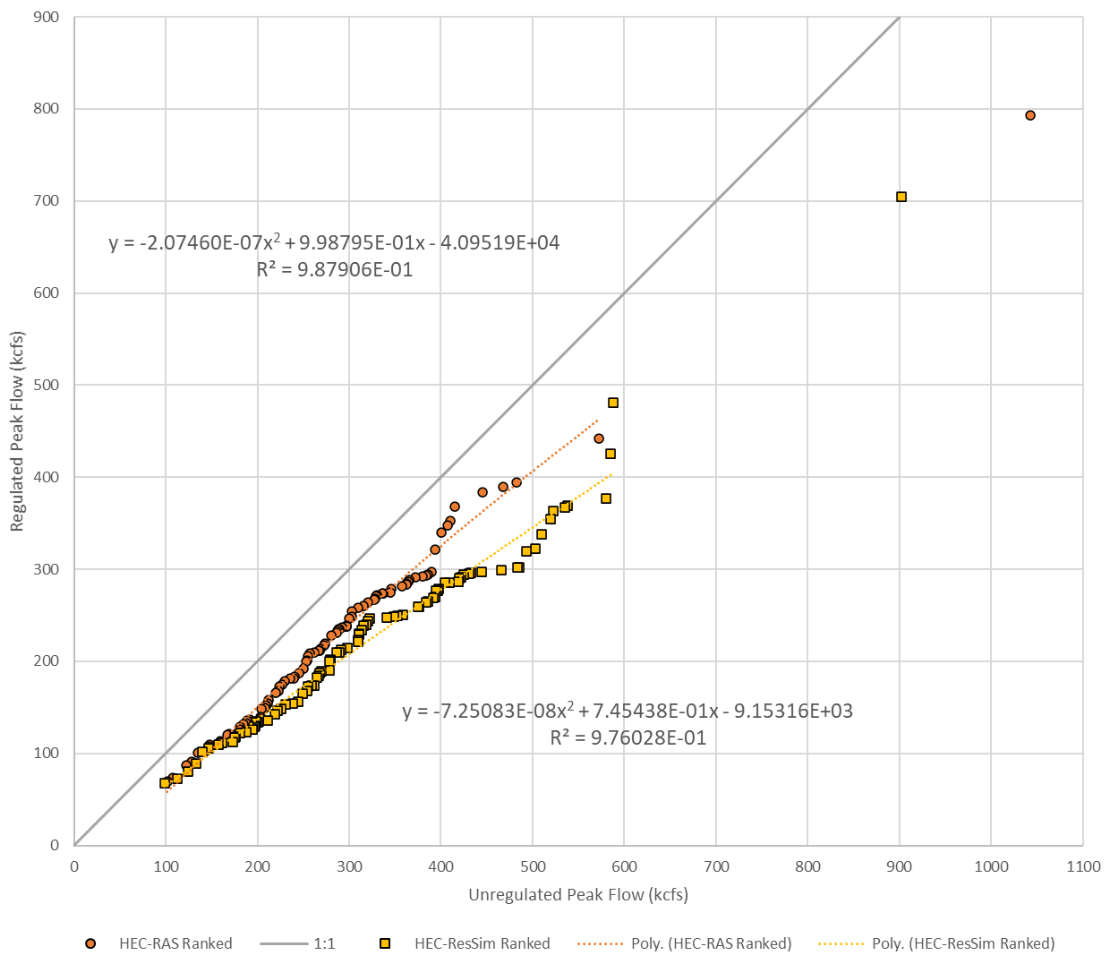


Figure 5-40. Boonville, MO Comparison of HEC-ResSim and HEC-RAS routed POR Ranked Flows

5.3.5.1 Addition of Scaled Floods, Boonville, MO

HEC-ResSim routed scaled floods were added to the regulated-unregulated plot to extend the relationship beyond the flows experienced in the period of record. Figure 5-41 shows the polynomial fit to the rank ordered scaled floods. The three largest scaled floods (1951 plus 2.0 standard deviations and 1993 plus 1.5 and 2.0 standard deviations) were removed when fitting the polynomial to the rank ordered data due to their effect on the upper end of the curve, and the lack of a need to define the transform to these extreme flows. Figure 5-42. Figure 5-19 shows the polynomial fit to the combined dataset of the period of record and scaled floods. Figure 5-43 shows the final selected transform relationship in black with the polynomial fit to the combined rank ordered data as a dashed red line.

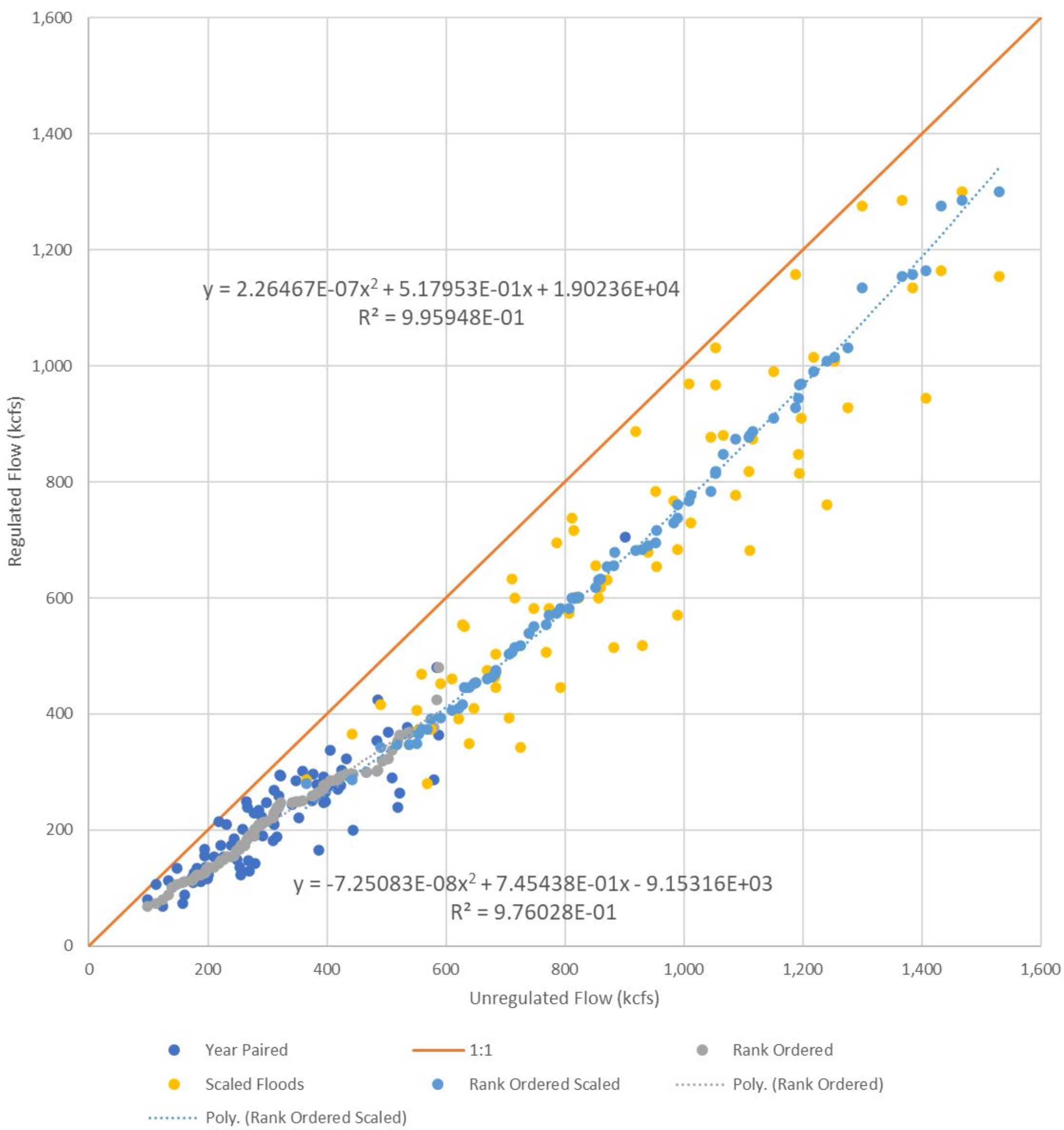


Figure 5-41. Boonville, MO HEC-ResSim Period of Record and Scaled Flood Events with Best Fit Polynomials

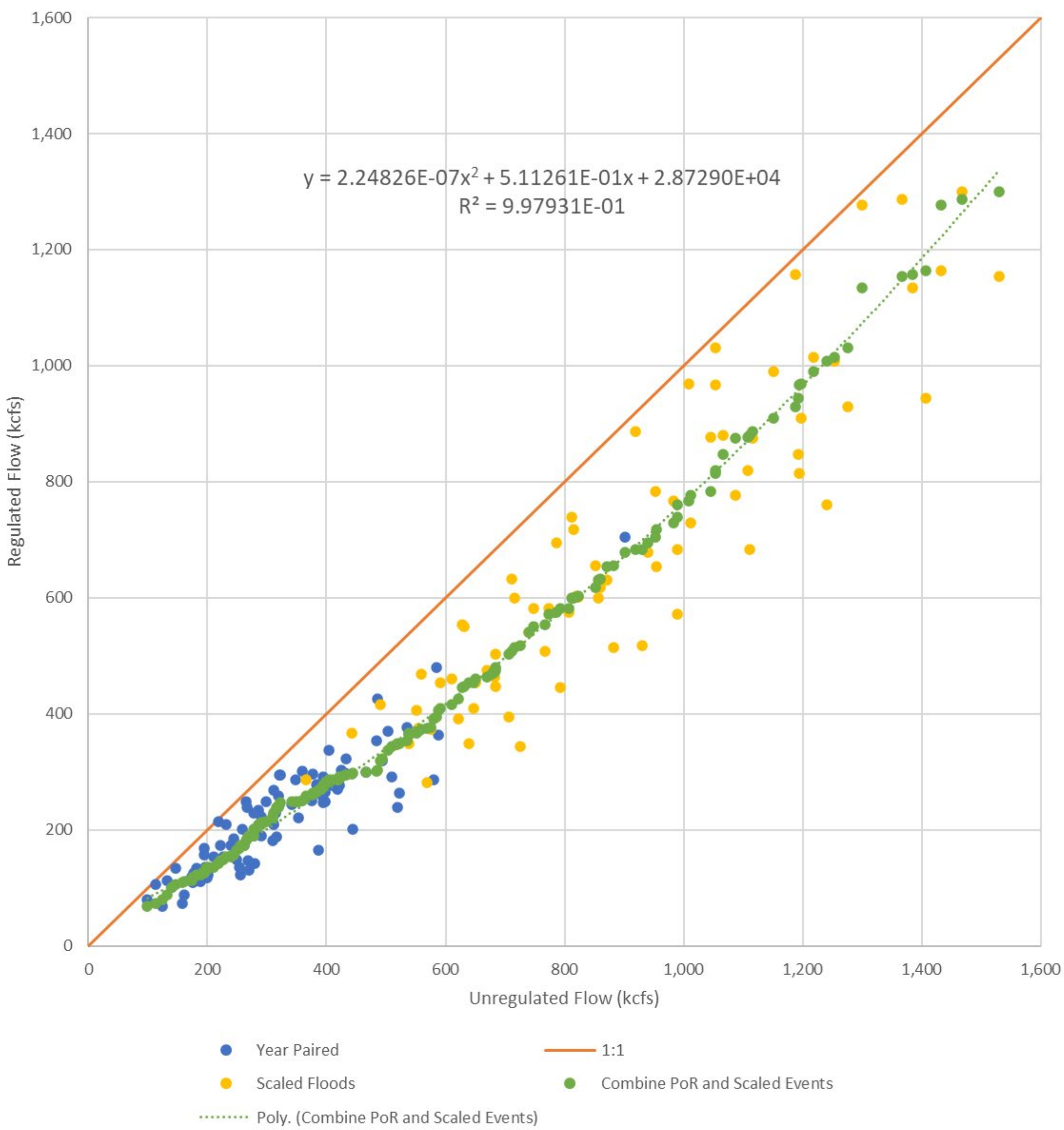


Figure 5-42. Polynomial Fit to Combined Period of Record and Scaled Floods for Boonville, MO

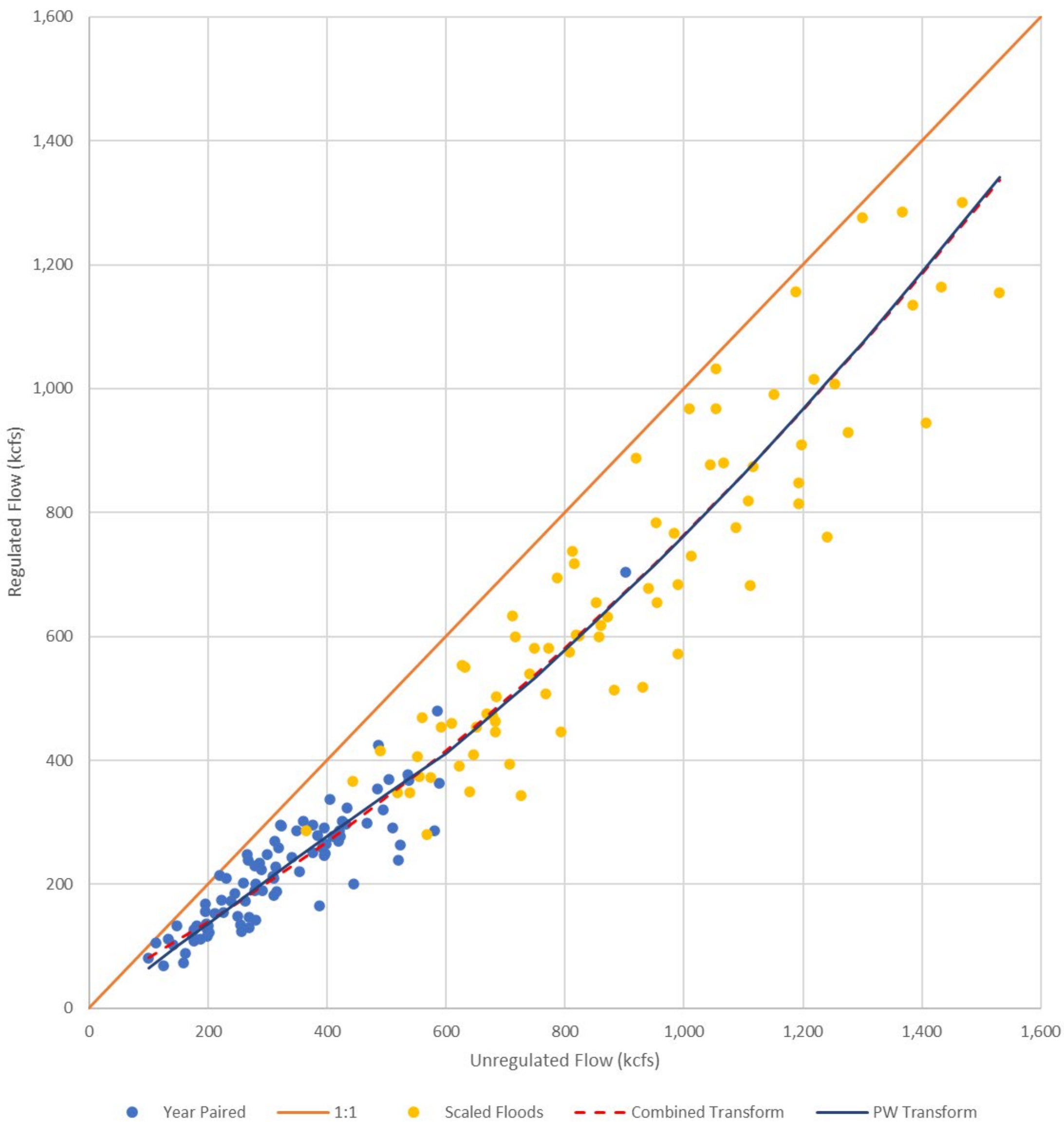


Figure 5-43. Final Unregulated-Regulated Transform for Boonville, MO

5.3.6 Hermann, MO

Period of record regulated and unregulated peak annual flows for Hermann, Missouri are plotted in Figure 5-44. Figure 5-45 presents the rank ordered data with a second order polynomial fit through the data. All period of record events were maintained in the analysis. Figure 5-46 depicts the HEC-RAS routed peak annual flows along with rank ordering and a second order polynomial fit to the ranked data. Figure 5-47 compares the period of record data for the HEC-ResSim and HEC-RAS data. As for other gages, the HEC-RAS data plots to the left of the HEC-ResSim data, reflecting smaller unregulated peak flows from the HEC-RAS routing. For similar reasons as the other gages, given overall minor differences in results for the full analysis using HEC-RAS routings as opposed to HEC-ResSim routings, the remainder of the analysis focuses on the HEC-ResSim routings.

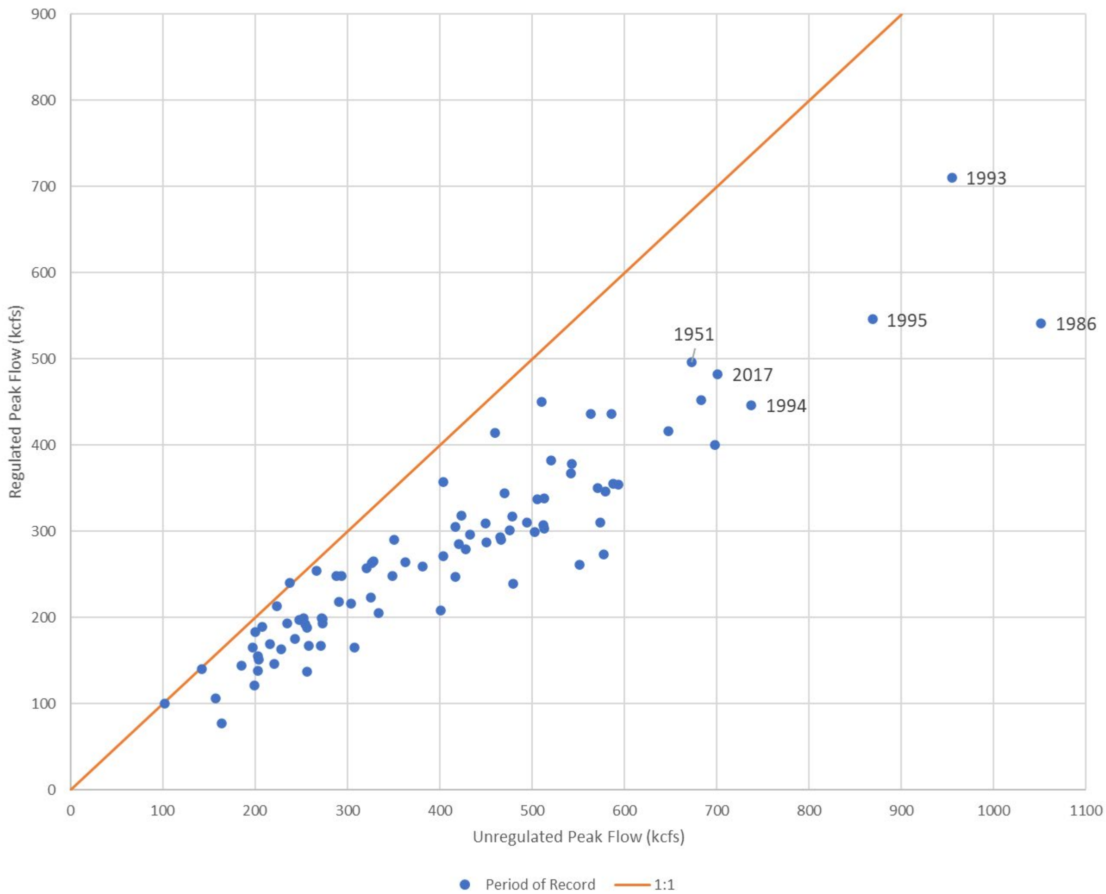


Figure 5-44. Hermann, MO HEC-ResSim Regulated vs. Unregulated Period of Record Annual Flow Peaks

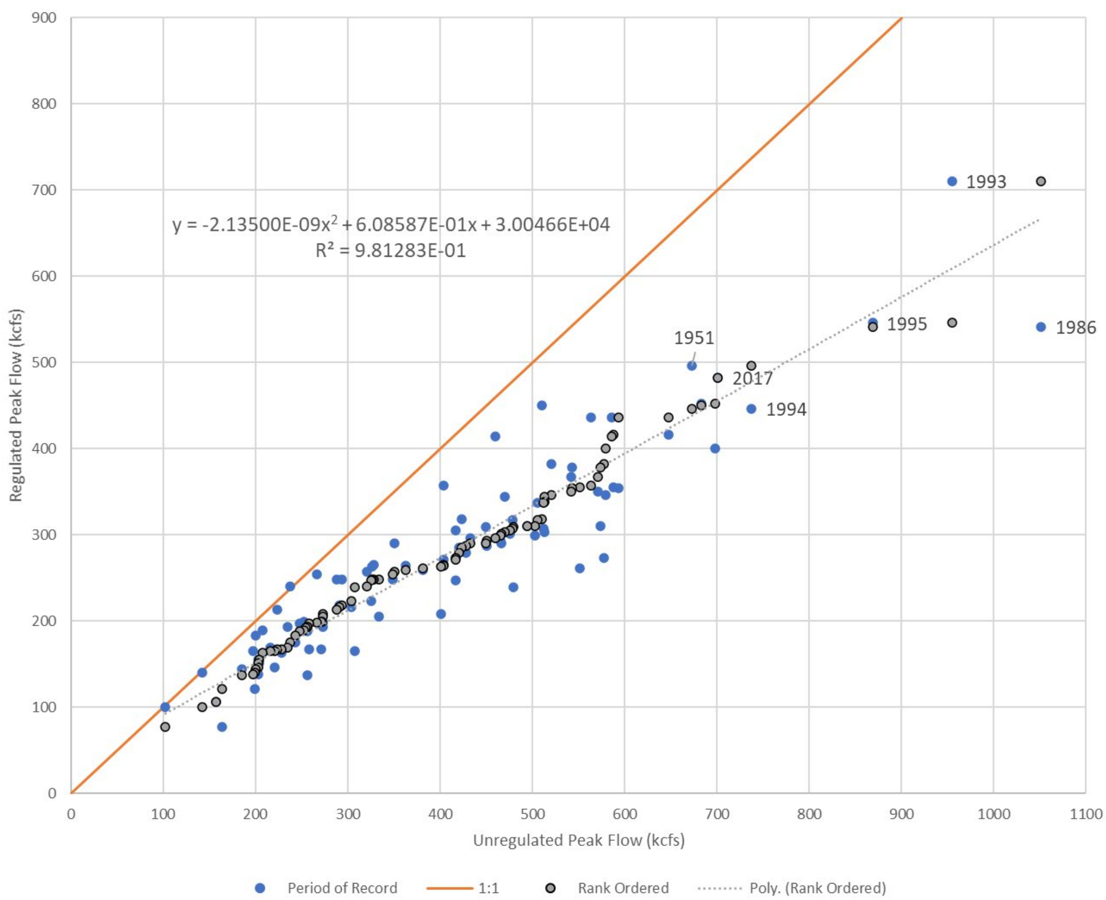


Figure 5-45. Hermann, MO HEC-ResSim Period of Record and Rank Ordered Annual Flow Peaks with Trendline

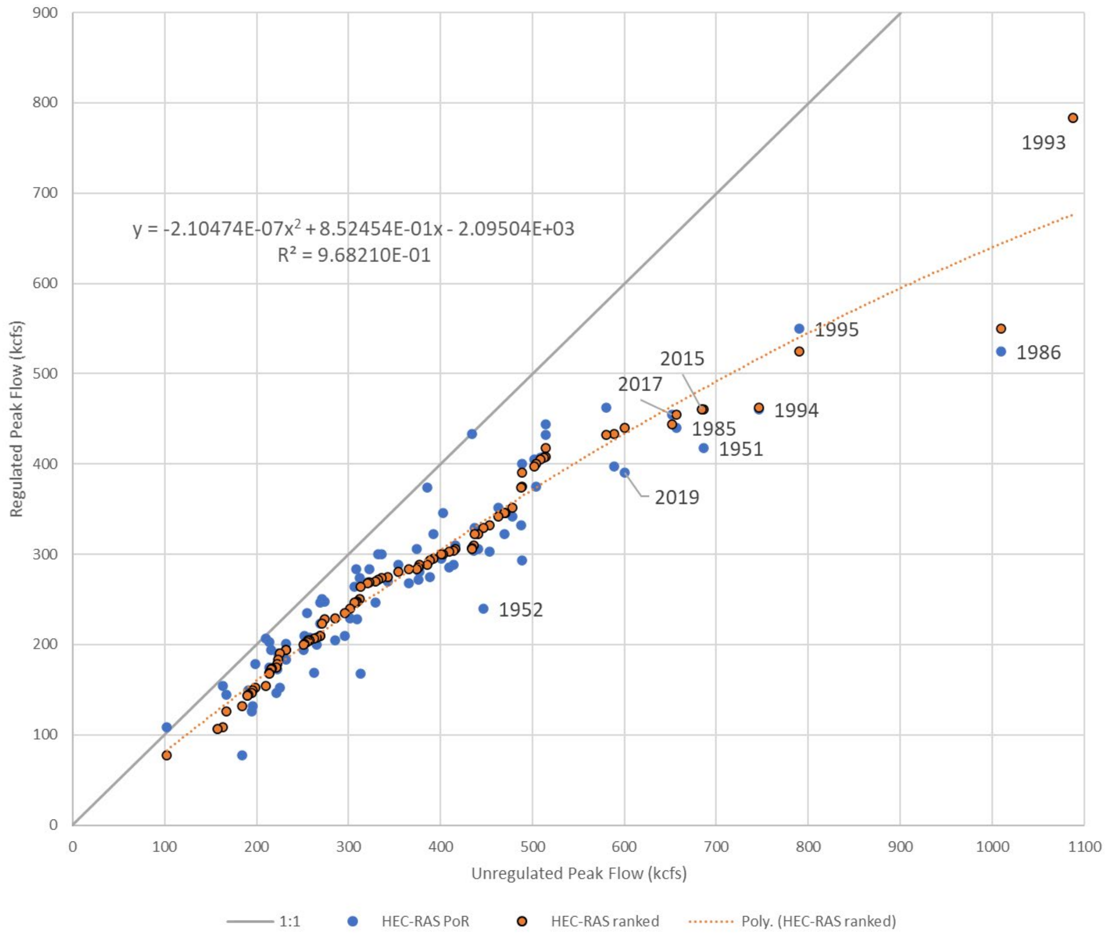


Figure 5-46. Hermann, MO HEC-RAS Routed Period of Record and Rank Ordered Annual Peak Flows with Trendline

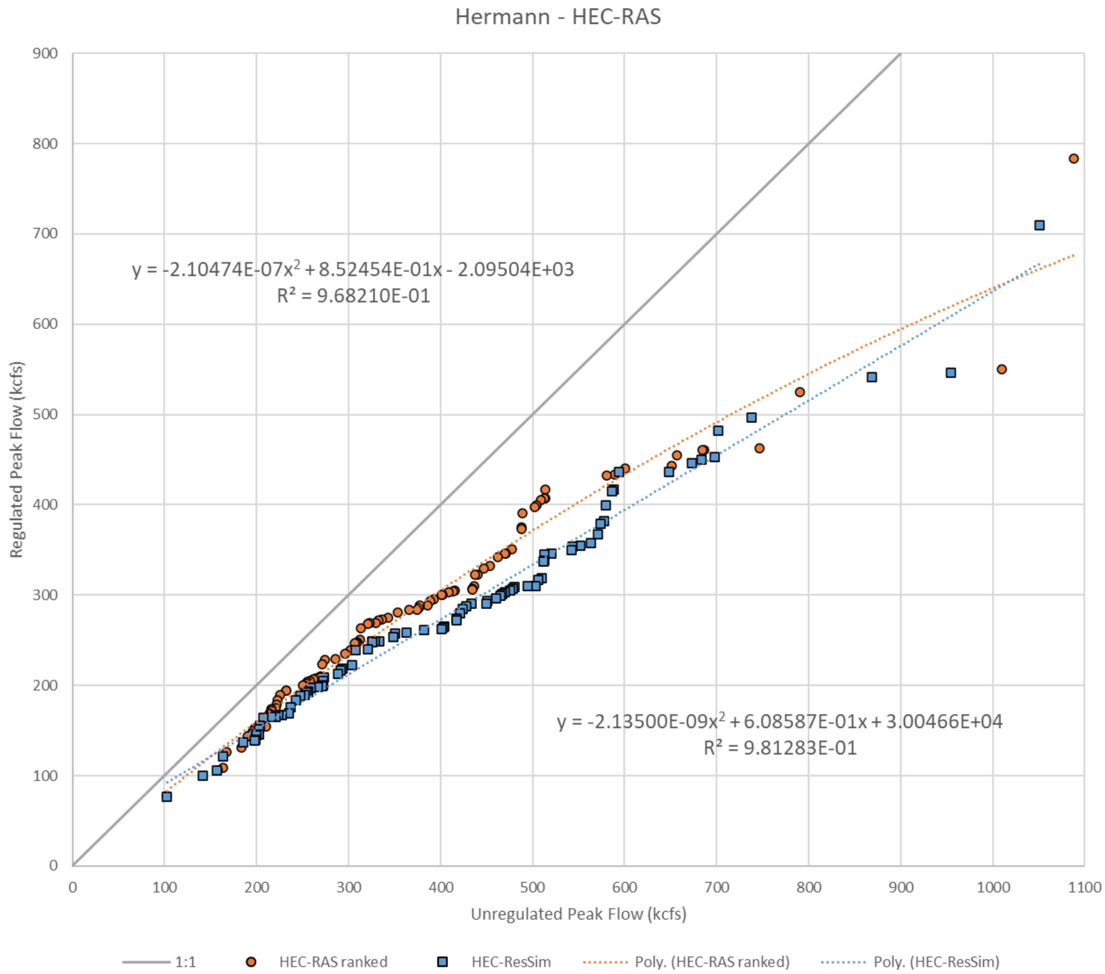


Figure 5-47. Hermann, MO Comparison of HEC-ResSim and HEC-RAS routed POR Ranked Flows

5.3.6.1 Addition of Scaled Floods, Hermann, MO

HEC-ResSim routed scaled floods were added to the regulated-unregulated plot to extend the relationship beyond the flows experienced in the period of record. Figure 5-48 shows the polynomial fit to the rank ordered scaled floods. The three largest scaled floods (1951 plus 2.0 standard deviations and 1993 plus 1.5 and 2.0 standard deviations) were removed when fitting the polynomial to the rank ordered data due to their effect on the upper end of the curve, and the lack of a need to define the transform to these extreme flows.
Figure 5-49 shows the polynomial fit to the combined dataset of the period of record and scaled floods. Figure 5-50 shows the final selected transform relationship in black with the polynomial fit to the combined rank ordered data as a dashed red line.

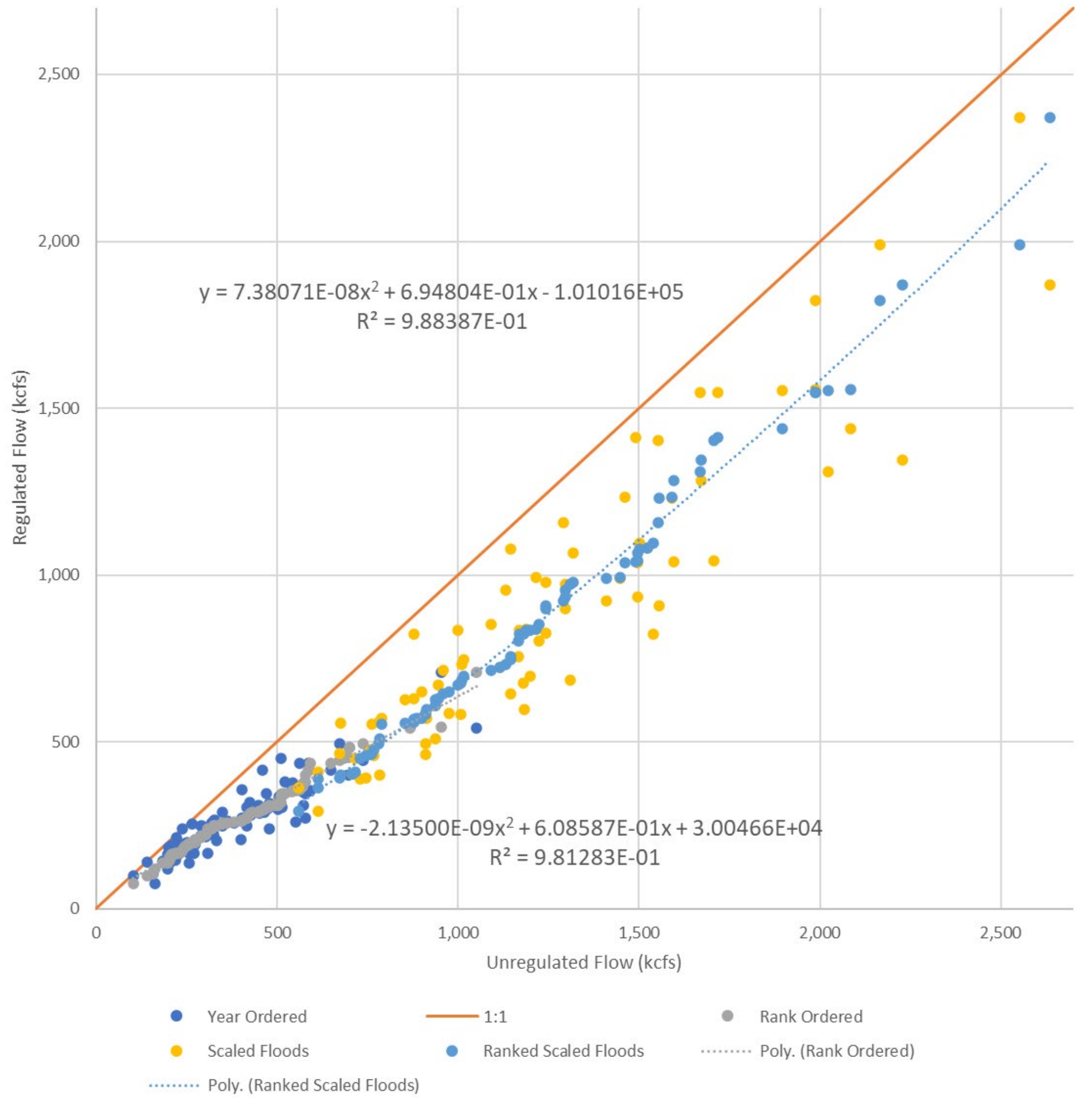


Figure 5-48. Hermann, MO HEC-ResSim Period of Record and Scaled Flood Events with Best Fit Polynomials

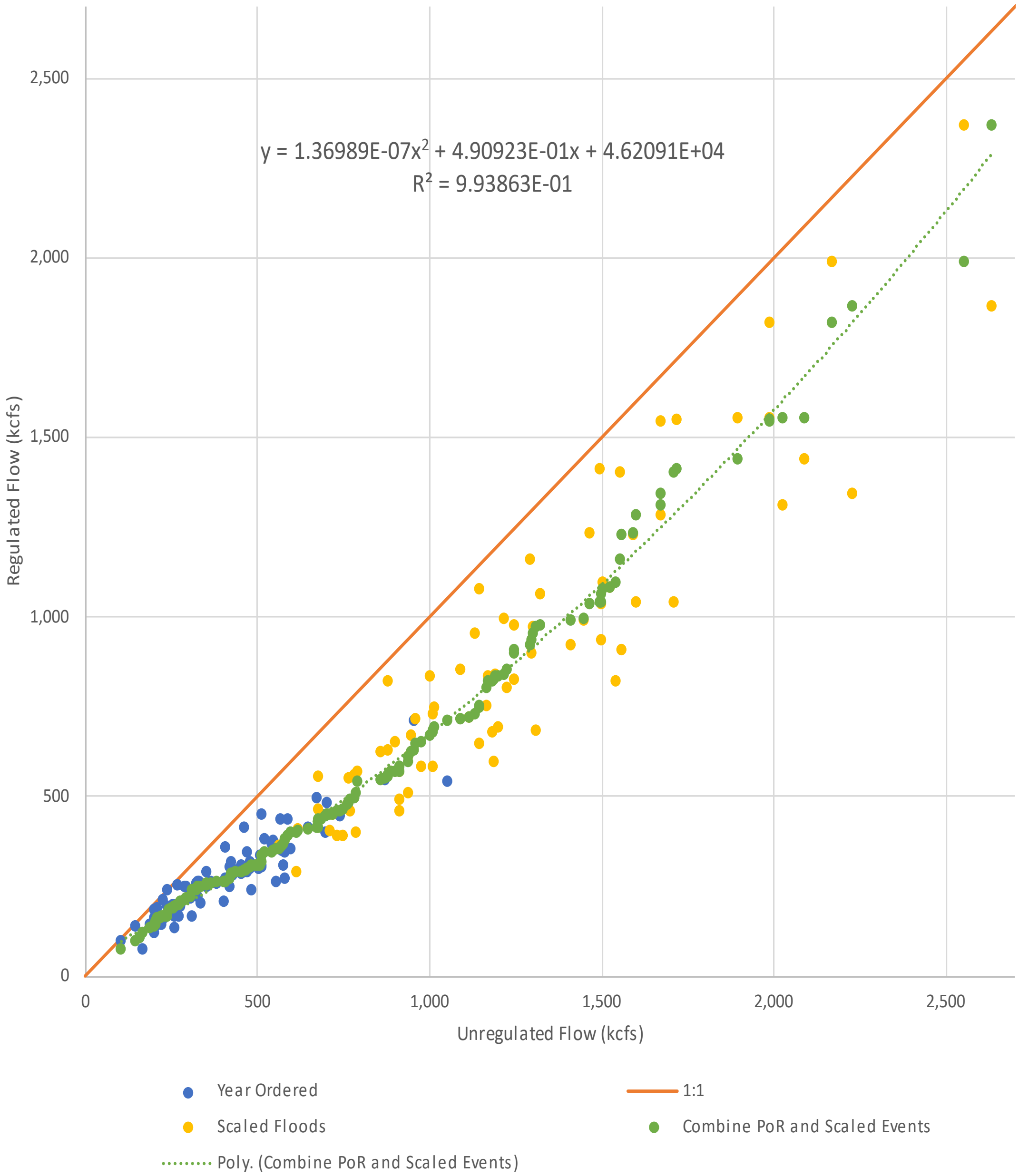


Figure 5-49. Polynomial Fit to Combined Period of Record and Scaled Floods for Hermann, MO

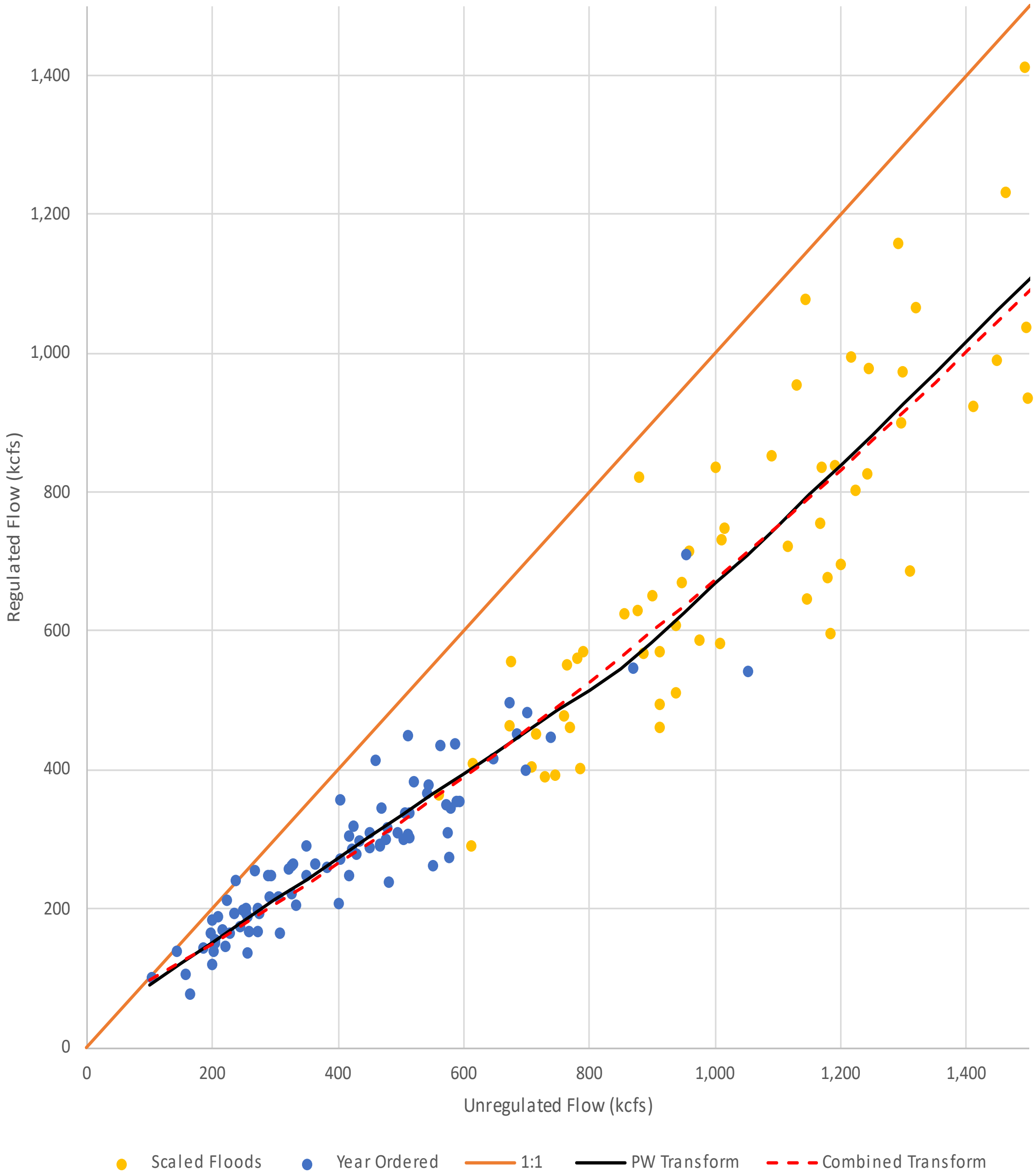


Figure 5-50. Final Unregulated-Regulated Transform for Hermann, MO

5.4 Regulated Flow Frequency Results, Transform Method

Results of the transformed regulated flow frequencies were compiled using Hirsch/Stedinger (H-S) plotting positions consistent with the Bulletin 17C flow frequency analysis for the regulated 90-year systematic POR. This was done by removing the historic peaks from the unregulated data from SSP and using the same plotting positions as the unregulated flows for the 90 years of regulated record. For comparison purposes, the Weibull plotting position of the regulated data was also shown, which tended to plot as more frequent for the same flow than if using the H-S plotting positions. Figures 5-51 through 5-60 present plots of the Transform Method, Regulated Flow Frequency Results as compared to the unregulated flow frequency curves for each of the 10 study gages. Table 5-1 presents the values for the regulated flow frequencies at each gage. As seen in the figures, the regulated flow frequencies plot lower than the unregulated flow frequencies, thus showing benefits of peak flow reduction provided by upstream dams. As seen in Figure 5-57, at the Kansas City gage, the transform relationship developed for Kansas City Levees (USACE 2021) was plotted for comparison to the current study results, which showed higher flows than the current study. The addition of more scaled floods in the current study, some producing lower regulated flows for a given unregulated flow, is the primary difference between the two relationships. This highlights potential uncertainty in developing relationships to transform the unregulated flows into regulated flows, as also seen in the scatter plots in the previous sections.

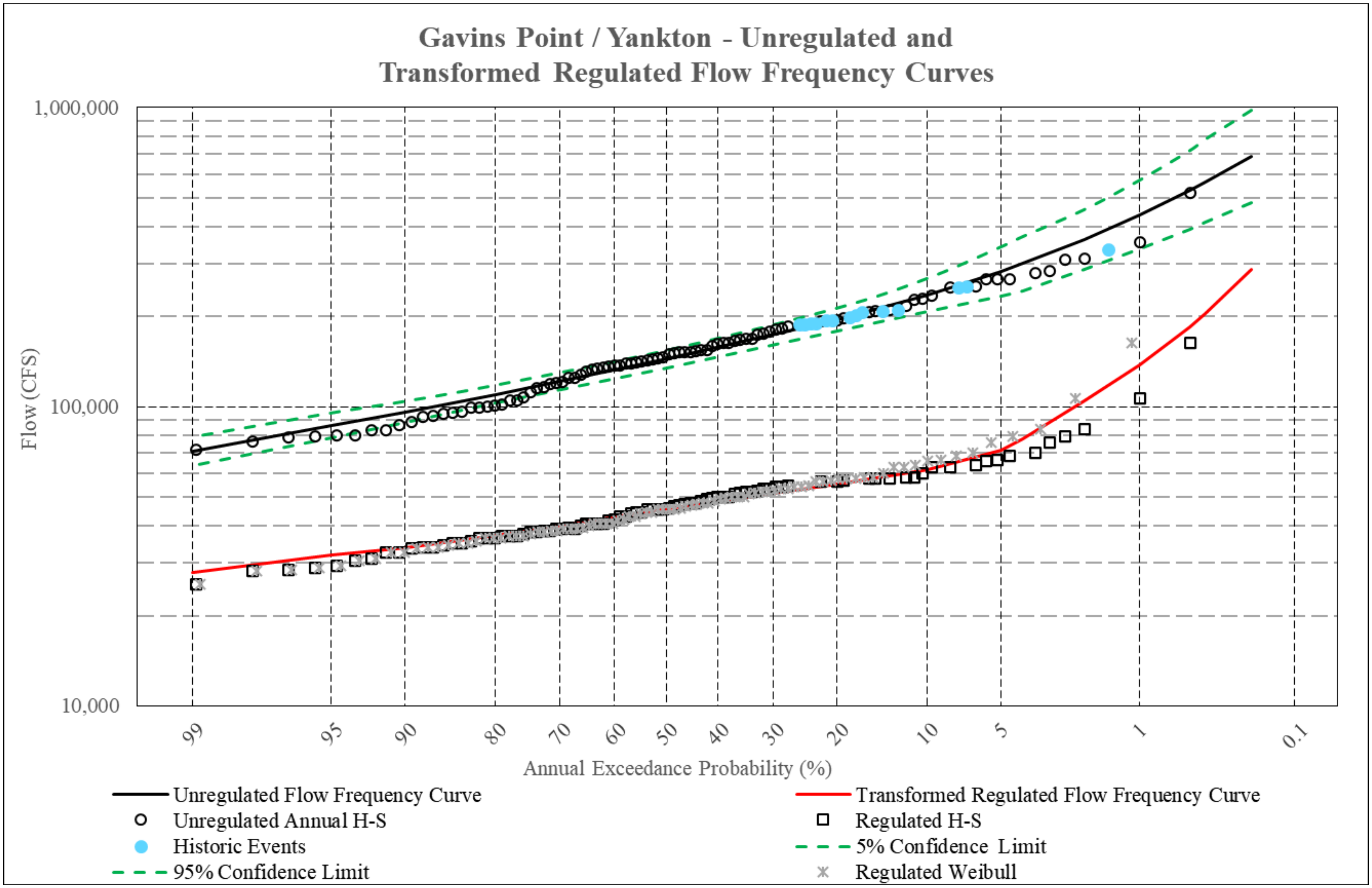


Figure 5-51. Gavins Point / Yankton – Unregulated and Transformed Regulated Flow Frequency Curves

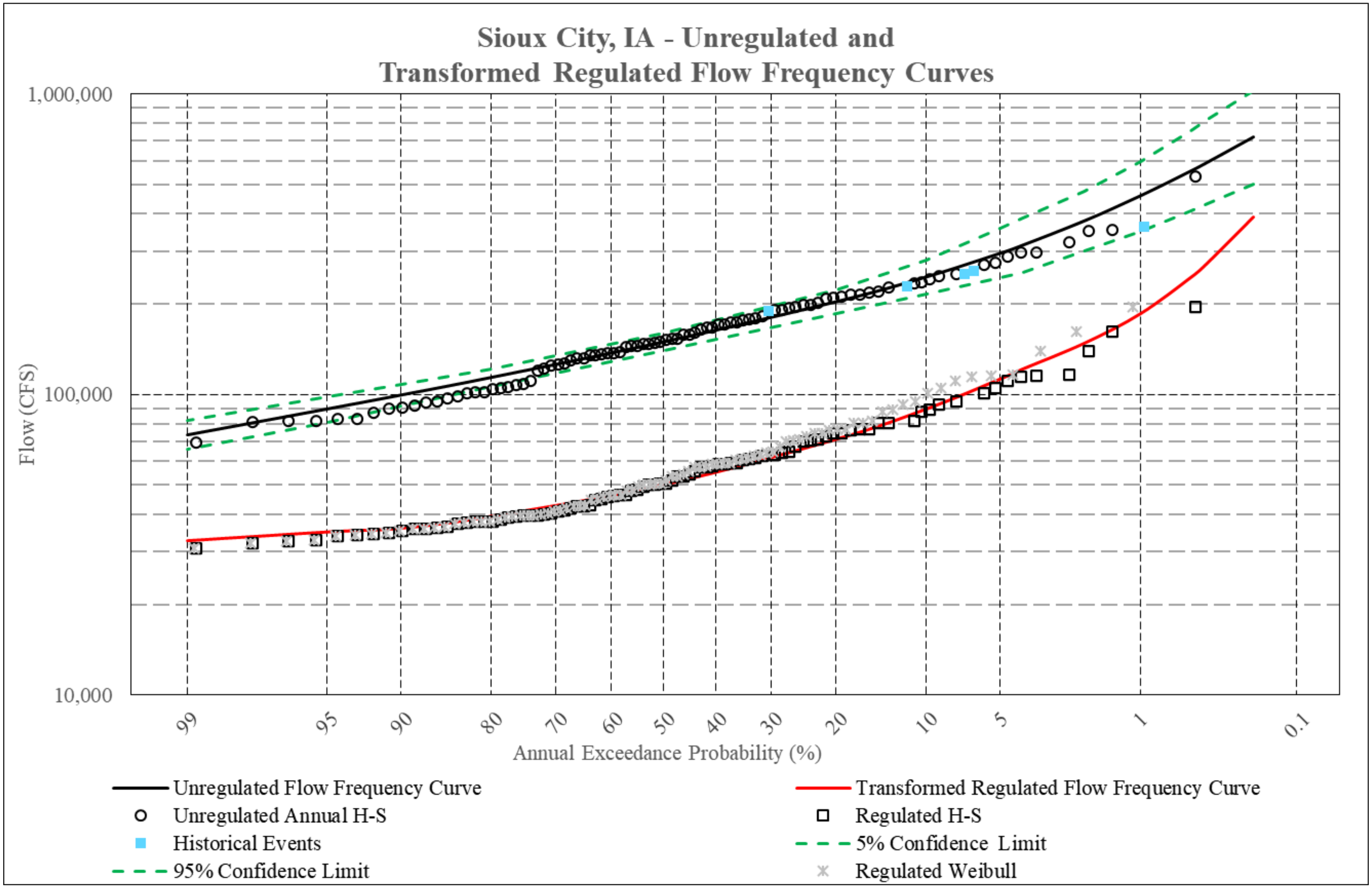


Figure 5-52. Sioux City, IA – Unregulated and Transformed Regulated Flow Frequency Curves

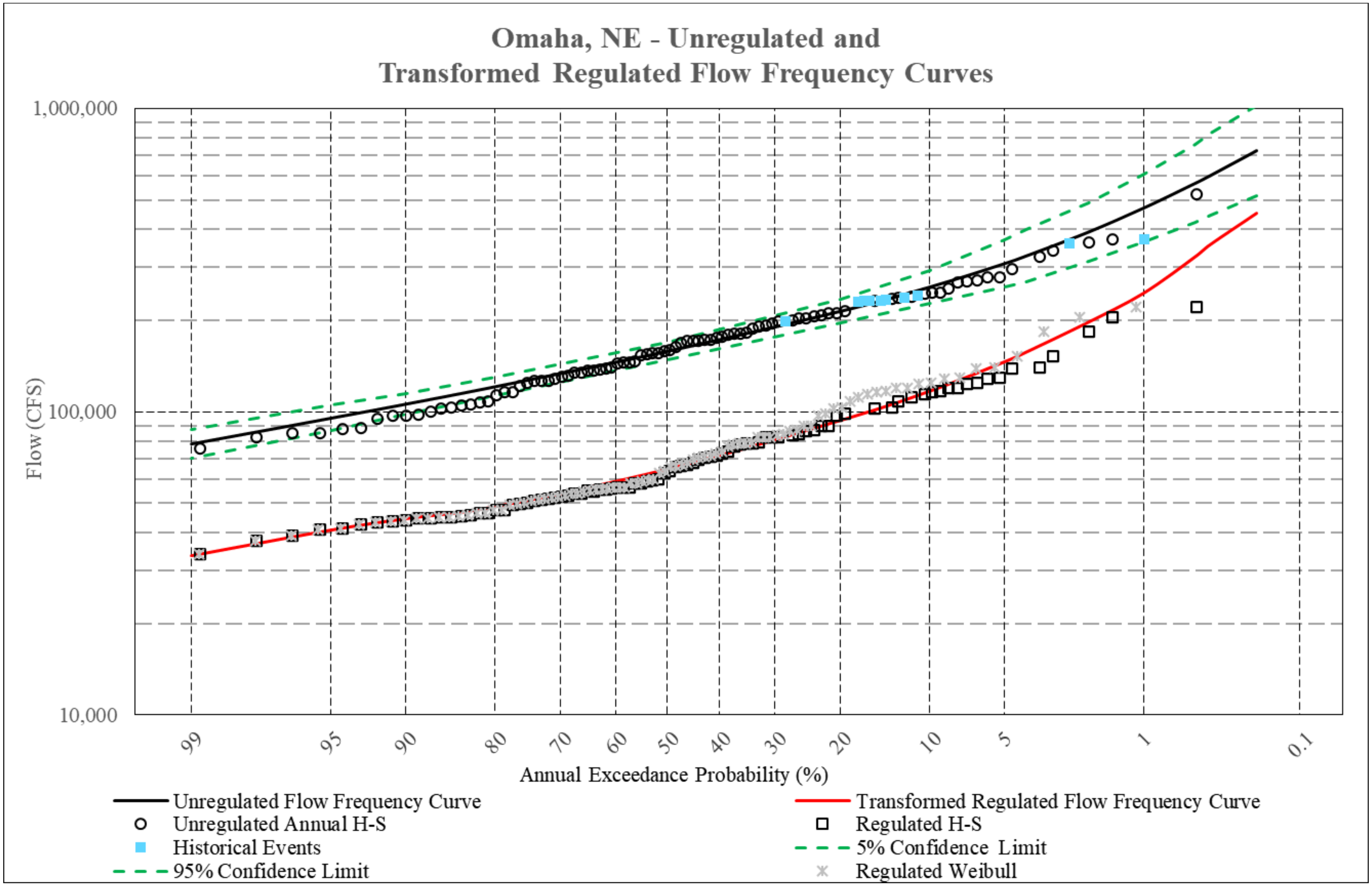


Figure 5-53. Omaha, NE – Unregulated and Transformed Regulated Flow Frequency Curves

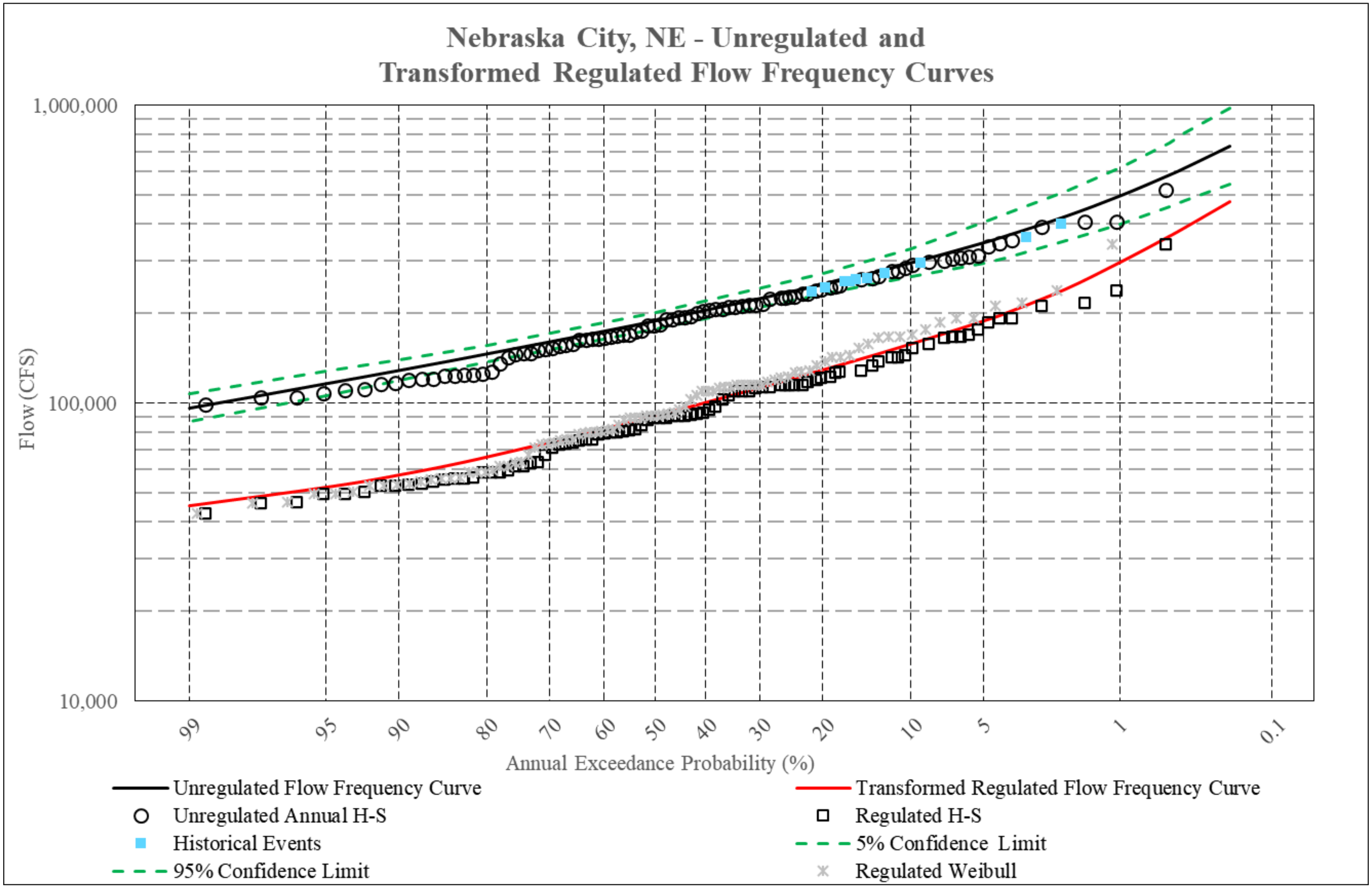


Figure 5-54. Nebraska City, NE – Unregulated and Transformed Regulated Flow Frequency Curves

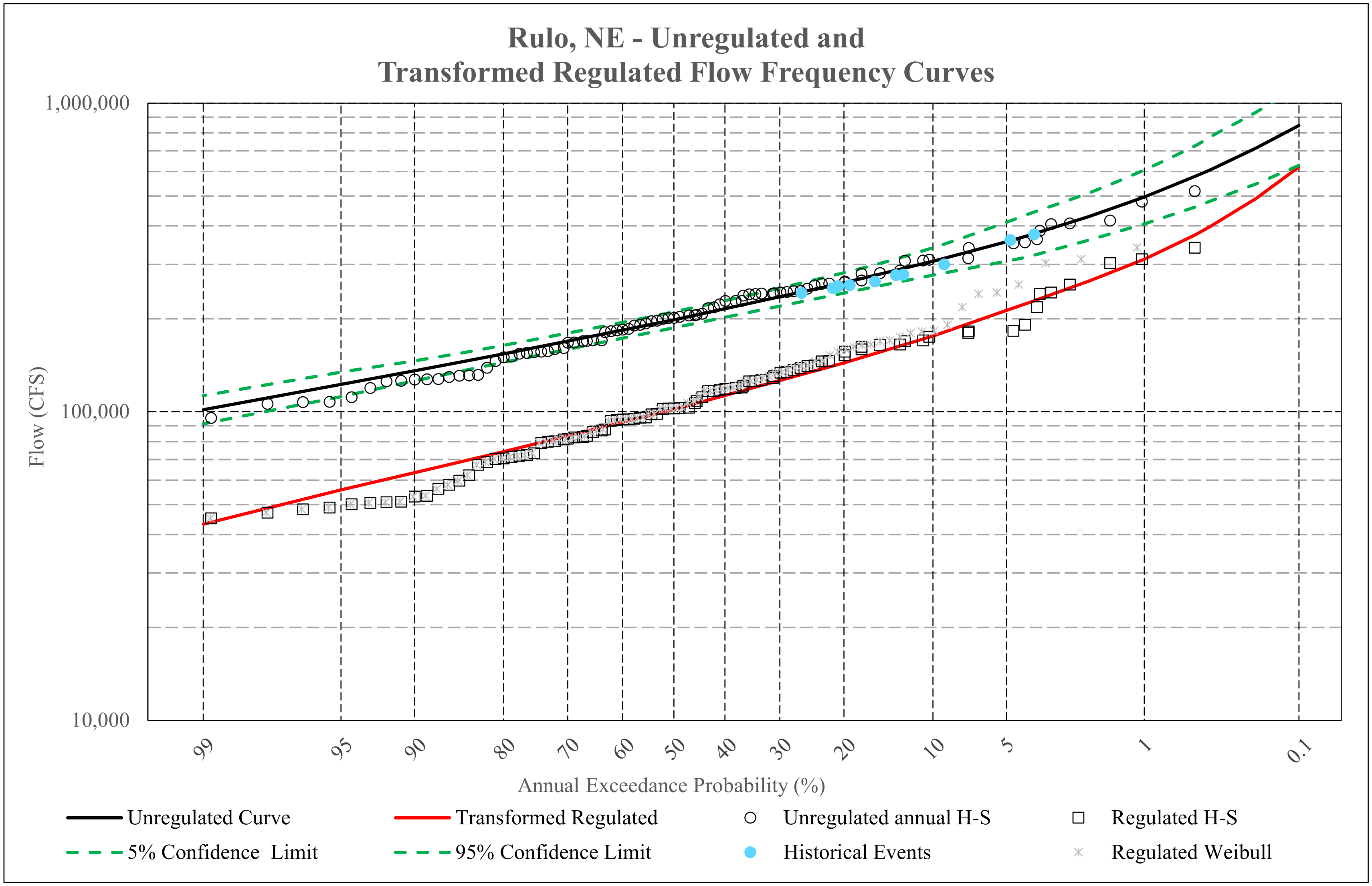


Figure 5-55. Rulo, NE – Unregulated and Transformed Regulated Flow Frequency Curves

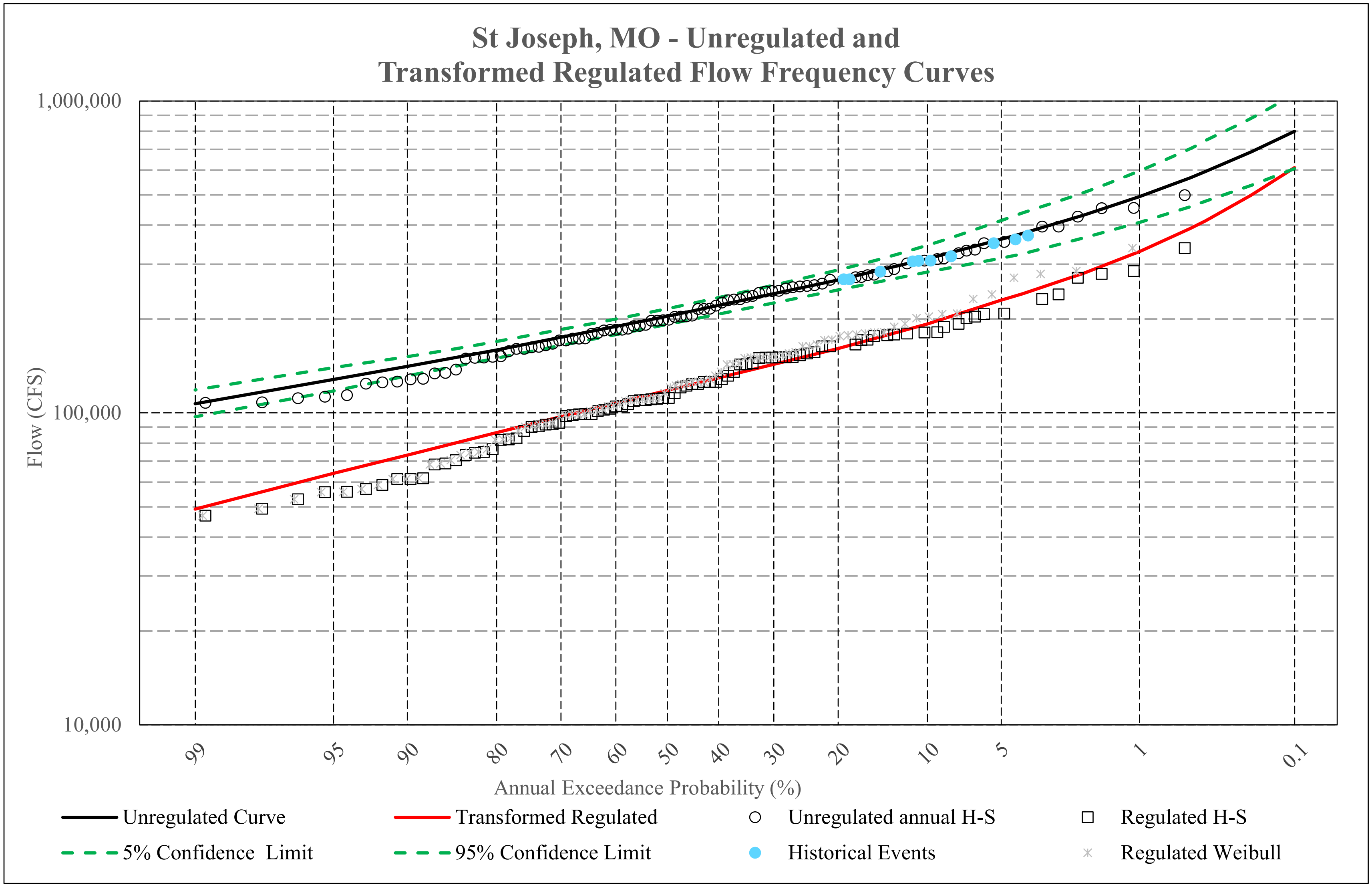


Figure 5-56. St Joseph, MO – Unregulated and Transformed Regulated Flow Frequency Curves

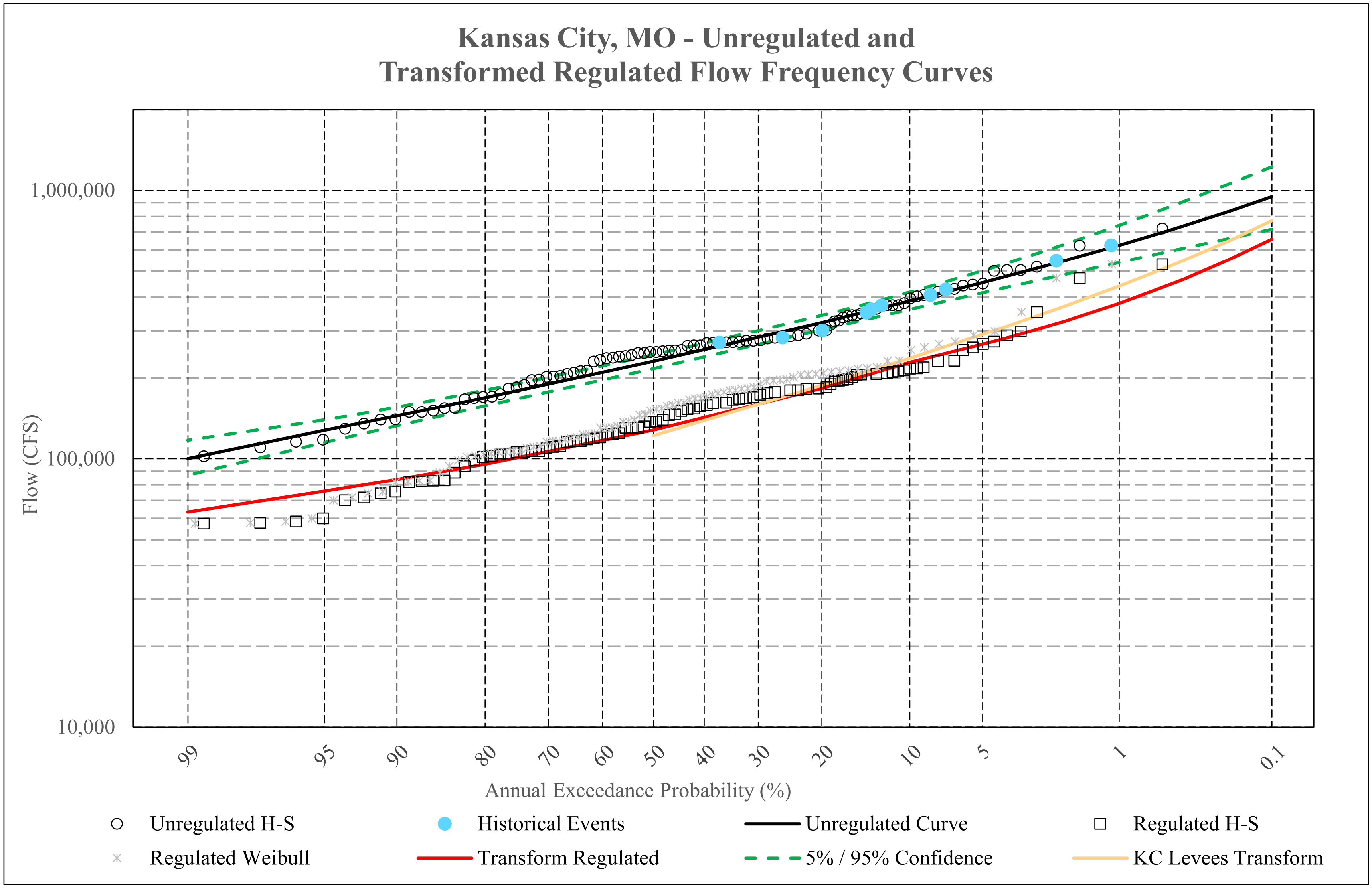


Figure 5-57. Kansas City, MO – Unregulated and Transformed Regulated Flow Frequency Curves

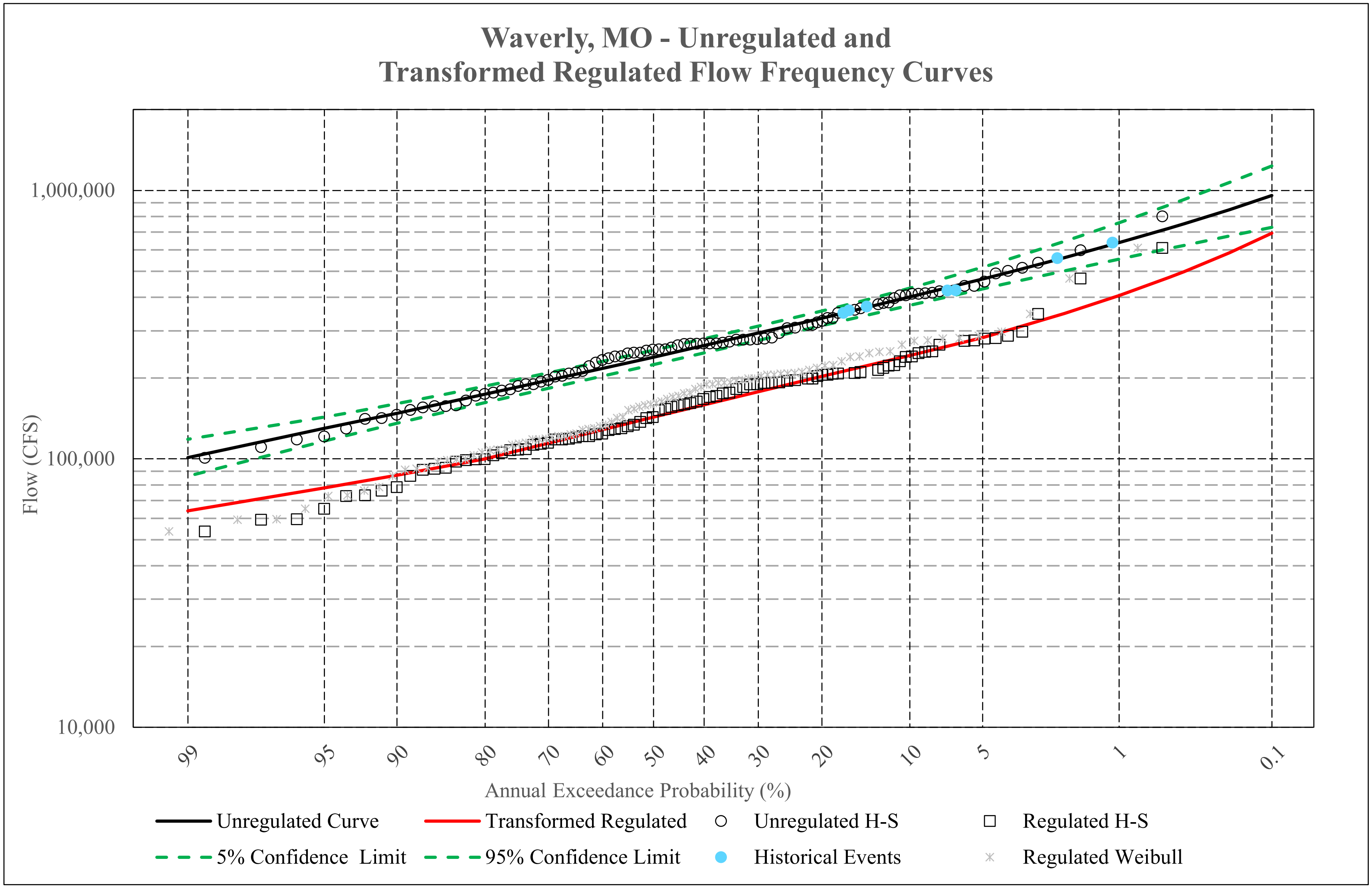


Figure 5-58. Waverly, MO – Unregulated and Transformed Regulated Flow Frequency Curves

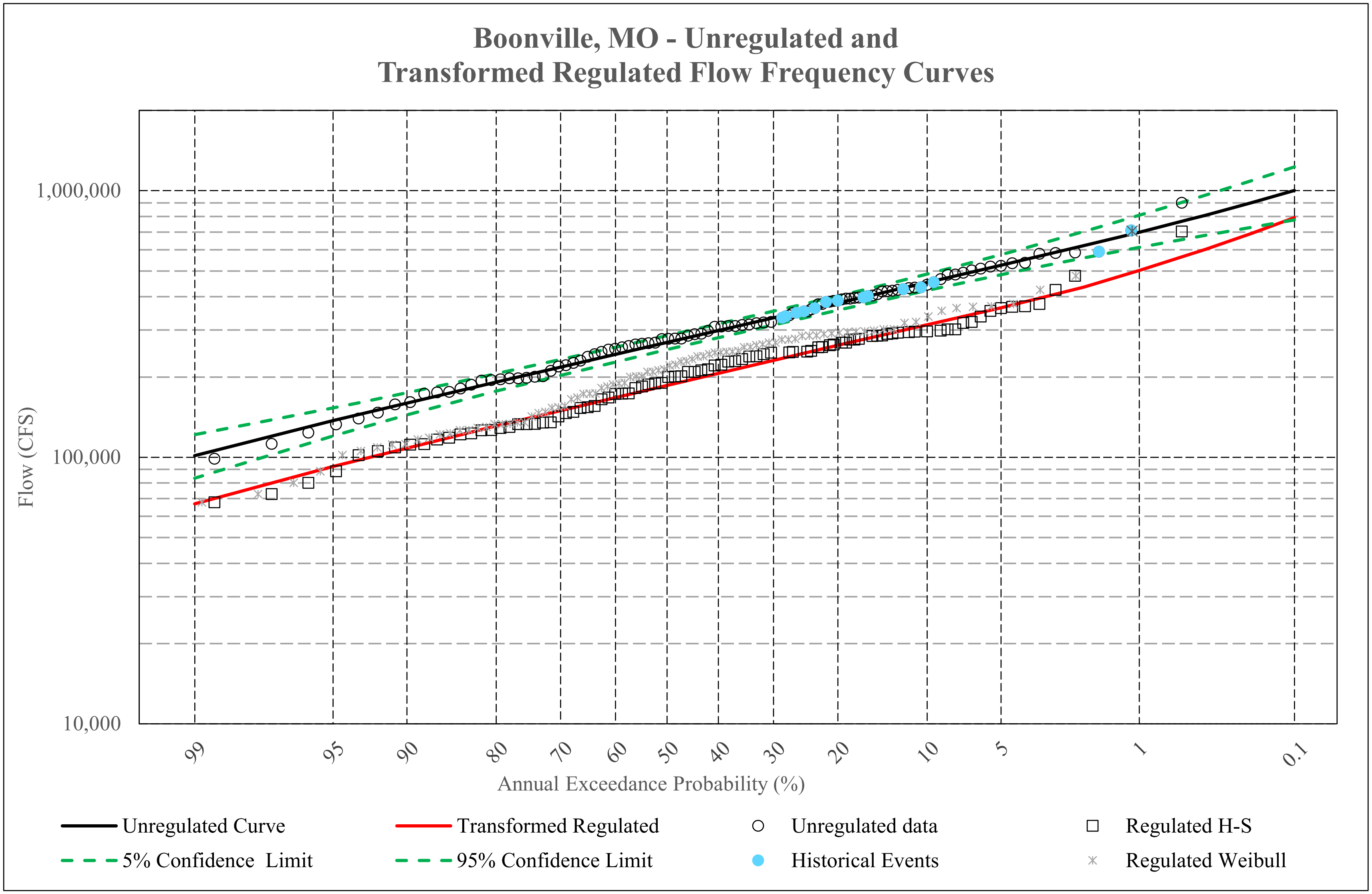


Figure 5-59. Boonville, MO – Unregulated and Transformed Regulated Flow Frequency Curves

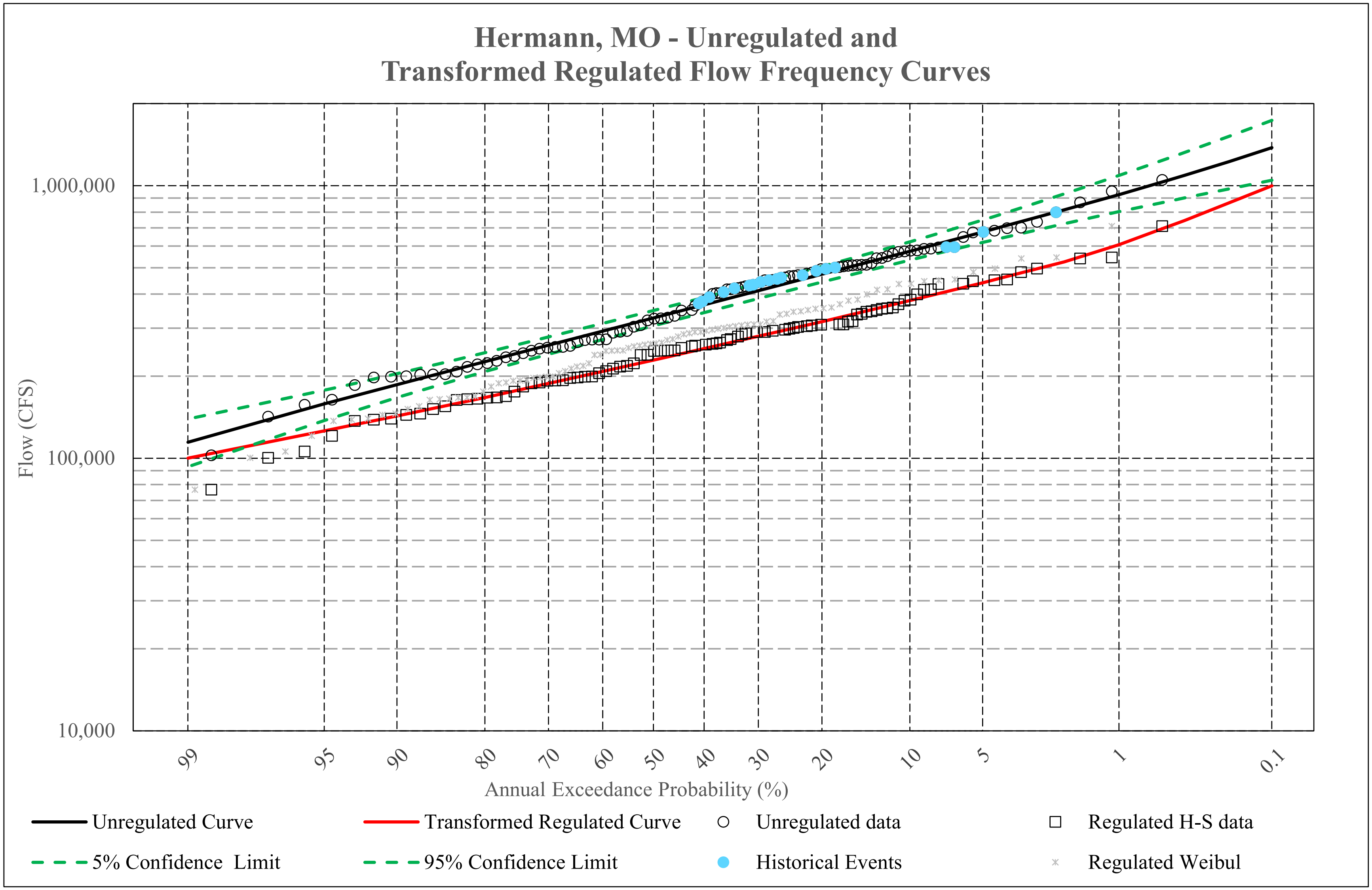


Figure 5-60. Hermann, MO – Unregulated and Transformed Regulated Flow Frequency Curves

Table 5-1. Transform Method Regulated Flow Frequency Curves, Expected Probability (Flow in CFS)

AEP(%)	Gavins Point	Sioux City	Omaha	Nebraska City	Rulo	St Joseph	Kansas City	Waverly	Boonville	Hermann
0.2	289,000	388,000	453,000	477,000	491,000	499,000	553,000	586,000	691,000	865,000
0.4	205,000	273,000	357,000	390,000	398,000	413,000	469,000	498,000	602,000	744,000
0.5	185,000	246,000	324,000	365,000	373,000	390,000	445,000	474,000	577,000	710,000
1	138,000	186,000	246,000	298,000	312,000	329,000	380,000	406,000	502,000	607,000
2	105,000	148,000	197,000	242,000	265,000	281,000	326,000	348,000	435,000	525,000
4	78,000	121,000	157,000	200,000	225,000	241,000	281,000	298,000	381,000	461,000
5	71,500	113,000	146,000	189,000	213,000	230,000	267,000	283,000	364,000	440,000
10	61,600	89,500	117,000	159,000	176,000	193,000	229,000	243,000	314,000	379,000
20	55,300	71,100	93,400	130,000	144,000	161,000	183,000	203,000	263,000	317,000
50	45,500	50,200	64,600	90,600	101,600	118,000	128,000	143,000	186,000	229,000
80	37,100	39,400	48,500	66,000	74,200	86,500	95,400	100,000	131,000	167,000
90	33,800	36,000	44,300	57,500	63,400	73,200	83,700	87,000*	108,000	143,000
95	31,800	35,000	40,600	52,300	55,800	64,000	75,800	78,000*	92,300	126,000
99	27,900	32,700	33,400	45,300	47,000*	49,200	63,300	64,000*	66,900	100,000

*Includes a graphical adjustment scaled between upstream and downstream gages to smooth resultant low flows

6. Monte Carlo Analysis with HEC-WAT

Previous Missouri River planning studies such as ManPlan EIS utilized a POR simulation approach. The Missouri River POR includes a variety of flood and extended droughts that gave a wide assessment of impacts to operations. However, the POR is always in the same order (e.g. 2011 always follows 2010) and large flood events tend to "reset" the reservoir system by refilling the reservoirs after droughts or drawdowns due to operational changes; therefore, any operational changes tended to have a select number of years where changes could occur, and impacts observed. Comments were raised during an external review of the ManPlan EIS that the number of times an operational change within several of the alternatives was able to run was not sufficient to adequately quantify changes in risk. The USACE acknowledges that while the POR approach was adequate for most situations, a different approach would be needed to quantify risk. Therefore, the USACE committed to develop a Monte Carlo approach for both ResSim and RAS so changes in risk due to operational changes could be adequately quantified.

A Monte Carlo analysis is conducted by first approximating a known distribution with 1000s of events and then simulating or transforming each event to approximate an unknown distribution. For this study, unregulated flow frequency is estimated using the Bulletin 17C procedures and individual events were used to approximate that distribution. Those events were then simulated with the MR ResSim model to calculated regulated flows for those events, which can be used to estimate regulated flow frequency. Figure 6-1 depicts the approximation of unregulated flow frequency with many events that are then transformed into regulated events after simulating through the MR ResSim model.

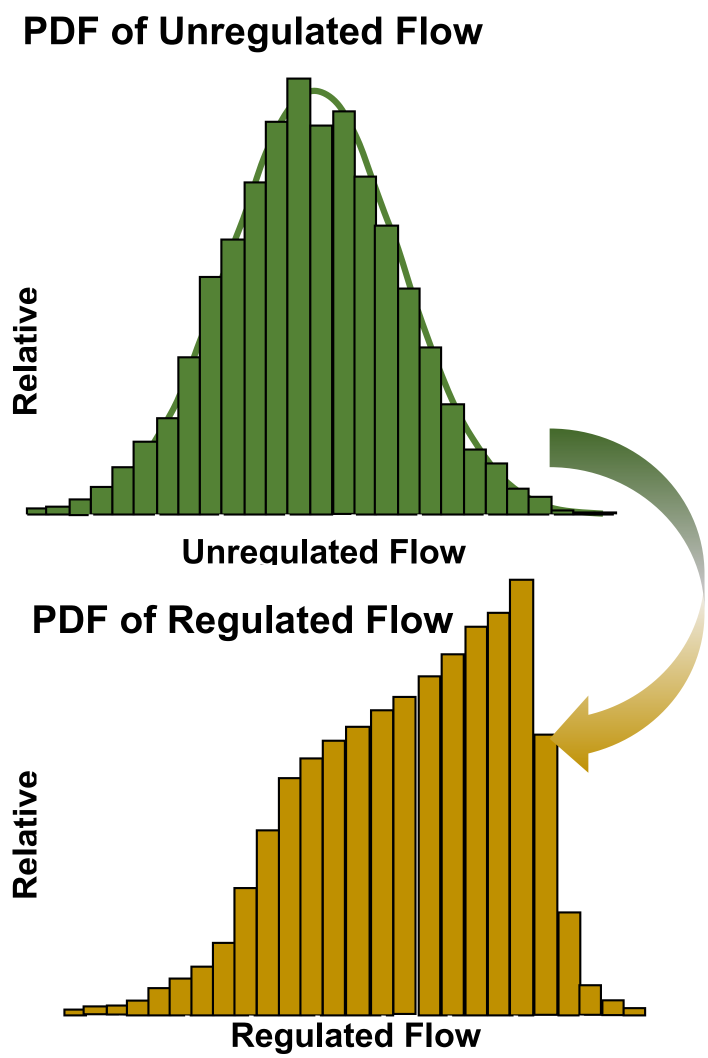


Figure 6-1. Graphic Depicting General Monte Carlo Procedure

The Monte Carlo approach chosen for this study utilizes Watershed Analysis Tool HEC-WAT (WAT) to perform a classic bootstrap sampling events to simulate 1000s of events with various reservoir conditions, forecasts, and flows. This method randomly chooses from pre-defined hydrologic events or years from either the historical sample and/or carefully created synthetic events (years), forming a new period of system-wide flows to simulate. This method of bootstrapping is also known as sampling from an empirical probability distribution formed by the historical record. When an event is sampled, the hydrology of that year is used "whole," for the entire event and for all locations in the watershed. This assures that the flows in one part of the watershed can occur with flows in another, because they either did occur that way historically, or have been judged to be feasible in the creation of a synthetic event. Further, when sampling entire events, flows that occurred at the beginning of the event remain with the flows that occurred at the end of the event.

Previous Monte Carlo efforts conducted by USACE centered around the concept that one event was equivalent to one year where reservoir conditions were reset after each event. Events were sampled from a historical sample based on the historical POR with each event having the same probability (1/n) of occurrence. The historical sample was supplemented with synthetic, scaled events of a defined probability based on volume-probability curves in order to capture the upper end of the flow distribution. Events are combined into lifecycles and lifecycles are grouped into realizations with all the events used to produce the mean frequency curve.

The Missouri River Basin is one of the largest and hydrologically diverse basins in the country. Therefore, the Missouri River mainstem reservoir system was designed to handle widely varying runoff by allocating 16.3 million acre-feet (MAF) of annual flood control and multiple use storage and 38.5 MAF of carryover and multi-use storage. The carryover storage allows the reservoirs to draft storage during extended droughts, ensuring all authorized purposes are still met. Due to this carryover storage, a modification to the previous Monte Carlo approach was needed. Instead of a lifecycle consisting of 50 separate events, each one year in duration, a lifecycle consisted of 50 events simulated as a 50-year continuous simulation so that the model could capture extended droughts and flood events with varying reservoir conditions. Lifecycles were still grouped into realizations and all events were used to produce the mean frequency curve.

As stated in preceding paragraphs, previous Monte Carlo approaches based the historical sample on the historical POR. The historical POR can create limitations since the historical POR may not be diverse enough to quantify the upper end of the frequency curve with confidence. In this study, the historical sample was bolstered with 500 additional events from a synthetic flow record called the Big Bucket. The events in the Big Bucket were generated by "scrambling" the historical POR – randomly joining different years of flow in different regions of the Missouri River Basin and different seasons of a year, while maintaining the original spatial and temporal correlations. Development of the Big Bucket is described in more detail in Section 6.1. The resulting historical sample with both the historical POR and Big Bucket events is a much richer sample of potential flows throughout the basin than the original historical sample. Synthetic, scaled events were also used to further supplement historical sample to capture the upper end of the flow distribution. Figure 6-1 shows the general process followed for the WAT Monte Carlo methodology that will be discussed in more detail in the coming sections.

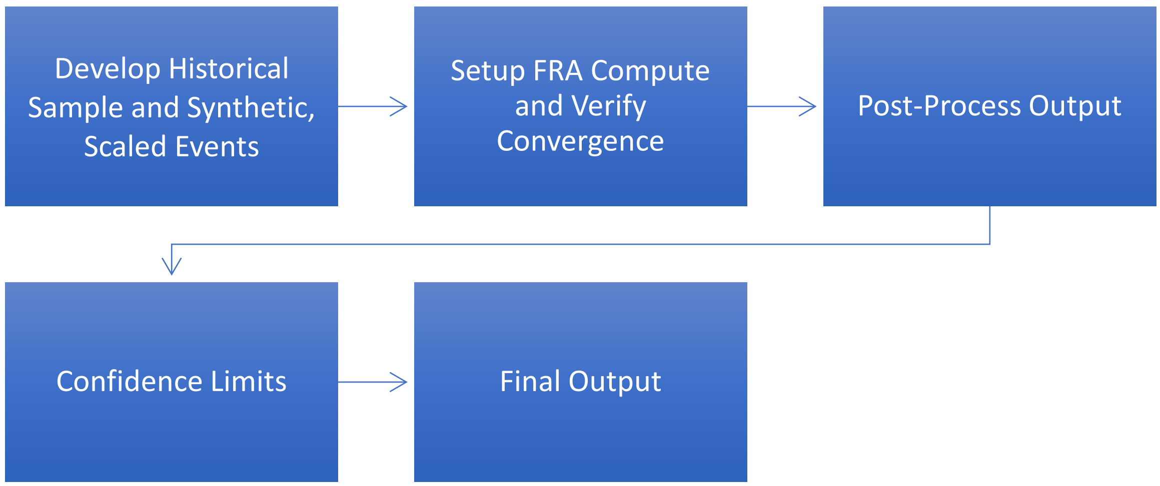


Figure 6-2. General WAT Monte Carlo Process

6.1 Synthetic Flow Record (Big Bucket)

Currently, the "historical/synthetic bootstrap" method within the WAT can only choose events that are "whole" in space and time. The Missouri River Basin is extremely large and spans widely spaced regions that can experience hydrology that is somewhat independent of other regions. To consider a richer description of the hydrology, sampling was completed external of the WAT to produce the Big Bucket. The synthetic flow record contained flows that occurred in one region and in one year combined with flows that occurred in another region in a different year. This sampling would make an event that is, for example, 1972 flows in an upper part of the basin and 1959 flows in a lower part of the lower basin. While the hydrology in different regions is somewhat independent, it is not perfectly independent (correlation equal to zero), and so what spatial correlation exists between the volume of flow in the different regions must be maintained in this random sampling. Thus, the random selection of years between the regions must be done by correlated sampling using computed spatial correlations.

In addition to keeping the watershed spatially whole, the current "historical/synthetic bootstrap" sampling method used by the WAT keeps the event temporally whole. However, in addition to combining flows from different years for different regions, the Missouri River Monte Carlo bolstered the available hydrology by creating a synthetic dataset external of the WAT based on three seasons: early spring, late spring, and remainder. The external sampling allowed the seasons from one year to be matched with seasons from a different year. For example, the early spring flows from 1976 could be followed by the late spring flows of 1992 and the remainder flows from 1930. Combining seasons from different years in a given region also requires that the random sampling maintain correlation, in this case serial or auto-correlation capturing the relationship of one season to the next.

Because the "historical/synthetic bootstrap" method within the WAT does not currently allow for randomly selecting different years of hydrology for each region of the watershed, or for each season of the year, a synthetic dataset was created externally. That dataset randomized four separate regions of the watershed, see Figure 6-1 and Table 6-1, over 3 different seasons, see Table 6-2. The four regions were separated at gages along the Missouri River and split based on runoff drivers or geographic area. The mountainous region is the drainage area above Garrison Dam, where runoff is driven by the mountain snowpack. The northern plains region is comprised of the drainage area between Garrison Dam and Sioux City, IA, where runoff from the plains snowpack occurs. The southern plains and Missouri hills regions are the drainage areas from Sioux City, IA to Rulo, NE and Rulo, NE to Hermann, MO, respectively.

Each season is also split based on runoff drivers where the early spring season (01Mar to 30Apr) is typically when runoff from the plains snowpack runoff occurs. The late spring season (01May to 31Jul) is typically when runoff from the mountain snowpack occurs. These two seasons represent the bulk of the runoff that occurs in the Missouri River Basin so the remainder season (01Aug to 28Feb) captures the remainder of the annual runoff.

When the sampling is complete, the Big Bucket is 500 events of synthetic data that maintains the spatial correlation between the four regions in each season and maintains the serial correlation of each season to the previous season in each region. The Monte Carlo simulation within the WAT uses a historical sample comprised of both the historical POR with full-year random sampling that maintains the annual serial correlation, defining an event as starting on March 1 and continuing through the end of September. In the Missouri River Basin, this period represents when most of the runoff occurs.

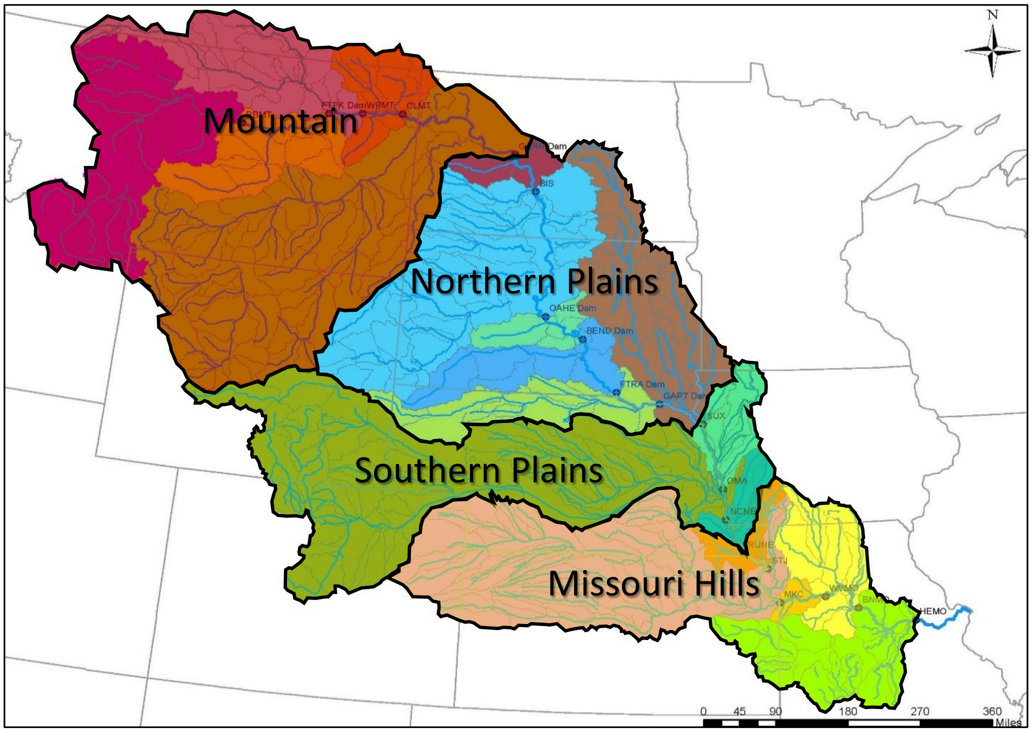


Figure 6-3. Regions Represented in the Big Bucket

Table 6-1. Regions Represented in the Big Bucket

Region	Stations
Mountains	Above Garrison Dam
Northern Plains	Garrison Dam to Sioux City, IA
Southern Plains	Sioux City, IA to Rulo, NE
Missouri Hills	Rulo, NE to Hermann, MO

Table 6-2. Seasons Represented in the Big Bucket

Season	Dates
Early Spring	01Mar – 30Apr
Late Spring	01May – 31Jul
Remainder	01Aug – 28Feb

6.1.1 Historical POR Correlation

Any synthetic dataset could be created and used as the historical sample within the WAT, but in order to ensure it was representative of the historical POR, the spatial and serial correlations of the historical POR were first analyzed. To do this, the sum of volume of flow at all locations within a region for the full season was calculated for each of the four regions and three seasons. This volume was used for computing and maintaining both spatial and serial correlation. Spatial correlations between regions for each season are shown in Table 6-3. Serial correlations for each season and each region are shown in Table 6-4. Each value in Table 6-4 is the serial correlation between the season in that row and the season in the row above it. The season before early spring is remainder, defining the first row.

Table 6-3. Region to Region Spatial Correlations for Each Season

Season		Spatial Correlation			
		Mountain	**N. Plains**	**S. Plains**	**Mo. Hills**
Early Spring	Mountain	1.00			
	N. Plains	0.57	1.00		
	S. Plains	0.27	0.56	1.00	
	Mo. Hills	0.20	0.39	0.71	1.00
Late Spring	Mountain	1.00			
	N. Plains	0.60	1.00		
	S. Plains	0.29	0.77	1.00	
	Mo. Hills	0.25	0.51	0.67	1.00
Remainder	Mountain	1.00			
	N. Plains	0.41	1.00		
	S. Plains	0.45	0.80	1.00	
	Mo. Hills	0.37	0.49	0.66	1.00

Table 6-4. Season So Season Serial Correlation

Season	Serial Correlation			
	Mountain	**N. Plains**	**S. Plains**	**Mo. Hills**
Early Spring	0.40	0.49	0.53	0.43
Late Spring	0.52	0.61	0.69	0.39
Remainder	0.69	0.76	0.76	0.43

6.1.2 Generating Synthetic Flow Record

The method of random sampling used to create the Big Bucket uses a bootstrap procedure that re-samples from the 90-year historical POR. Thus, for any region and any season, the frequency of flows will mimic the frequency of that historical record, and additionally will never draw a flow volume that is greater than the largest or less than the smallest volume in the record. However, the sum of flows in the four regions, reflecting the state of the entire watershed, can be more extreme (either larger or smaller) than the observed extremes, and is in fact a goal of this re-sampling procedure. This outcome can be seen for the Early Spring season in Figure 6-2. Purple, gray, orange and blue solid circles show the historical POR volumes in the four regions, and the same color hollow diamonds show the 500 sampled values. Note that the largest and smallest values simply repeat the historical extreme so there are plateaus in the sampling at the tails of the curve. The green markers represent the sum of flow volume in all regions, and these are both larger and smaller than the historical extremes at either end of the frequency curve.

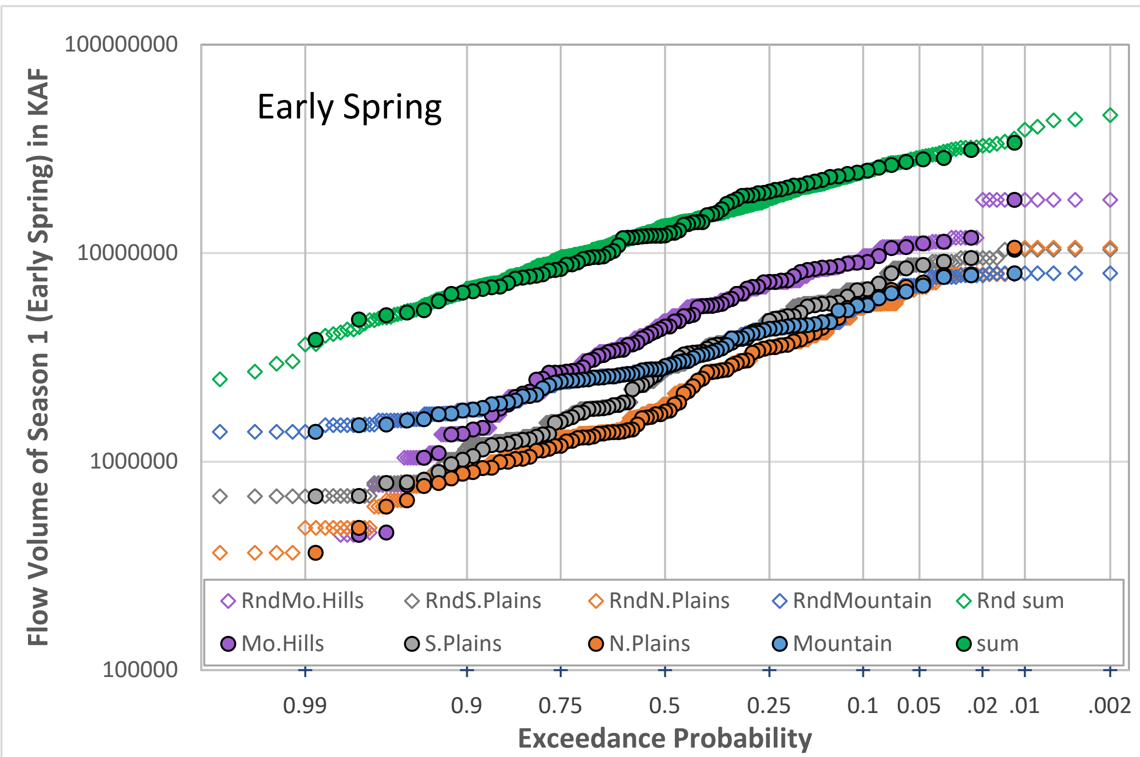


Figure 6-4. Historical and Re-sampled Frequency Curve for Four Regions and the Sum of All Regions

The sampling approach that produced the results in Figure 6-2 was developed for this study. This method that bootstraps (re-samples) the historical record, combines correlated sampling that maintains spatial correlation with a Periodic AR(1) Autoregressive Lag 1 model that maintains serial correlation. The method first uses a multivariate joint Normal distribution with a correlation matrix for each season (made up of the spatial correlations between the regional flow volumes in that season shown in Table 6-3) to transform independent Z ~ N[0,1] values to correlated Z ~ N[0,1] values. Those random, correlated joint Normal variates are then used to generate the random error term of a periodic AR(1) model for each region to produce standard Normal values for each season with specified serial correlation. Note, the stream of values doesn't have a single serial correlation, but being periodic instead has a correlation value applied to each transition from season A to season B, with a different value for season B to season C. Finally, the serially correlated Standard Normal values are transformed to Uniform[0,1] and used to re-sample historical years based on the regional flow volumes in the specified season.

The approach can be described as a series of steps as follows with an example pattern of random sampling to generate 500 years with 3 seasons in each year, with 4 watershed regions shown in Table 6-5:

- Step 1 is generating spatially correlated Standard Normal random values described in Section 6.1.2.1
- Step 2 is generating series of serially correlated Standard Normal random values that maintain the spatial correlation described in Section 6.1.2.2
- Step 3 is transforming Standard Normal N[0,1] values to Uniform[0,1] values described in Section 6.1.2.3
- Step 4 is using those U[0,1] random values to re-sample the appropriate season from the historical record described in Section 6.1.2.4

Table 6-5. Pattern of Sampling to Generate 500 Years with 3 Seasons in Each Year, with 4 Watershed Regions

Year 1	Season 1	*region 1, 11*	*region 2, 11*	*region 3, 11*	*region 4, 11*
Year 1	Season 2	*region 1, 12*	*region 2, 12*	*region 3, 12*	*region 4, 12*
Year 1	Season 3	*region 1, 13*	*region 2, 13*	*region 3, 13*	*region 4, 13*
Year 2	Season 1	*region 1, 21*	*region 2, 21*	*region 3, 21*	*region 4, 21*
Year 2	Season 2	*region 1, 22*	*region 2, 22*	*region 3, 22*	*region 4, 22*
Year 2	Season 3	*region 1, 23*	*region 2, 23*	*region 3, 23*	*region 4, 23*
Year 3	Season 1	*region 1, 31*	*region 2, 31*	*region 3, 31*	*region 4, 31*
Year 3	Season 2	*region 1, 32*	*region 2, 32*	*region 3, 32*	*region 4, 32*
Year 3	Season 3	*region 1, 33*	*region 2, 33*	*region 3, 33*	*region 4, 33*
Year 500	Season 3	*region 1, 5003*	*region 2, 5003*	*region 3, 5003*	*region 4, 5003*

The italic "region K, ij" represents a value from random sampling, for region K in year i and season j. Thus, for 500 years of 3 seasons each, this table has 1500 rows, and sampling is done in each row for each for the 4 regions of the watershed. The product of the sampling is ultimately a historical year for each region in each season, whose flows will be used to populate that season in the 500-year synthetic record.

6.1.2.1 Spatial Correlation: Use of the Multivariate Normal distribution for Correlated Sampling

In this step spatially correlated Standard Normal Z ~ N[0,1] values are generated, one for each subbasin in each time period. Because there are to be 500 events of 3 seasons each, this requires 1500 random Z values per region. Four regions require 6000 total Z values. The notation N[0,1] refers to a Normal distribution with mean = 0 and standard deviation = 1, otherwise known as the standard Normal distribution.

Spatially correlated Z values come from correlated sampling that makes use of the multivariate Normal distribution. As described below, first independent (uncorrelated) arrays Z ~ N[0,1] are generated, and then they are transformed through the multivariate Normal distribution to maintain the specified cross-correlations.

- We have computed correlation matrix = Σ
  - Σ is defined for each season by computing correlation of full-season regional volumes, found in Table 1
- We want a matrix **X** ~ MN(0, Σ) of correlated random values
  - MN is multivariate Normal, matrix **X** has a column for each of 4 regions
- We generate independent random $Z_i \sim N(0,1)$ arrays, forming matrix **Z** = (Z_1, Z_2, Z_3, Z_4)
  - matrix **Z** has one array/column for each of the 4 regions, with each array having 1500 values.
- We use Cholesky Decomposition to find a matrix **C** such that
  - $\mathbf{C}^T\mathbf{C} = \Sigma$
  - note, there is a C matrix found for each season, because there is a matrix Σ for each season
  - We transform the independent Z matrix to the correlated X matrix by multiplying
  - $\mathbf{X} = \mathbf{C}^T\mathbf{Z} \sim MN(0,\mathbf{C}^T\mathbf{C}) \sim MN(0, \Sigma)$

Matrix Z holds independent random values, and matrix X holds correlated random values. An example with only 2 variables is easier to show graphically, so Figure 6-5 shows pairs of values from Z and then the same pairs from X. The correlation imposed here is 0.5.

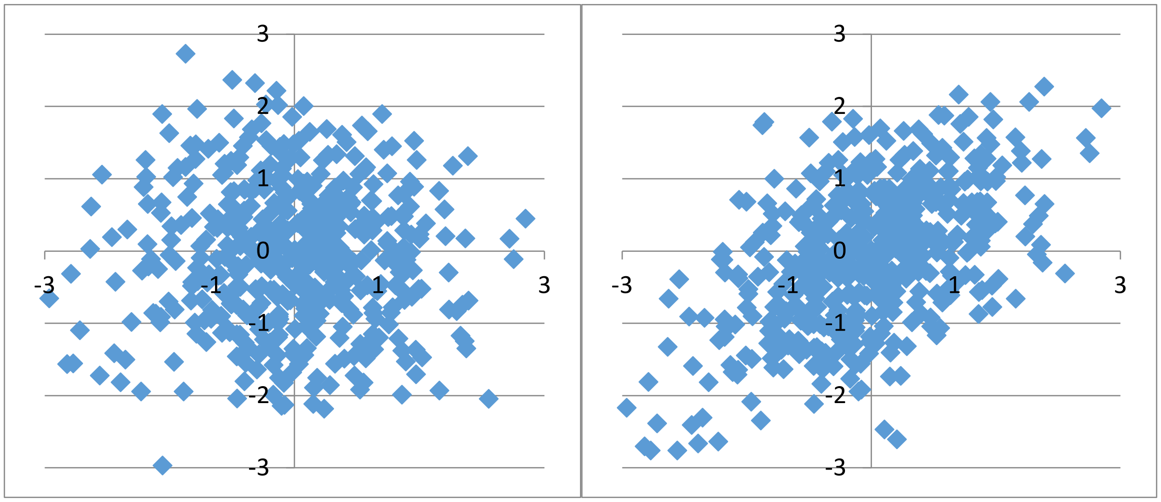


Figure 6-5. Pairs of Independent Standard Normal Values on Left, and Transformed Pairs of Correlated Standard Normal Random Values on Right (Correlation is 0.5.)

Matrix X holds the 4 columns of 1500 rows, where each row is a set of correlated random values based on the correlation matrix Σ for each of the 3 seasons of the year, with each row (set of 4 values) using the spatial correlation matrix for the season it will be used to sample. In other words, sequential rows use different correlation matrices because they will sample different seasons. The values in matrix X are used to generate the random term of the periodic autoregressive AR(1) series described below in Section 6.1.2.2.

6.1.2.2 Serial Correlation: Use of Periodic Autoregressive Lag 1 model, AR(1)

In this step, 4 series of serially correlated random values are generated, one for each region, with 1500 values in each series that step through the 3 seasons, totaling 500 events. The Periodic Autoregressive lag 1 AR(1) model is used for generating the serially correlated standard Normal series of $Z \sim N[0,1]$ values that will ultimately be used for re-sampling from the historical record, or the empirical probability distribution it creates. The notation $N[0,1]$ refers to a Normal distribution with mean = 0 and standard deviation = 1, otherwise known as the standard Normal distribution.

The AR(1) value for each time step is the sum of a deterministic component and a random component. The deterministic component is the mean value, plus the previous period's deviation from that mean reduced (multiplied) by the serial correlation. The random component is a Normal distribution with a mean of zero and standard deviation adjusted from 1 to account for the serial correlation (see equations below). The result of these terms is a series of values that are standard Normally distributed and serially correlated, using correlations in Table 2. A series is generated for each of the 4 regions of the watershed, with the random components (one for each) using the Z values that come from the same row of matrix X (ensuring spatial correlation between regions is maintained).

A periodic AR(1) series Y is built by computing each subsequent value for time period t from the deterministic and random components mentioned above, and shown below. Since the series is periodic, some parameters such as ρ_t = serial correlation are dependent on time step t, because each step t is a particular season and each of the 3 seasons has different correlation with the previous season. Other parameters, such as μ = mean = 0 and σ = standard deviation = 1, are not dependent on t.

Y_t = deterministic term + random term

$$Y_t = \mu + \rho_t (Y_{t-1} - \mu) + \varepsilon_t \sim N[0, \sigma e_t]$$

where:

t = time period, identified as one of the three defined seasons of the year

$\mu = 0$

$\sigma = 1$

ρ_t = serial correlation of time period t with period t-1, specified by season

$\sigma e_t = \sigma * \text{sqrt}(1 - \rho_t^2)$

The Z ~ N[0, 1] values developed in Step 1 are used to generate the random ε_t term. Defined in this way, the resulting series Y_t is simply Z ~ N[0, 1] values that are serially correlated as specified. A series Y_t is generated for each of the 4 regions of the watershed, each one using the appropriate column of the **X** matrix of spatially correlated Z values to generate the random term.

To be complete, series Y_t should be noted as Y_{tj}, where j is one of the regions, and correlation values ρ_t should be ρ_{tj} to reflect not just the values for each season but rather the values for each season for each region. The description above neglects the region specification for simplicity to aid clarity, but the computation spreadsheet takes it into account. Thus, the series of Y_{tj} values generated here are Z ~ N[0,1] values that are both serially correlated and spatially correlated as defined in Tables 2 and 1.

6.1.2.3 Transform the Serially and Spatially Correlated Z Values to U[0,1]

Random sampling in a Monte Carlo simulation uses Uniformly distributed values between 0 and 1, U[0,1], to act as a cumulative probability in the distribution being sampled (in this case an empirical distribution). Thus the Z ~ N[0,1] must be transformed to U[0,1]. This task is done using the standard Normal distribution to transform Z into p, where p is U[0,1]. In the spreadsheet that implements this sampling method, Excel's Normal distribution =norm.s.dist(Z) is used for this task. Figure 6-6 displays pairs correlated N[0,1] values on the left, and those same pairs transformed to U[0,1] on the right.

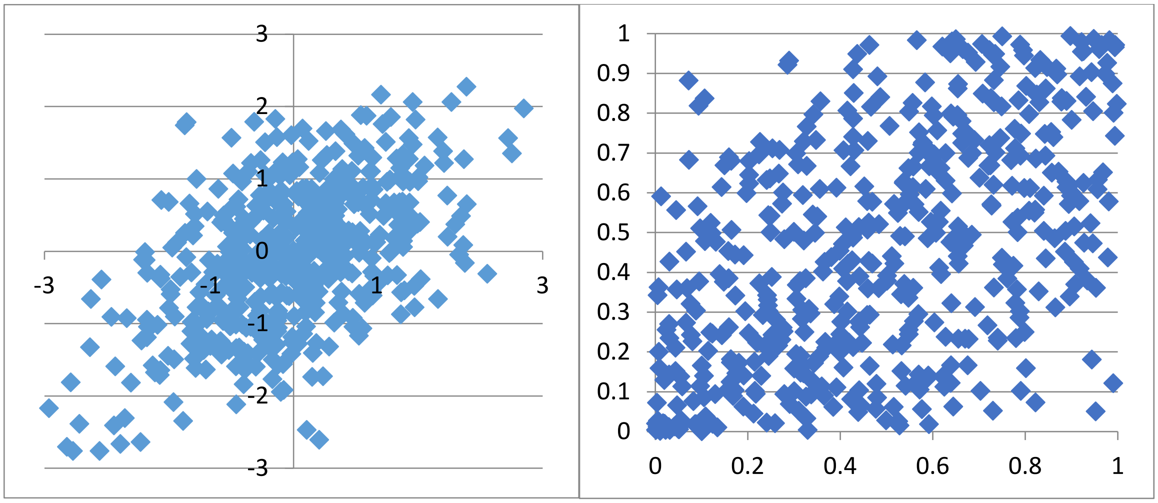


Figure 6-6. Correlated Normal[0,1] Pairs on the Left, and Correlated Uniform[0,1] Pairs on the Right

6.1.2.4 Bootstrap Sampling: Sampling from the empirical distribution formed by the historical record

Re-sampling values from an historical record, or the empirical distribution it forms, simply assumes all historical years are equally likely to occur again. Thus, each year is assigned a likelihood of 1/N when sampling from N years of record. With no correlation involved, the order the years/seasons are arranged when being sampled does not matter. But when either spatial or serial correlation must be maintained in the sampling, the years must be ordered by the seasonal volumes used to compute the correlations. Then, when two random values are similar, the two seasonal volumes selected will be similar in their relative volume (compared to the rest of the data). Therefore, with correlated sampling, the historical seasons/years must first be ordered by magnitude of seasonal volume.

When the seasons/years are ordered by magnitude and each assigned a likelihood of 1/N, those likelihoods can be accumulated from 0 to 1 to form an empirical CDF (cumulative distribution function) for sampling. This ordering is done for each of the 4 regions, for each of the 3 seasons, forming 12 CDFs appearing as ranked lists of seasonal volumes and the accumulation of incremental likelihood 1/N. Table 6-6 shows as an example the tabular form of the CDF for the Mountain region in the Early Spring season (separated into two halves). Each row has a ranked seasonal volume. The table has a column for the incremental probability, the cumulative probability, the ranked volume, and the year that produced that volume. The sampling process seeks the U[0,1] value in the cumulative probability column, and takes the associated seasonal volume and year from that row as the sampled value. Figure 6-7 shows graphically the empirical CDFs for Early Spring for the S. Plains and Mountain regions with probability on the horizontal axis. It shows only the seasonal volumes, but as seen in the tabular form of the CDF, each of those values retains knowledge the year that produced it. To generate the synthetic 500-event record, the sequence of 4 arrays of 1500 values (one array for each region, and one value for each of 3 seasons in the 500 events) are used to sample seasonal volume values (and so the events that produced them) from those 12 empirical CDFs.

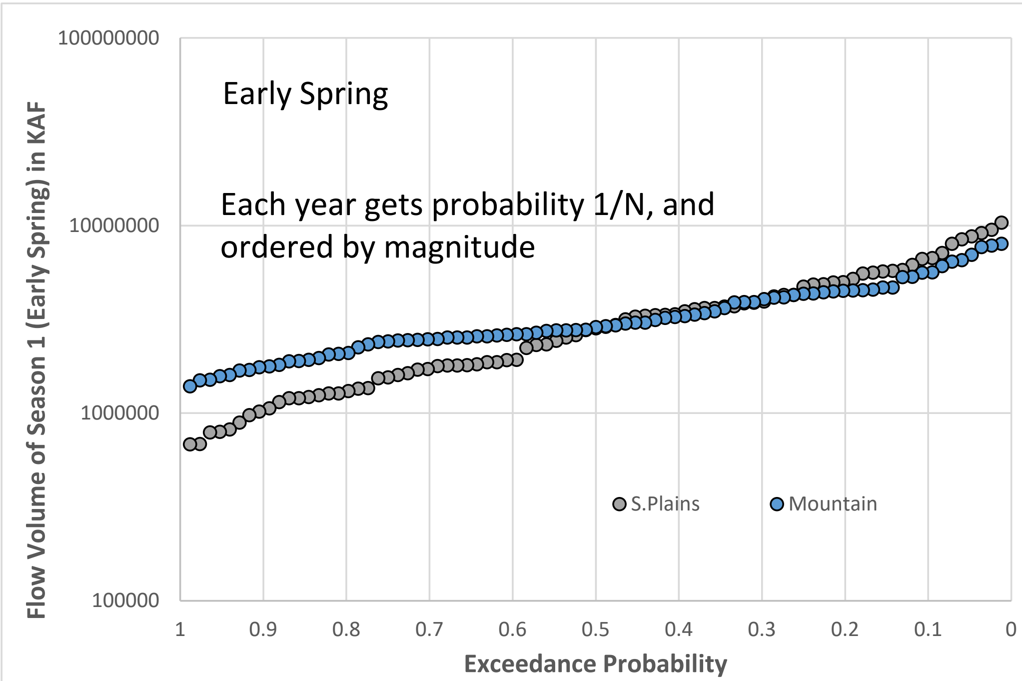


Figure 6-7. Empirical Distributions of Seasonal Volume in Early Spring for S. Plains and Mountain

Figure 6-8 shows an image of Step 4 from the sampling spreadsheet, showing only the first 12 rows representing 4 years of 3 seasons each year. Columns A – D show the spatially correlated U[0,1] values for each region from Step 3, transformed from the first 12 rows of correlated matrix X created in step 2. Columns F and G simply show the year and season being sampled in that row. Columns I – L show the seasonal volumes sampled from the appropriate empirical CDF using the U[0,1] value for that region. Columns M – P show the year in which that flow volume occurred, and thus the year from which flows will be taken to populate that season in that region's locations to create the 500-event synthetic record.

As an example, looking in the Early Spring (season 1) Mountain CDF tabulated in table 3, the first value in column A (0.6129) leads to the selection the first value of column I (2,615,854), which came from year 1987 shown in column M. Thus, for the Early Spring season of the first year of synthetic record, in the Mountain region, flows from 1987 will be used.

Table 6-6. Empirical CDF for Seasonal Volume of Late Spring in the Mountain Region

Early Spring Mountain		Empirical CDF	
incr.prob 1/N	cum.prob	ranked seasonal vol	year
	0		
0.012	0.012	8006344	1952
0.012	0.0241	7828401	1979
0.012	0.0361	7690112	1978
0.012	0.0482	6995913	1943
0.012	0.0602	6531330	1972
0.012	0.0723	6414831	2011
0.012	0.0843	6075939	1969
0.012	0.0964	5633536	1997
0.012	0.1084	5607984	1947
0.012	0.1205	5323455	1971
0.012	0.1325	5313786	1996
0.012	0.1446	4669766	1975
0.012	0.1566	4669166	1949
0.012	0.1687	4562525	1965
0.012	0.1807	4517117	1994
0.012	0.1928	4504997	1960
0.012	0.2048	4493964	1986
0.012	0.2169	4454154	1951
0.012	0.2289	4406215	1950
0.012	0.241	4350389	1982
0.012	0.253	4331944	1959
0.012	0.2651	4259777	1976
0.012	0.2771	4144906	1944
0.012	0.2892	4125377	1939
0.012	0.3012	4052984	1967
0.012	0.3133	3911257	1999
0.012	0.3253	3904208	1930
0.012	0.3373	3894050	1948
0.012	0.3494	3627966	2009
0.012	0.3614	3491493	1968
0.012	0.3735	3409902	1989
0.012	0.3855	3355956	1974
0.012	0.3976	3287777	1942
0.012	0.4096	3254500	1955
0.012	0.4217	3222788	1966
0.012	0.4337	3140403	1945
0.012	0.4458	3042138	1956
0.012	0.4578	3036268	1970
0.012	0.4699	3008387	2003
0.012	0.4819	2936300	1962
0.012	0.494	2911638	1933
0.012	0.506	2873583	1936

		ranked	
incr.prob 1/N	cum.prob	seasonal vol	year
0.012	0.5181	2786405	1946
0.012	0.5301	2771159	1998
0.012	0.5422	2766794	1954
0.012	0.5542	2764763	1957
0.012	0.5663	2741649	1985
0.012	0.5783	2680212	1993
0.012	0.5904	2634888	1983
0.012	0.6024	2631360	1938
0.012	0.6145	2615854	1987
0.012	0.6265	2598225	2006
0.012	0.6386	2568863	1973
0.012	0.6506	2565201	2012
0.012	0.6627	2534766	1984
0.012	0.6747	2530612	1990
0.012	0.6867	2528183	1963
0.012	0.6988	2484880	1932
0.012	0.7108	2476717	1980
0.012	0.7229	2459065	2007
0.012	0.7349	2446879	1958
0.012	0.747	2442589	2001
0.012	0.759	2417884	2010
0.012	0.7711	2395732	1934
0.012	0.7831	2324701	2004
0.012	0.7952	2247042	1995
0.012	0.8072	2094846	1977
0.012	0.8193	2068729	1940
0.012	0.8313	2054836	1953
0.012	0.8434	1964321	2000
0.012	0.8554	1925249	1937
0.012	0.8675	1898752	1964
0.012	0.8795	1886868	1991
0.012	0.8916	1809163	1941
0.012	0.9036	1775093	1935
0.012	0.9157	1757935	1981
0.012	0.9277	1702357	1992
0.012	0.9398	1690449	1988
0.012	0.9518	1595420	1931
0.012	0.9639	1575537	2008
0.012	0.9759	1508495	2005
0.012	0.988	1494847	2002
0.012	1	1388196	1961

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
serially &spatially correlated uniform variates								sampled seasonal volumes				year having sampled seasonal vol			
Mountain	N.Plains	S.Plains	Mo.Hills					Mountain	N.Plains	S.Plains	Mo.Hills	**Mountain**	**N.Plains**	**S.Plains**	**Mo.Hills**
U1	U2	U3	U4		year	season		Q1	Q2	Q3	Q4	**S1yr**	**S1yr**	**S3yr**	**S4yr**
cor U[0,1]	cor U[0,1]	cor U[0,1]	cor U[0,1]					season vol	season vol	season vol	season vol				
0.6129	0.5267	0.4144	0.7254		1	1		2615854	1687280	3340480	2723709	**1987**	**2006**	**1975**	**1989**
0.4118	0.5132	0.6106	0.7898		1	2		7829764	1531152	4077453	2928215	**2009**	**2000**	**1957**	**1959**
0.5604	0.5709	0.7962	0.8104		1	3		5154077	1441031	2633040	3125621	**1969**	**1974**	**1963**	**1938**
0.6634	0.7484	0.8482	0.6459		2	1		2530612	1191462	1218971	3355295	**1990**	**1964**	**1950**	**1968**
0.3274	0.6673	0.7383	0.2491		2	2		8454315	1262711	2733175	11258934	**1957**	**1977**	**2002**	**2007**
0.5975	0.6919	0.7625	0.3982		2	3		5058843	1159028	2970505	9385663	**1989**	**1962**	**2002**	**1958**
0.1911	0.4431	0.6562	0.1298		3	1		4504997	2174360	1803193	8669262	**1960**	**1947**	**1966**	**1947**
0.2198	0.2241	0.7430	0.1436		3	2		9070315	3111438	2733175	13733250	**1993**	**2009**	**2002**	**1999**
0.0543	0.1381	0.3702	0.0834		3	3		8430845	2974164	6750364	20313114	**1993**	**1999**	**1959**	**1985**
0.8860	0.4518	0.7246	0.2952		4	1		1809163	2119509	1631770	6768328	**1941**	**1943**	**2000**	**1965**
0.6443	0.0628	0.0750	0.0046		4	2		5456249	6208218	12055361	22466629	**2007**	**1962**	**1945**	**1995**
0.6397	0.1668	0.4130	0.7303		4	3		4737709	2884171	5883097	4296035	**1958**	**1979**	**2004**	**1964**

Figure 6-8. Snapshot of Sampling Results for 1st 4 years of 500, with Correlated U[0,1] Values on the Left and Resulting Years of Flow Selected on the Right

Note: Description of these columns appears in the text.

Figure 6-9 is similar to Figure 6-6 and shows an image of the random sampling of seasonal volumes for the Early Spring season for regions Mountain and S. Plains. However, the horizontal probability axis in this figure has been changed from linear to Normal to better show the extremes. The solid markers are again the ranked 90-year historical record of seasonal volumes, plotted as empirical CDFs, and the hollow markers show the 500 sampled values of the Early Spring season for those regions. Note that the largest and smallest sampled values (hollow markers) are equal to the largest and smallest historical values (solid markers), as this re-sampling procedure may only select from the historical years and cannot produce an outcome that is more extreme. It is not until we sum the volumes across all of the regions that the values will be more extreme than the historical record. Figure 6-9 shows this outcome for the Early Spring season (season 1), with the green markers representing the sum of volume of the 4 regions.

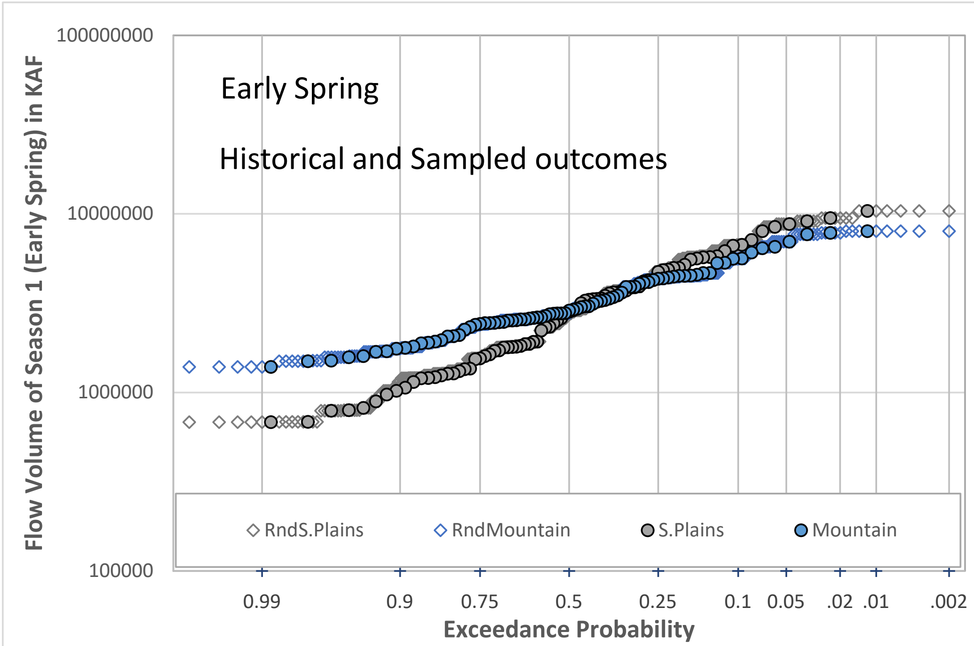


Figure 6-9. Historical and Sampled Seasonal Volumes of the Early Spring Season at Mountain and S. Plains

The outcome of this sampling process is 1500 seasons of a specified historical year for each of the 4 regions of the watershed. For example, in looking at Figure 6-5 we saw that the historical year for Early Spring (season 1) in the Mountain region of the first year is 1987. Therefore, the flows in Early Spring at every location in the Mountain region are used to form the beginning of the 500 event "big bucket" synthetic time series. Flows from different years are used for that season in other regions, as shown in columns N - P. And flows from other years are used in the following Late Spring season (season 2) at all locations. A DSS file was created using a script that copied and pasted those historical flows from the correct years (of the 90 historical) for each season of each year at each location, to form the 500-event DSS records for each location.

6.2 HEC-WAT Watershed

6.2.1 Missouri River ResSim Model

The Missouri River Mainstem ResSim (MR ResSim) model was originally created to assess alternatives developed for the Man Plan EIS. Inflows between 1930 and 2012 were run through the model, which simulated the operations of the six mainstem reservoirs. All tributary reservoir operations were captured in the historical POR or through incorporation of the Reclamation depletions. The MR ResSim model was calibrated, tested and thoroughly reviewed for the Man Plan EIS but only for events seen in the 1930-2012 POR. Since the Big Bucket had larger events than what had occurred in the historical POR, improvements to the scripted rules within the model were needed. One such rule dealt with how the model releases water during extreme floods when the exclusive flood control or even surcharge zones are occupied, specifically when Oahe Dam would utilize its spillway. Oahe's spillway is earthen lined and is utilized only when the project is in surcharge or during emergency situations when there is not enough available capacity from the powerhouse and flood tunnels because of the damages and costly repairs that would need to be completed should it be utilized. The Oahe spillway has never been used for regulation purposes. The closest it came was during 2011 when both Fort Peck and Garrison had entered their respective surcharge zones and Oahe Reservoir peaked 0.3 feet below the top of the spillway gates. Because Oahe's spillway is a last resort and the fact that most water needed to maintain Gavins Point at its guide curve elevation comes from Oahe, releases from Gavins Point (most downstream project) are limited to the combined capacity of Oahe's flood tunnels and powerhouse, which is approximately 164,000 cfs. Improvements were made to the MR ResSim model's logic during extreme events to not only capture this operational criteria but also to know when to utilize Oahe's spillway because the event is large enough to surcharge Oahe.

Along with improvements to the model's operations during large events, the MR ResSim model was merged with two other ResSim models: Lower Kansas and Osage, which were recently developed as part of the Corps Water Management System (CWMS) modeling initiative. Both watersheds contain several reservoirs that can have an impact on peak flows during floods. By combining these ResSim models with the MR ResSim model, the MR ResSim model is able to better capture the regulated flows in the lower Missouri River.

The final modification to the MR ResSim model allowed the model to work with the Big Bucket and within the WAT. Each year within the historical POR had a monthly runoff forecast for each mainstem reservoir reach. This allowed the model to forecast long term reservoir releases and ensure that all stored flood waters were evacuated prior to the start of the next runoff season. However, the Big Bucket has never occurred so there are no monthly runoff forecasts. A feature in the WAT allows a form of those forecasts to be created based on known runoff and the error statistics of the historical runoff forecasts. The WAT can look ahead in the simulation and calculate the runoff in each reach, which becomes the known flow. Forecasts are then created by utilizing the forecast error statistics to vary the forecasted volume around the known flow for the remainder of the calendar year. Modifications to the MR ResSim model allow the model to split out the calendar-year volume into monthly totals so monthly forecasts are created based on the year selected from the Big Bucket.

6.2.2 Hydrologic Sampler

The Hydrologic Sampler is a plug-in built for the WAT software with the purpose of allowing users to generate hydrologic time series necessary for a Monte Carlo or Flood Risk Analysis

(FRA) compute. It uses pseudo random number generation to create flow or precipitation input time series required for an FRA simulation. For this study, only ResSim resides in the MR WAT watershed, so flow is used for input. For flow sampling, two methods are available: Correlated Flow Frequency Curves and Bootstrapping Historical/Synthetic Basin-wide Events. The MR WAT watershed is setup to use the latter method to utilize the historical sample. In either method, the Hydrologic Sampler randomly samples the hydrology, generating as many hydrologic time series as necessary for the FRA simulation. These sampled hydrologic time series form the input for a 50-event, continuous simulation or lifecycle that allow the simulation to capture the effects of varied reservoir levels, flows, and runoff forecasts. Fifty lifecycles are combined into realizations with maximums and minimums of various parameters extracted from all events to create the frequency curves.

6.2.2.1 Hydrographs

Development of the Big Bucket was done externally of the WAT, but the random sampling of the historical sample is done within the WAT. Sampling of the historical sample still needs to be related to the historical POR, meaning the WAT should not over sample dry events to create long-term droughts or have too many back-to-back flood events. This is captured with an annual serial correlation parameter for the Basin and a total volume time series created externally of the WAT. Even though the Basin is large, the WAT can currently only use one location for the total volume, so the most downstream computation point in the MR ResSim model was selected, Hermann, MO. The WAT will calculate the total volume during a specified season, which was defined as March 1 to September 30, to rank each event. This season specification is when the bulk of the Basin runoff typically occurs. The annual serial correlation was set to 0.4, which was based on correlation in the historical POR. Knowledge uncertainty was included in the analysis by specifying an "Equivalent Years of Record". This captures uncertainty in each realization by creating a sub-sample from historical sample and synthetic, scaled events termed the Small Bucket. For example, for this study, the Missouri River has a 90-year historical POR so 90 would be used as the "Equivalent Years of Record". When the WAT begins a realization, a 90-event Small Bucket would be sampled from the historical sample and synthetic, scaled events based on the incremental probabilities assigned to each event. Each event in the Small Bucket is assigned an equal likelihood of occurrence or incremental probability and then the WAT samples events from the Small Bucket to build each lifecycle within the realization. Synthetic events and incremental probabilities are described in Section 1.2.2.3.

6.2.2.2 WAT Forecasts

As previously mentioned, the MR ResSim model requires monthly volume forecasts for each of the mainstem dam reaches to ensure all stored flood waters have been evacuated by the start of the next runoff season and that System storage is balanced. Although the model had historical forecasts for the historical POR, forecasts are not available for the Big Bucket or synthetic, scaled events. The WAT forecast feature was used instead of developing forecasts. This option has the added benefit of allowing the analysis to capture forecast uncertainty. For example, if a monthly volume forecast is consistently under forecasting volume to start a year, releases will be lower than needed in the spring and summer and potentially higher in the fall because more water needs to be evacuated from the reservoirs over a shorter period. On the other hand, if forecasts are consistently over forecasting volumes to start a year, releases will be higher than needed in the spring and summer and potentially lower in the fall because more stored flood waters were evacuated earlier in the year. These variations also allow more scenarios to be simulated while still using the same events. If the same event is sampled from the historical sample, a different WAT forecast could be created based on the error statistics, which results in a different regulated flow.

Historical forecasts from 1971–2019 were compared to historical runoff in the five forecasting reaches above Gavins Point Dam to estimate the error statistics. Big Bend inflows are included in the Fort Randall forecast so there are only error statistics for five reservoir reaches. Mean error intercept and slope, standard error and serial correlation were calculated for each forecast reach. In general, forecast accuracy improves later in the year. This is due to uncertainty in the peak plains and mountain snowpack early in the year, which are the most reliable indicators of runoff in the upper MR Basin. Figure 6-10 shows that January calendar year forecasts in the Garrison reach tend to be closer to the mean with more variation in the error while Figure 6-11 shows that the July calendar year forecasts in the Garrison reach improve in accuracy. By July, there is more certainty in runoff because the main runoff from plains and mountain snowpack have occurred. These forecast nuances are captured in the final runoff statistics shown in Table 6-7 through Table 6-11.

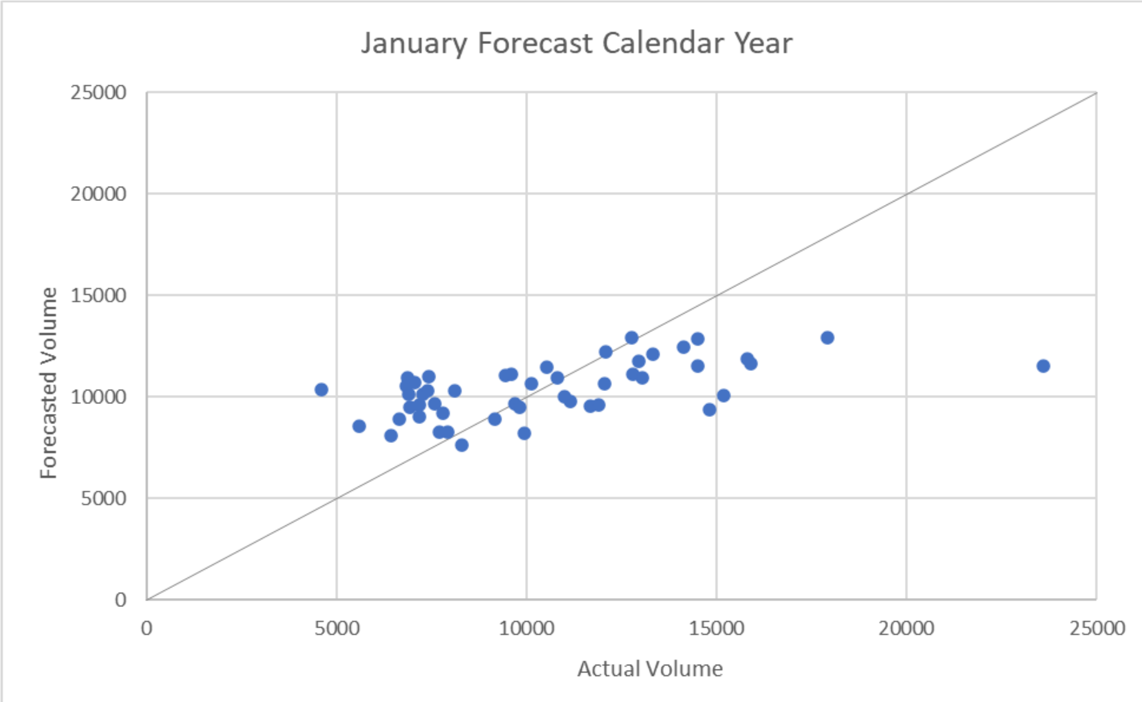


Figure 6-10. Garrison Forecast vs. Actual Volume for January Forecasts

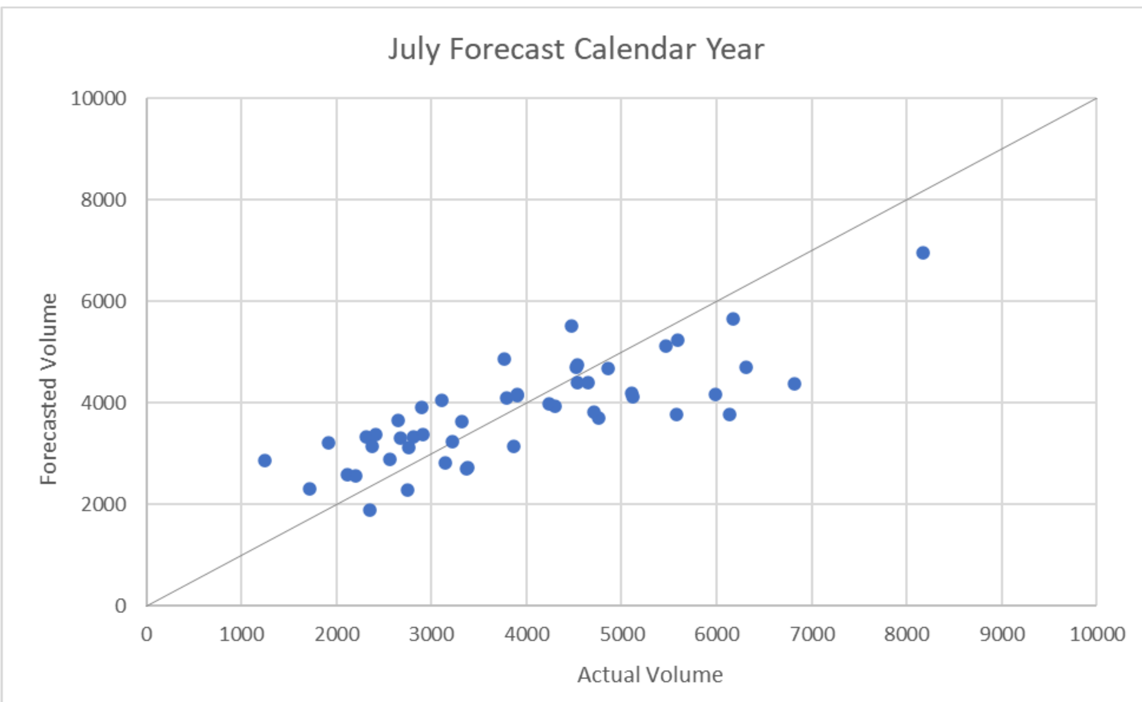


Figure 6-11. Garrison Forecast vs. Actual Volume for July Forecasts

Table 6-7. Fort Peck Forecast Statistics

Date	Min Forecast Override (KAF)	Relationship of Mean Error to Magnitude		Standard Error (KAF)	Serial Correlation
		Intercept (KAF)	Slope		
1-Mar	0.0	3857.4	-0.669	882.5	
1-Apr	0.0	3318.2	-0.633	934.4	0.919
1-May	0.0	2237.2	-0.495	882.0	0.900
1-Jun	0.0	1335.7	-0.412	727.1	0.920
1-Jul	0.0	911.5	-0.536	341.2	0.881
1-Aug	0.0	681.0	-0.580	188.3	0.917
1-Sep	0.0	521.6	-0.524	202.5	0.873
1-Oct	0.0	322.9	-0.440	140.0	0.936
1-Nov	0.0	223.9	-0.424	91.2	0.875
1-Dec	0.0	181.2	-0.646	50.6	0.752
1-Jan	0.0	5505.7	-0.798	663.6	0.000
1-Feb	0.0	4531.5	-0.720	817.6	0.877

Table 6-8. Garrison Forecast Statistics

Date	Min Forecast Override (KAF)	Relationship of Mean Error to Magnitude		Standard Error (KAF)	Serial Correlation
		Intercept (KAF)	Slope		
1-Mar	0.0	6211.4	-0.656	1339.1	
1-Apr	0.0	5675.2	-0.656	1406.4	0.936
1-May	0.0	3954.0	-0.515	1184.5	0.921
1-Jun	0.0	2258.4	-0.332	1084.3	0.922
1-Jul	0.0	1805.4	-0.485	595.7	0.900
1-Aug	0.0	1285.5	-0.658	302.9	0.878
1-Sep	0.0	949.9	-0.709	279.7	0.898
1-Oct	0.0	595.8	-0.684	204.5	0.823
1-Nov	0.0	466.3	-0.776	98.7	0.730
1-Dec	0.0	191.4	-0.818	56.1	0.676
1-Jan	0.0	8173.6	-0.790	1072.8	0.000
1-Feb	0.0	7101.6	-0.722	1246.8	0.852

Table 6-9. Oahe Forecast Statistics

Date	Min Forecast Override (KAF)	Relationship of Mean Error to Magnitude		Standard Error (KAF)	Serial Correlation
		Intercept (KAF)	Slope		
1-Mar	0.0	1757.5	-0.838	582.7	
1-Apr	0.0	1239.6	-0.797	360.9	0.665
1-May	0.0	836.3	-0.807	319.1	0.887
1-Jun	0.0	615.8	-0.809	218.2	0.650
1-Jul	0.0	317.9	-0.847	176.0	0.723
1-Aug	-200.0	206.7	-0.894	129.8	0.882
1-Sep	-200.0	156.7	-0.842	128.6	0.863
1-Oct	-200.0	70.7	-0.784	105.7	0.838
1-Nov	-700.0	-17.5	-0.478	86.0	0.685
1-Dec	-100.0	-1.8	-0.736	45.5	0.649
1-Jan	0.0	2064.4	-0.939	302.9	0.000
1-Feb	0.0	1934.0	-0.887	536.6	0.603

Table 6-10. Fort Randall Forecast Statistics

Date	Min Forecast Override (KAF)	Relationship of Mean Error to Magnitude		Standard Error (KAF)	Serial Correlation
		Intercept (KAF)	Slope		
1-Mar	0.0	751.9	-0.934	158.4	
1-Apr	0.0	562.7	-0.967	113.8	0.607
1-May	0.0	430.3	-0.974	93.5	0.635
1-Jun	0.0	310.5	-0.957	96.7	0.584
1-Jul	0.0	176.1	-1.001	83.3	0.807
1-Aug	0.0	119.1	-0.982	57.7	0.769
1-Sep	0.0	76.6	-0.992	44.1	0.665
1-Oct	0.0	39.6	-1.001	29.7	0.783
1-Nov	-100.0	17.5	-1.040	43.0	0.044
1-Dec	-100.0	2.6	-0.696	39.6	0.167
1-Jan	0.0	846.1	-0.975	96.5	0.000
1-Feb	0.0	775.6	-0.916	156.6	0.547

Table 6-11. Gavins Point Forecast Statistics

Date	Min Forecast Override (KAF)	Relationship of Mean Error to Magnitude		Standard Error (KAF)	Serial Correlation
		Intercept (KAF)	Slope		
1-Mar	0.0	1240.8	-0.932	129.8	
1-Apr	0.0	1049.2	-0.927	97.0	0.748
1-May	0.0	903.0	-0.917	81.1	0.829
1-Jun	0.0	743.8	-0.913	74.2	0.713
1-Jul	0.0	584.2	-0.911	70.0	0.709
1-Aug	0.0	425.7	-0.853	81.9	0.604
1-Sep	0.0	319.7	-0.815	69.5	0.731
1-Oct	0.0	203.5	-0.691	56.0	0.747
1-Nov	0.0	142.2	-0.746	36.2	0.839
1-Dec	0.0	56.4	-0.589	45.4	0.403
1-Jan	0.0	1418.5	-0.924	188.6	0.000
1-Feb	0.0	1345.3	-0.944	131.4	0.463

6.2.2.3 Synthetic Events & Incremental Probabilities

Even though the historical sample provides larger and smaller events than observed during the historical POR, this does not guarantee less frequent events such as the 0.002 annual exceedance probability (AEP) event are accurately represented. To ensure the Monte Carlo analysis had large enough events that would allow the tails of the WAT frequency curves to potentially match the tails of the Bulletin 17C frequency curves, it was supplemented with fifteen synthetic, scaled events, or fifteen events from the historical POR that were scaled to match peak volumes for defined AEPs. The WAT initially defines the incremental probability of occurrence for each event in the historical sample as 1/590, which means large events with a small AEP have the same likelihood of being sampled as small events with a bigger AEP. Synthetic, scaled events are assigned a specific incremental probability based on their AEP, so the WAT will sample those events close to what their AEP. Adding a variety of events over a range of AEPs can help move the tails of the frequency curve closer to the Bulletin 17C frequency curves.

Previous studies used one scaling factor for the entire basin to scale an event from the historical POR, but this can cause unreasonable flows in certain areas of the basin. For example, if a historical event is scaled by 2.0 for the entire basin, which results in a 0.002 AEP event at Sioux City, IA, high incremental inflows in the basin could result in local events that that have unreasonable probabilities based on meteorological limitations. A different approach was utilized for this study by analyzing the volume frequency curves for each region and developing scaling factors based on standard deviation increments. Table 6-12 lists the scaling factors for each of the four regions at 0.5 standard deviation increments.

Table 6-12. Scaling Factors for Each Region at 0.5 Standard Deviation Increments

	Scaling Factors					
Region	**0.5σ**	**1.0σ**	**1.5σ**	**2.0σ**	**2.5σ**	**3.0σ**
Mountain	1.12	1.26	1.42	1.60	1.80	2.02
N. Plains	1.31	1.71	2.23	2.91	3.80	4.97
S. Plains	1.21	1.46	1.76	2.12	2.56	3.08
Mo. Hills	1.31	1.73	2.27	2.98	3.91	5.14

One limitation with the WAT setup is only one AEP can be assigned for each synthetic event. Since the Missouri River Basin is large and the runoff varies widely throughout the Basin, each synthetic event was examined to ensure the location used to assign the AEP was representative of where the bulk of the inflow entered the Missouri River. This was done so a large, infrequent event at one location was not assigned a frequent AEP and over sampled by the hydrologic sampler. Each event's AEP was taken from the volume-frequency curve that best represented the event, and the volume-frequency curves were developed with the same data as the Bulletin 17C frequency curves. Table 6-13 lists the synthetic events, their assigned AEPs and locations used to assign those AEPs.

Table 6-13. Synthetic Events on the Missouri River

Year	Location for AEP	σ	Duration	AEP	WAT Assigned AEP
2019	NCNE	1.0	3-Day	0.0048	0.0050
1947	SUX	2.0	1-Day	0.0046	0.0050
1995	HEMO	0.5	3-Day	0.0044	0.0040
1967	MKC	1.0	7-Day	0.0042	0.0040
1978	SUX	1.5	31-Day	0.0041	0.0040
1952	OAHE	1.0	1-Day	0.0033	0.0030
1943	HEMO	1.0	3-Day	0.0032	0.0030
1972	SUX	2.0	15-Day	0.0031	0.0030
1997	SUX	1.0	181-Day	0.0022	0.0020
2010	NCNE	1.5	91-Day	0.0021	0.0020
1960	HEMO	1.5	15-Day	0.0014	0.0010
1944	HEMO	1.5	3-Day	0.0012	0.0010
1993	MKC	0.5	3-Day	0.0009	0.0008
2011	SUX	1.0	181-Day	0.0005	0.0005
1951	DESO	0.5	3-Day	0.0002	0.0002

After initial examination of the frequency curves, it was determined the frequency curves along the Kansas River and Osage River were skewing the results along the Missouri River. This was caused by the types of events in the historical POR for those watersheds. Along the Kansas River, the historical record had two large events and one extreme event, but the remainder of the record had relatively small events. The resulting frequency curves, shown in Figure 6-12, over sampled the three largest events and several plateaus or stair-steps occurred because there was not enough variety in events to create a smooth curve. In particular, the frequency curve produced by the WAT over-estimated flows near the 0.01 AEP, which in turn caused the WAT to over-estimate the frequency curve at Kansas City.

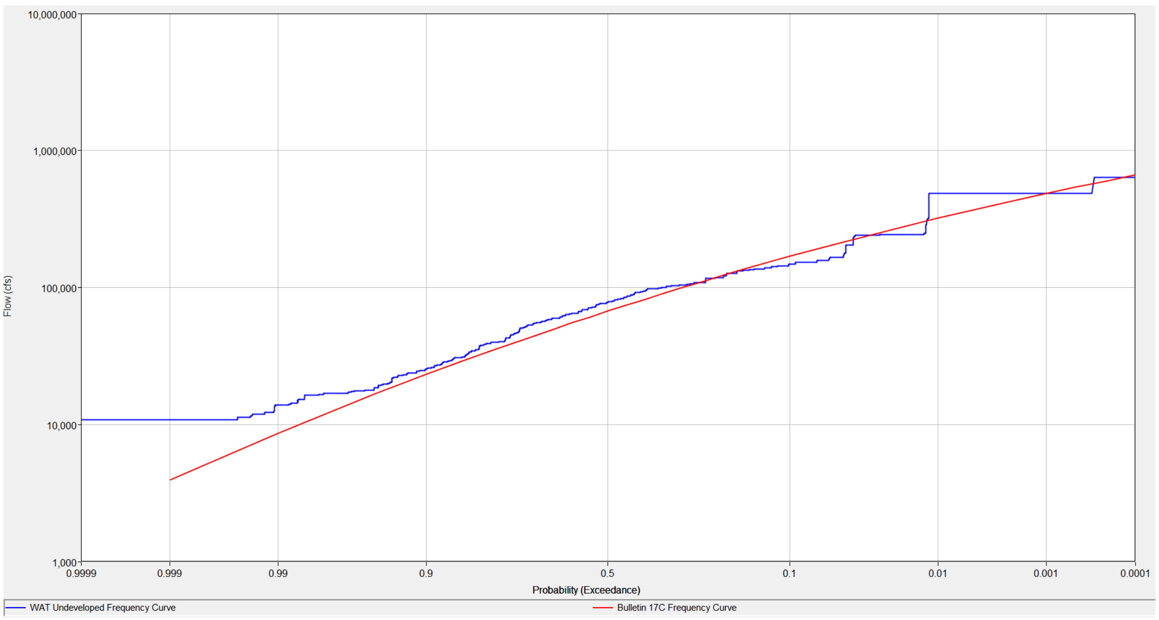


Figure 6-12. WAT 1-Day Frequency Curve at De Soto, KS Compared to Bulletin 17C Frequency Curve Prior to Correcting with Synthetic Events and Incremental Probability Overrides

Two steps were taken to correct the issue. The first added more synthetic events, specific to the Kansas and Osage Rivers, to smooth out the frequency curves. Table 6-14 lists the synthetic events used to help smooth the frequency curves on the Kansas and Osage Rivers.

Table 6-14. Synthetic Events on the Kansas and Osage Rivers

Year	Location for AEP	σ	Duration	AEP	WAT Assigned AEP
1971	DESO	2.5	1-Day	0.0292	0.0200
1985	DESO	1.5	1-Day	0.0167	0.0200
1992	DESO	2.0	1-Day	0.0131	0.0100
1971	DESO	3.0	1-Day	0.0086	0.0090
2007	DESO	1.0	1-Day	0.0068	0.0070
1985	DESO	2.0	1-Day	0.0045	0.0050
1992	DESO	2.5	1-Day	0.0035	0.0040
2007	DESO	1.5	1-Day	0.0015	0.0020
1981	STTM	1.5	1-Day	0.0180	0.0200
1941	STTM	2.0	1-Day	0.0156	0.0200
1974	STTM	2.0	1-Day	0.0075	0.0080
1984	STTM	2.5	1-Day	0.0016	0.0010
1982	STTM	3.0	1-Day	0.0005	0.0005

The second step was to utilize incremental probability overrides. When the historical sample was initially setup in the Hydrologic Sampler, each event had the same likelihood of being sampled each year after accounting for serial correlation. When synthetic events are added, the probability of some events in the historical sample are reduced by the total probability assigned to the synthetic, scaled events. The WAT takes most of the probability away from the larger volume events, so the cumulative probability still equals one.

After examination, it was determined that the default reduction of probability was not reasonable for this setup. Because the historical sample contains 590 events, the incremental probability of the events is already small. Adding synthetic events further reduced the incremental probabilities, making some of those events nearly zero. A different approach, one where the incremental probability of every event was reduced equally was needed to avoid extremely small incremental probabilities for some events within the historical sample. After the incremental probabilities were adjusted, years within the historical sample containing the largest events on the Kansas and Osage Rivers were adjusted to match the estimated AEP for each event at the most downstream gage on the river. On the Kansas River, the 1951 event would be a 1/90 or 0.011 AEP based on the historical POR. However, based on the extrapolated Bulletin 17C frequency curve at De Soto, the 1951 event would be closer to 0.0011 AEP. The incremental probability for each year in the historical sample containing the 1951 event would need to be adjusted to ensure this event is accurately represented in the WAT sampling. Seven years within the historical sample contained the 1951 event so each year was assigned an incremental probability of 0.0011 divided by 7 or 0.000157. This ensured that the WAT sampling would more closely represent the 1951 event with an AEP of 0.0011 instead of 0.011. The same procedure was done for the 1986 event on the Osage River. Any year in the historical sample containing the 1986 event was given a probability override of 0.000633 instead of 0.011. The resulting WAT frequency curve matched the Bulletin 17C curve better, especially around the 0.01 to 0.002 AEPs as shown in Figure 6-13.

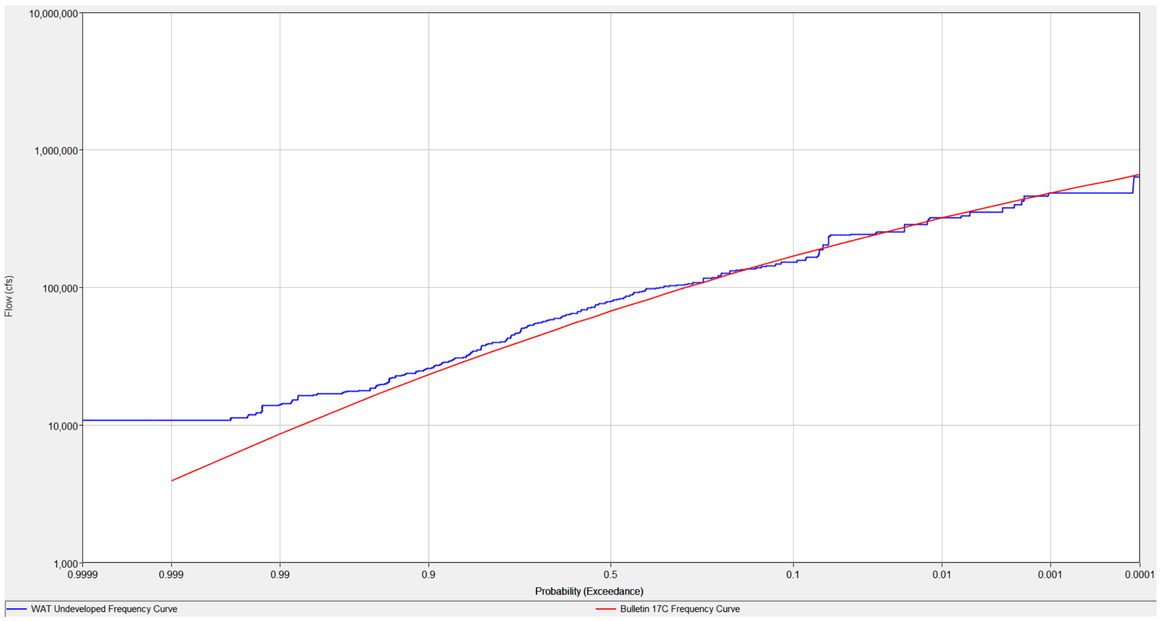
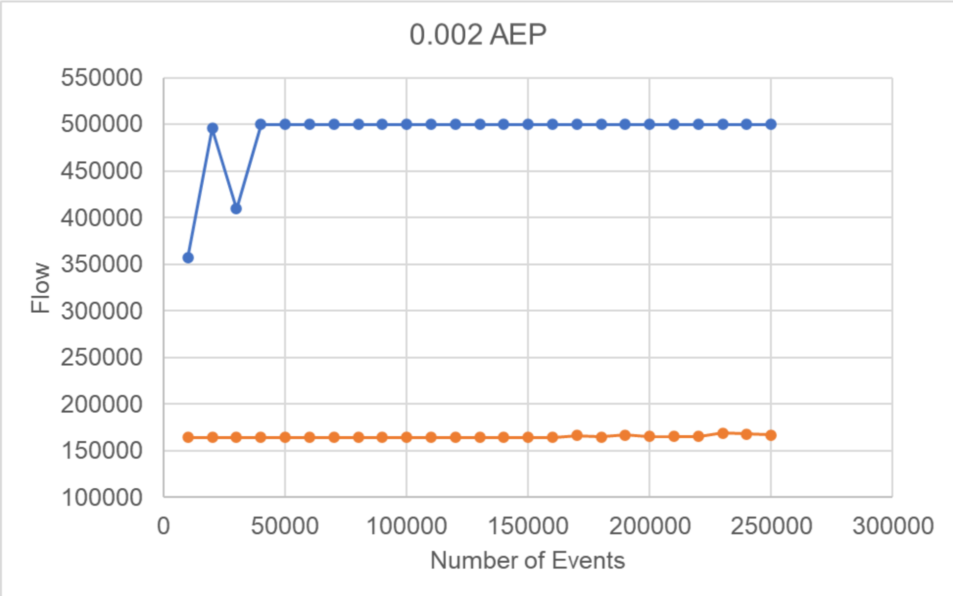


Figure 6-13. WAT 1-Day Frequency Curve at De Soto, KS Compared to Bulletin 17C Frequency Curve After to Correcting with Synthetic Events and Incremental Probability Overrides

6.2.3 FRA Simulation

With the Hydrologic Sampler setup complete, there is one last parameter that needs to be set for the FRA simulation, the number of events per realization. There is uncertainty in how many events are needed in each realization to achieve convergence at the desired AEPs. Convergence is defined as estimated flows at desired probabilities not significantly changing if more events are added to the simulation. The general rule of thumb to achieve convergence is to ensure the number of events per realization is half or a full order of magnitude greater than the return interval you want to converge. For example, if you want the 0.01 AEP or 100-yr return interval to converge, you will need 500 (1/2 order of magnitude) to 1000 (full order of magnitude) events per realization. If you want the 0.002 AEP or 500-yr return interval to converge, you will need 2500 or 5000 events per realization. The Missouri River Flow Frequency study is reporting the 0.002 AEP, so the FRA simulation used 2500 events per realization and 100 realizations for a total of 250000 events. Using 100 realizations also allows for the calculation of a confidence limit, which is an added benefit of the Monte Carlo analysis.

Even though the Missouri River Flow Frequency study followed the rule of thumb, a check was performed at multiple gages along the lower river to estimate how many events were needed to achieve convergence at the 0.01 and 0.002 AEPs. Figure 6-14 through Figure 6-17 show the convergence plots for Gavins Point, Nebraska City, Kansas City, and Hermann. Since variation in both regulated and unregulated values is close to zero by the time 250,000 events are considered, it can be inferred that the regulated and unregulated flows have converged during the FRA simulation and adding more events will not significantly change the output.



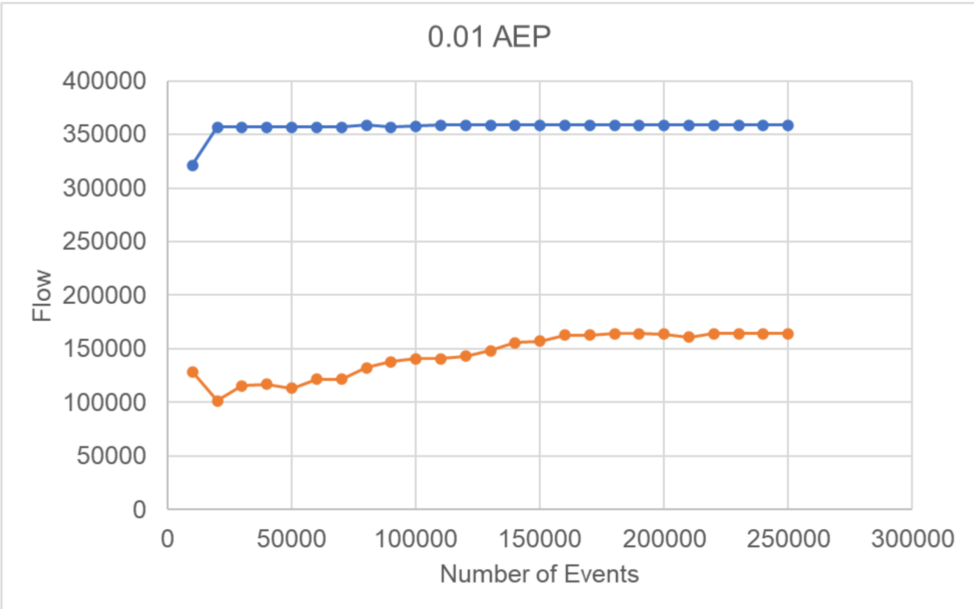


Figure 6-14. Gavins Point Unregulated and Regulated Convergence Plots for the 0.01 and 0.002 AEPs

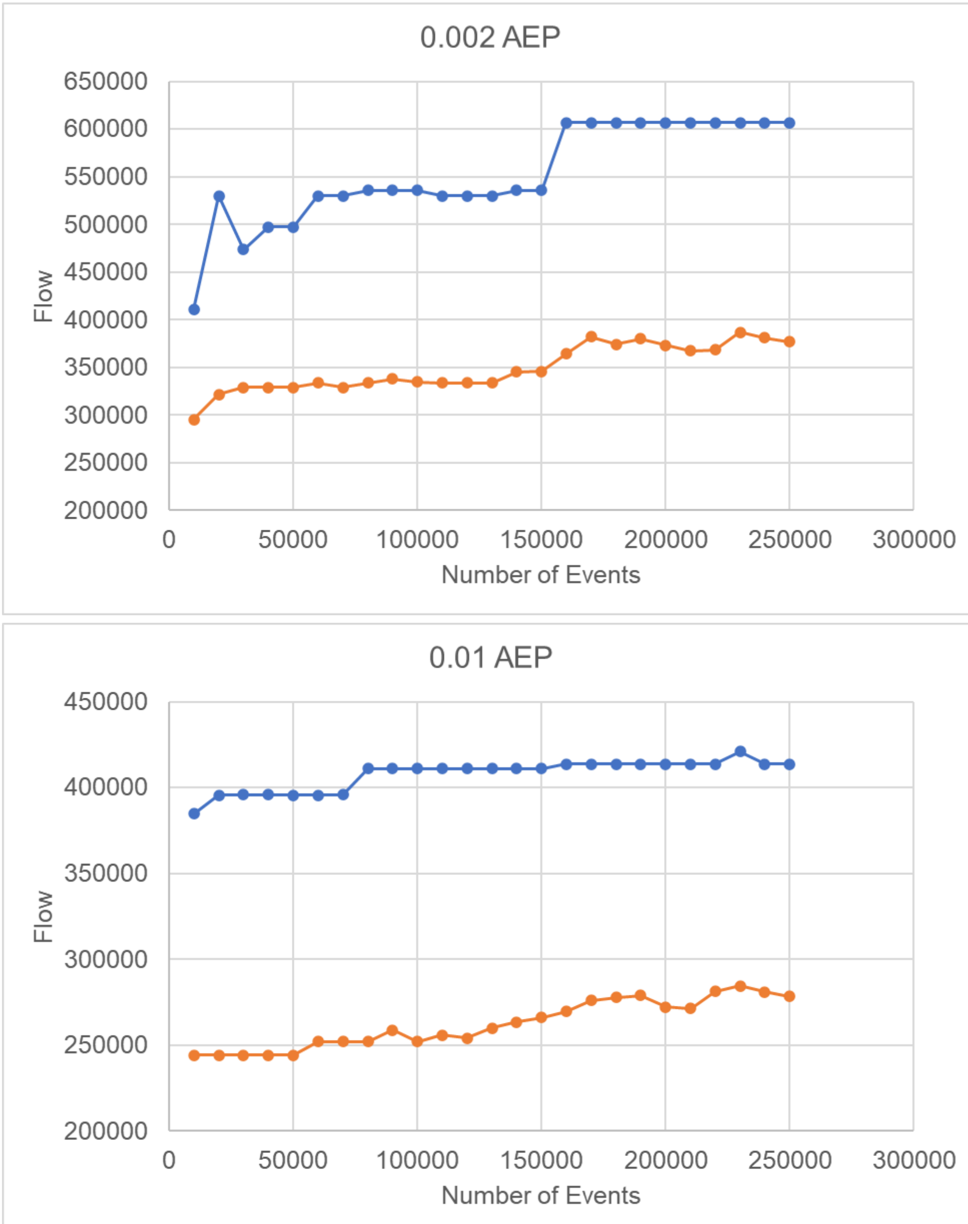


Figure 6-15. Nebraska City Unregulated and Regulated Convergence Plot for the 0.01 and 0.002 AEPs

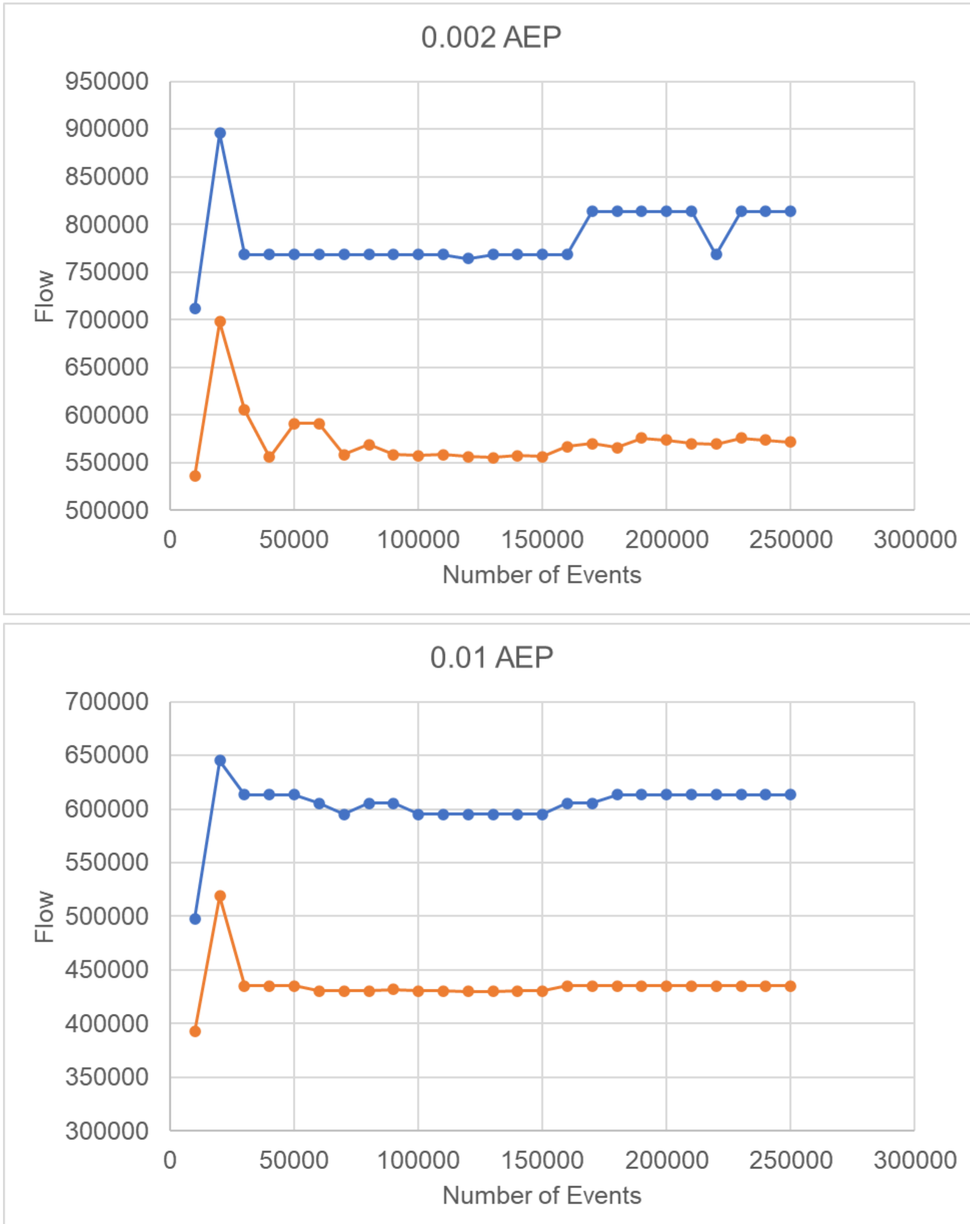


Figure 6-16. Kansas City Unregulated and Regulated Convergence Plot for the 0.01 and 0.002 AEPs

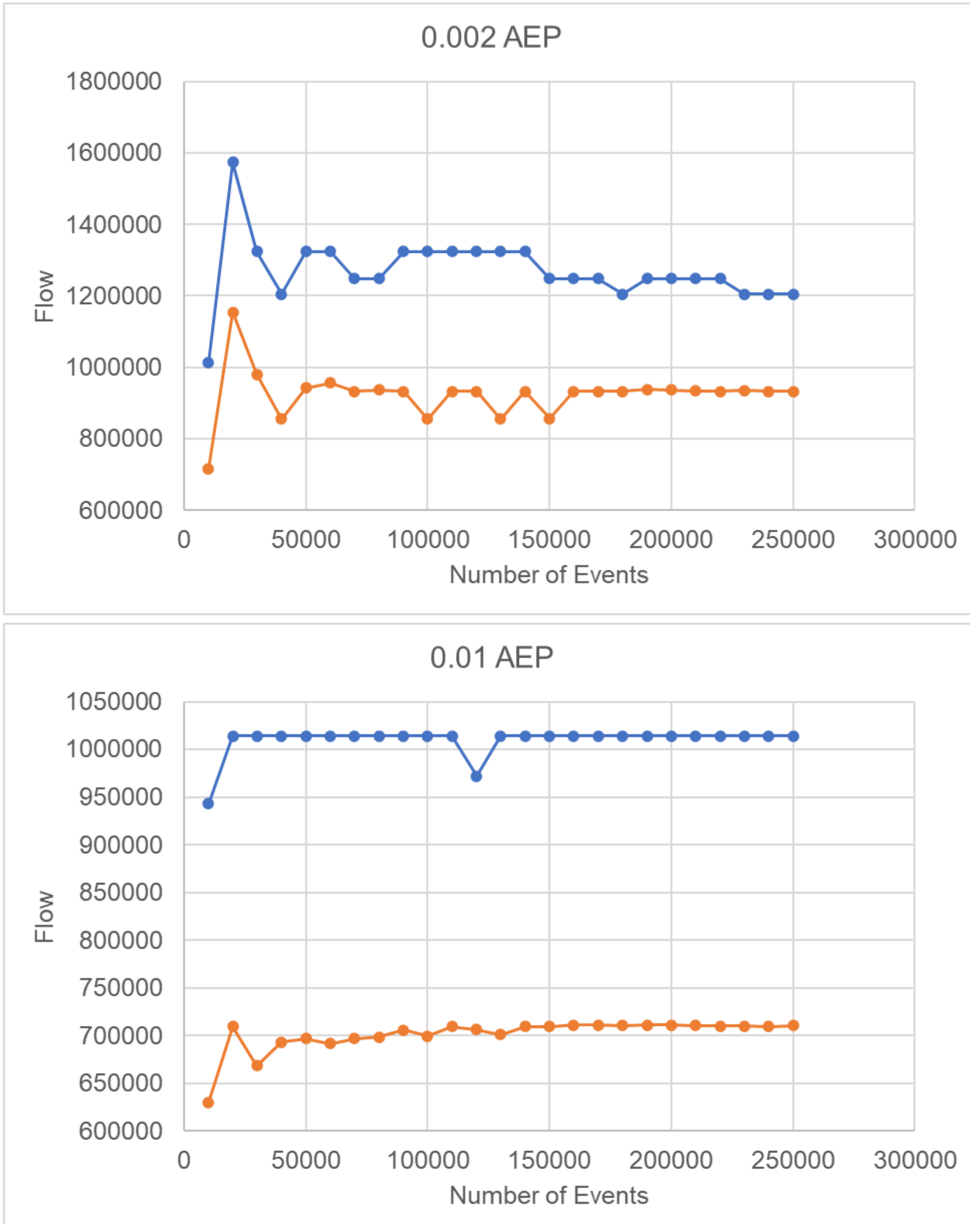


Figure 6-17. Hermann Unregulated and Regulated Convergence Plot for the 0.01 and 0.002 AEPs

6.3 WAT Results

Bulletin 17C is a widely accepted methodology for estimating unregulated flow frequency, so the Bulletin 17C estimates should be reproduced with the WAT. Therefore, with 250,000 years simulated and convergence verified, the last step to verify that the WAT was sampling and producing hydrology that closely matched the historical POR was to compare the 1-day volume frequency curves to the curves produced by the Bulletin 17C methodology. The Bulletin 17C frequency curves reported in the Missouri River Flow Frequency Study at gages between Gavins Point Dam/Yankton and St Joseph used a mixed-population analysis to account for the snowmelt events and their influence on the frequency curves. The WAT data only processed annual maximums, but with the large sample size of the WAT output, the WAT output should closely match the mixed-population curves.

Figure 6-18 through Figure 6-20 show the initial comparison between the WAT unregulated flow frequency curves and the Bulletin 17C flow frequency curves at three locations. At Gavins Point, Nebraska City and Kansas City, the WAT output underestimates the 1% AEP and the 0.2% AEP events, which was caused by a limitation within the WAT: an event's probability is defined for the entire basin, not for individual locations. By default, the WAT assigns each year in the historical sample the same incremental probability. The default incremental probabilities can be overridden, and user defined probabilities can be assigned to each year, which was done for two extreme floods on the Kansas and Osage Rivers, 1951 and 1986, that were skewing the results on the Missouri River. These user defined probabilities are estimated from the unregulated Bulletin 17C frequency curves at one location. However, that probability still represents the event at all locations in the basin. The AEP of events in the historical sample containing the 1951 and 1986 events could be accurately estimated based on one location because those events were mostly localized to a tributary watershed. The rain events that caused the 1951 and 1986 events were intense rain events that were localized over a relatively small area on one tributary, close to the gage used to estimate the AEP. This same issue exists for the synthetic, scaled events that were added to the WAT to help shape the upper end of the frequency curve. Each synthetic, scaled event was assigned an AEP based on the Bulletin 17C frequency curve for the location where most of the inflow occurred. Selected events were scattered throughout the basin to provide a variety of upper and lower basin floods of various durations. Even with a variety of events, it is difficult to adequately capture the correct AEP of an event at every location along the Missouri River because a 1% AEP event at Sioux City may only be a 10% AEP event at Omaha. Table 6-15 summarizes the incremental probabilities for each event in the historical sample and synthetic, scaled events.

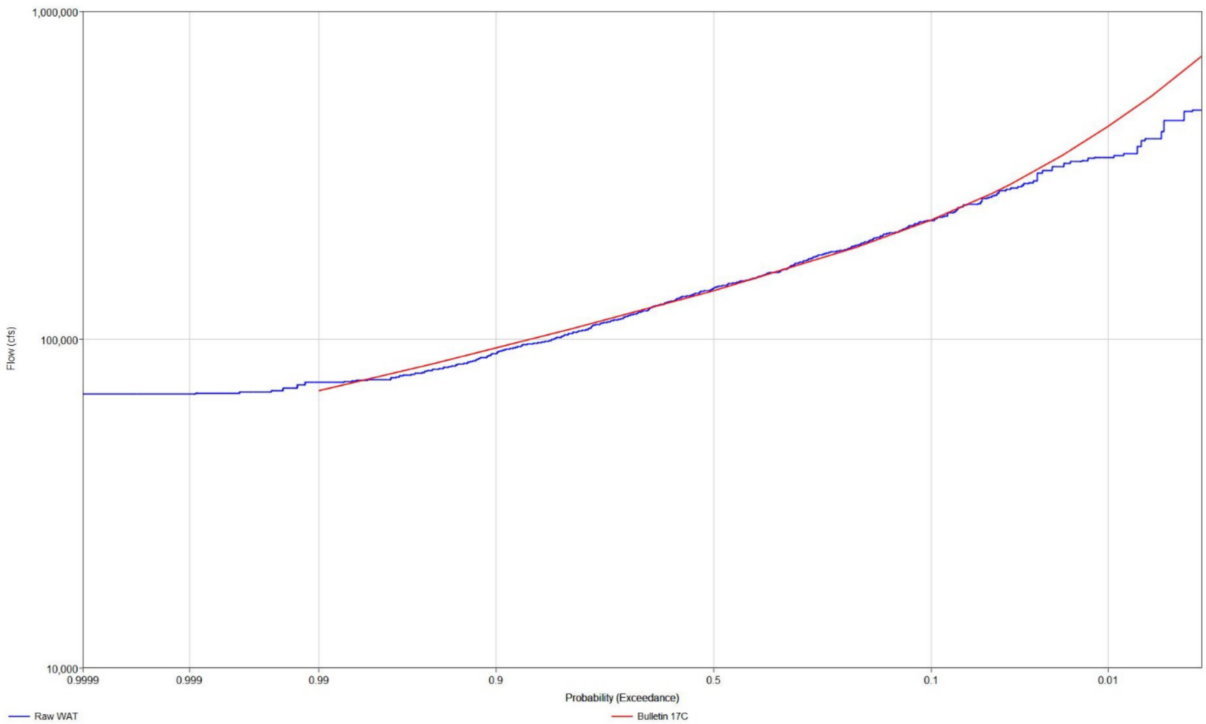


Figure 6-18. Gavins Point Unregulated Flow Frequency Curves

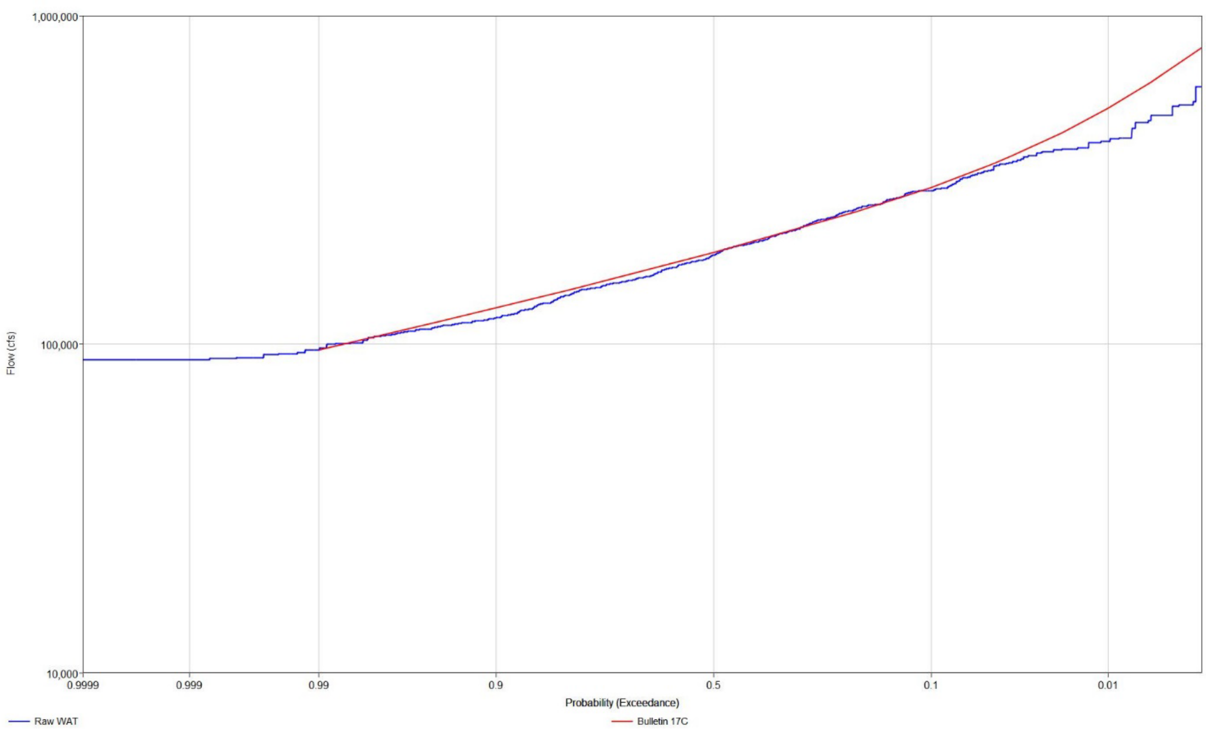


Figure 6-19. Nebraska City Unregulated Flow Frequency Curves

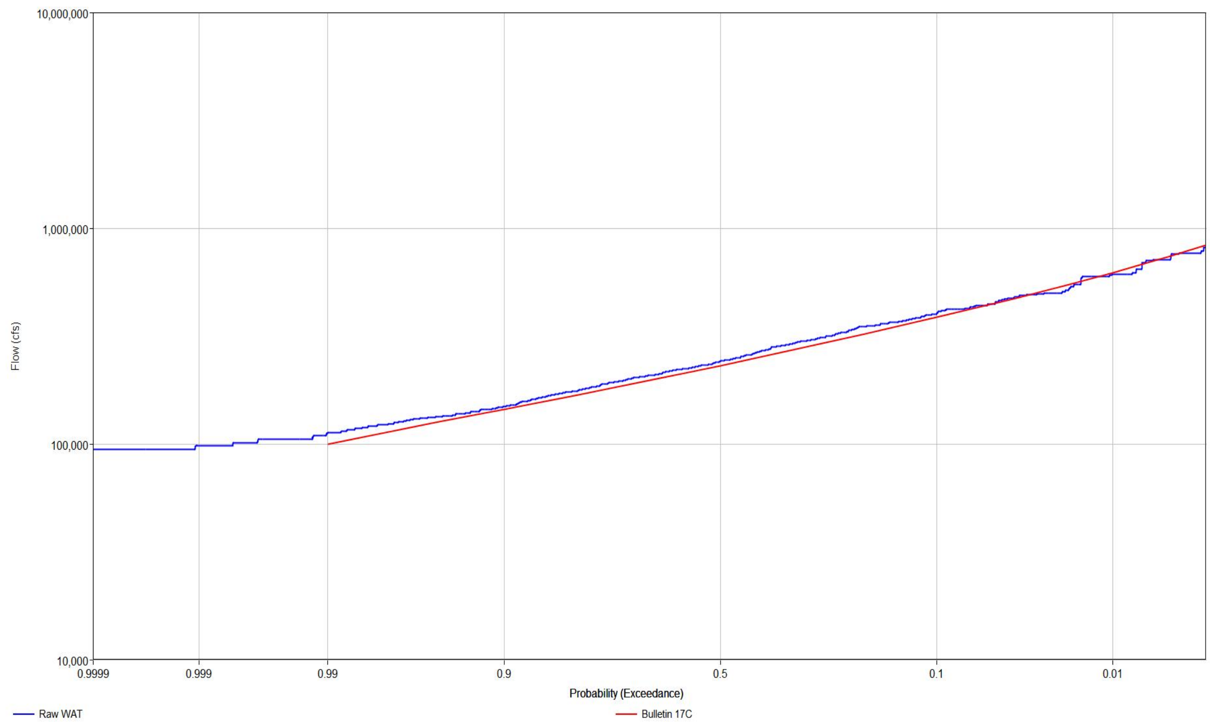


Figure 6-20. Kansas City Unregulated Flow Frequency Curves

Table 6-15. Summary of Incremental Probabilities for Each Year in the Simulation

Year		Probability	
Synthetic Event	**Type**	**Incremental**	**Cumulative**
1951 Years (7)	Historic	0.000157	0.001099
1986 Years (6)	Historic	0.000633	0.004897
All other Years (577)	Historic	0.001660	0.962717
SynDeso1971_25SD	Synthetic - 33	0.012465	0.975182
SynDeso1985_15SD	Synthetic - 50	0.004160	0.979342
SynSttm1941_20SD	Synthetic - 50	0.004160	0.983502
SynSttm1981_15SD	Synthetic - 50	0.004160	0.987662
SynDeso1992_20SD	Synthetic - 100	0.001254	0.988916
SynDeso1971_30SD	Synthetic - 111	0.001254	0.990170
SynSttm1974_20SD	Synthetic - 125	0.001254	0.991424
SynDeso2007_10SD	Synthetic - 142	0.002499	0.993923
SynDeso1985_20SD	Synthetic - 200	0.000423	0.994346
SynNcne2019_10SD	Synthetic - 200	0.000423	0.994769
SynSux1947_20SD	Synthetic - 200	0.000423	0.995192
SynDeso1992_25SD	Synthetic - 250	0.000319	0.995511

Year		Probability	
Synthetic Event	**Type**	**Incremental**	**Cumulative**
SynHemo1995_05SD	Synthetic - 250	0.000319	0.995830
SynMkc1967_10SD	Synthetic - 250	0.000319	0.996149
SynSux1978_15SD	Synthetic - 250	0.000319	0.996468
SynHemo1943_10SD	Synthetic - 333	0.000423	0.996891
SynOahe1952_10SD	Synthetic - 333	0.000423	0.997314
SynSux1972_20SD	Synthetic - 333	0.000423	0.997737
SynDeso2007_15SD	Synthetic - 500	0.000423	0.998160
SynNcne2010_15SD	Synthetic - 500	0.000423	0.998583
SynSux1997_10SD	Synthetic - 500	0.000423	0.999006
SynHemo1944_15SD	Synthetic - 1000	0.000091	0.999097
SynHemo1960_15SD	Synthetic - 1000	0.000091	0.999188
SynSttm1984_25SD	Synthetic - 1000	0.000091	0.999279
SynMkc1993_05SD	Synthetic - 1250	0.000382	0.999661
SynSttm1982_30SD	Synthetic - 2000	0.000195	0.999856
SynSux2011_10SD	Synthetic - 2000	0.000195	1.000051*
SynDeso1951_05SD	Synthetic - 5000	0.000257	1.000308*

* Due to rounding, the incremental probability exceeds 1.0 but is within an acceptable range defined by the WAT.

6.3.1 Post-Processing Output

This issue of events with different likelihoods in different locations can be addressed by a post-process that assigns weights to events in the output sample that cause the sample to reproduce that location's individual flow frequency curve. Defining these unequal weights has the same effect as changing how often those events were randomly sampled. In other words, increasing the weight on an event in the output sample has the result of that event being more likely, as if it had been sampled more frequently. Importantly, when the probability of an event differs across the basin, these output sample event weights must be defined separately at each location.

The process of assigning unequal weights on the events in the output sample, in order to force the output sample to reproduce a given frequency curve, can be used for various reasons. One reason is to allow reproduction of the frequency curve at different locations. Another reason is to force the output sample to match a different input frequency curve than was used in the compute. A WAT compute takes significant computing power and time, and sometimes an adjustment in weights can save the effort of a new compute by instead forcing the existing output sample to reproduce a different input sample. For example, we needed to match a frequency curve of a mixed population, when the compute was based on an unmixed population.

Making use of Monte Carlo output samples that are equally weighted requires no knowledge of weighting. Samples are treated as a simple collection of values, with sample statistics and frequency curves computed as is done with historical data, simply computing mean, standard deviation and skew and perhaps plotting positions. However, weighted samples need more careful attention. A weighted average is familiar:

$$\text{Weighted average} = [\ \textstyle\sum_{i=1,N} (w_i * X_i)] / [\ \textstyle\sum_{i=1,N} w_i]$$

and other weighted moments are computed similarly. But weighted plotting positions used to define annual exceedance probabilities, and so interpret a weighted sample as a probability distribution, are less familiar, and are described below.

6.3.1.1 Weighting Plotting Positions

With equally-weighted samples, each sample member has equal incremental probability. If the number of events = N, then to allow a sum of 1, each event has incremental probability 1/N.

A plotting position is an estimate of the exceedance probability of a member of a sample, in the simple case based only on the sample size N and the event's position within it. First, the sample is sorted and each event is assigned a rank i = 1,…., N, starting with i = 1 for the largest event. Thus, i is the number of events greater than or equal to event(i). The exceedance probability is the sum of the incremental probabilities of the events that are greater than or equal to event(i), so for an equally-weighted sample, exceedance probability $\approx$ i/N. Further, each event represents a probability range having width 1/N.

The Hazen plotting position was used as the basis for weighted plotting positions, and so will be used first in discussion of equally-weighted samples. The Hazen plotting positions for an equally-weighted sample are defined as:

$$\text{Probability } [Q \geq q(i)] = \text{Hazen plotting position}(i) = i/N - 0.5/N$$

The Hazen plotting position is thus the sum of incremental probability of all events greater (including the event itself), which is (i/N), minus half of the incremental probability of the event itself, which is (1/2 * 1/N). This subtraction removes half of the incremental probability of event(i), in effect centering the plotted event in the middle of the probability range it represents.

In general, the incremental probability of each event in a sample can be defined as the event's weight divided by the sum of all event weights. In the equally-weighted sample, each event has weight = 1, and so the sum of weights is sample size N, leading to incremental probability = 1/N.

In equation form, incremental probability is defined as:

incr.prob(i)= weight of event(i) / [Σj=1,N weight of event(j)]

When event weights are not equal, the incremental probability of each event in the sample is computed individually. One can make an effort to ensure that the sum of all weights is equal to the number of events to simplify the expression, but this effort is not required. The division by the sum of weights ensures than the incremental probabilities of all events will sum to 1.0.

For a plotting position of unequally weighted events, based on Hazen (above):

Plotting position(i) for event i = [Σj=1,i (incr.prob(j)] – 0.5*incr.prob(i)

The logic follows the Hazen plotting position for the equally-weighted sample. The first term (the summation) is the sum of incremental probabilities of event(i) and all larger events (having lower ranks). The second term is the subtraction of half of the incremental probability of event(i). This subtraction moves the estimated exceedance probability from including all of the incremental probability of event(i) to only half of it, in effect centering the plotted event to the middle of the probability range it represents.

6.3.1.2 Defining Output Weights

It was noted above that a required validation in Monte Carlo simulation is that the immediate output sample, before any analysis or transformation, will reproduce the historical/initial probability distribution in frequency analysis. In this study, the untransformed variable is the unregulated flows.

Also mentioned previously, an equally-weighted output sample that was generated from historical/initial sample probabilities defined for the entire watershed will often not reproduce the unregulated flow frequency curve for that location. Weighting of the output sample at each location throughout the watershed allows this reproduction.

In this study, only the upper end of the unregulated frequency curves captured by the output samples differed from the location-specific unregulated frequency curves in most cases. To impact the upper end, only the largest events in the output samples needed to be weighted to shift the output curves to match. Therefore, for a given location, these weights were defined manually, by trial and error, until a set of weights provided plotting positions of the output sample events that fell adequately close to the unregulated flow frequency curve for that location.

6.3.1.3 Output Weights for Each Location

Because the actual probability of a watershed-wide event can be different at each location in the watershed, a set of weights on events sampled into the output sample was developed and stored separately for each location. These weights must be carried through any analysis of the output sample as its events are transformed to regulated flows and the sample is processed into frequency curves or summary metrics. Note that output sample events might sort in a different order as regulated flows than they did as unregulated flows. Since the weights are applied to the events, the weight assigned to largest unregulated event would be assigned to the regulated event that results from the largest unregulated event and not necessarily the largest regulated event. Table 6-16 lists the weights for the largest four unregulated and regulated events from the output sample as an example.

Table 6-16. Largest Four Unregulated and Regulated Events at Gavins Point and their Applied Weights

Event Rank	Unregulated Flow (cfs)	Unregulated Weight	Regulated Flow (cfs)	Regulated Weight
1	772,353	5.0	311,000	1.0
2	581,941	6.0	310,500	6.0
3	499,951	2.0	307,000	6.0
4	495,786	2.0	306,500	0.9

6.3.2 Confidence Limits

Post-processing mean frequency curves based on all 250,000 events alters the uncertainty around the mean frequency curve because the incremental probability of some of the largest events were adjusted. In order to calculate accurate confidence limits around the adjusted mean frequency curve, the same post-processing is performed on each realization (2500 events) of data. Post-processing each realization allows for the same weight adjustment to be applied to the confidence limits when those are calculated. Confidence limits were calculated by creating a probability distribution around each quantile using data from each realization as shown in Figure 6-21. In this case, there were 100 realizations, so each quantile had 100 data points that defined the probability distribution. The 95 and 5 percent values were selected from that probability distribution to define the confidence limits around each quantile. Because the post-processing was performed on each realization, the confidence limits reflect the same adjustment made to the mean frequency curve as shown in Figure 6-22. Since the post-processing focused on the less frequent or larger events, the 95 percent confidence limit showed more of an adjustment than the 5 percent confidence limit. Mean frequency curves are shown in Figures 6-23 through 6-28 but the confidence limits are estimated vertically around each quantile. Estimating confidence limits vertically for the 95 and 5 percent limits means the largest and smallest 5 events are removed.

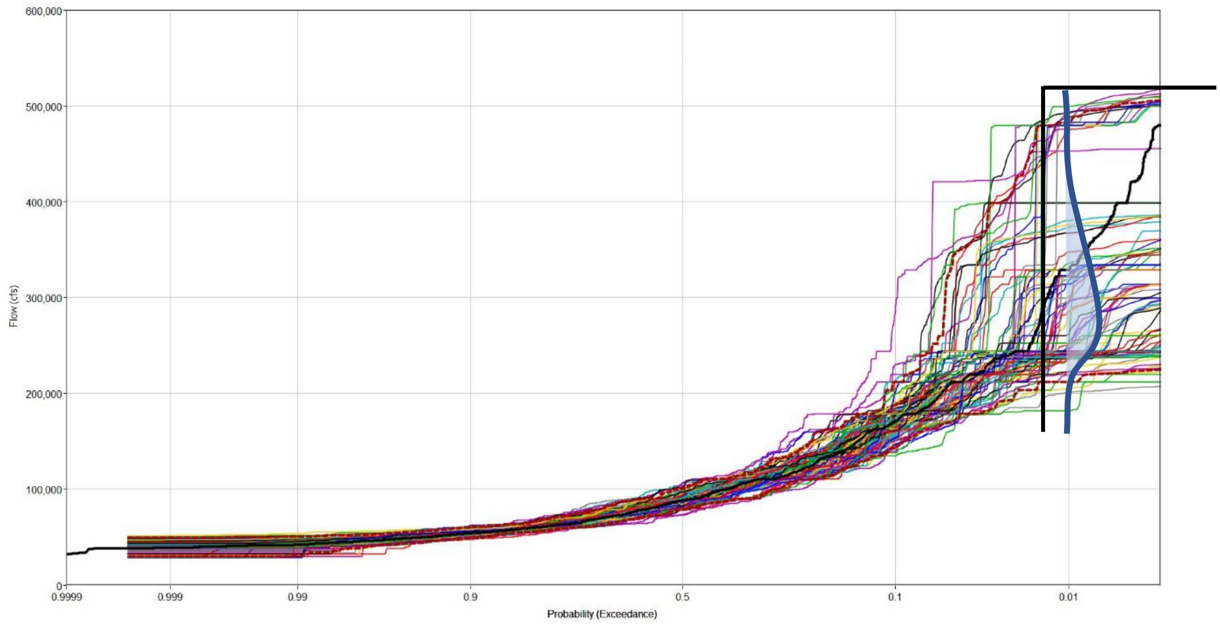


Figure 6-21. Frequency Curves of 100 Realizations

Note: 95 and 5 Percent Confidence Limits Shown as Red Dashed Lines at Nebraska City. An Example Vertical Probability Distribution is Shown in Shaded Blue.

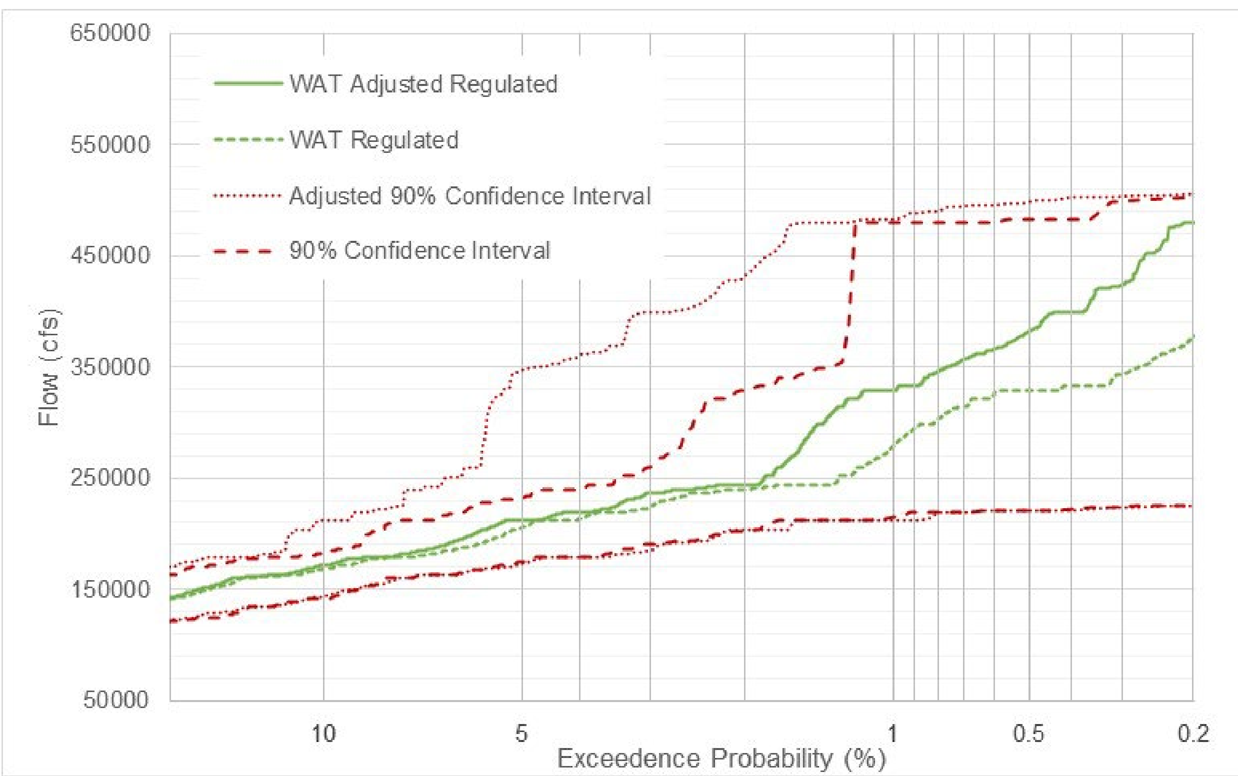


Figure 6-22. Mean and Confidence Limits for Both Raw and Weighted Frequency Curves at Nebraska City

6.3.3 WAT Final Results

Each year sampled by the Hydrologic Sampler is simulated through the ResSim model, producing regulated flows and after processing annual maximums of the 250,000 simulated years, regulated flow frequency curves. Using a Monte Carlo approach of calculating regulated flow frequency curves can account for all the different combinations of pool elevations, inflows, and operations associated with those combinations. Operational nuances can be captured better with this method versus other methods that fit curves through data. One such example is the influence operating Oahe's spillway has on the shape of the regulated flow frequency curve, described in Section 8.2.1. In comparison, the other method used in the Missouri River Flow Frequency Study is the transform method. This method uses a relationship between the unregulated flows with a known frequency (e.g., Bulletin 17C) and the corresponding regulated flows from simulated events. A curve is fit through the data so that the frequency of a regulated flow can be inferred as the equivalent frequency of the corresponding unregulated flow. The limitation with this method is that a curve fit through the data will have a hard time capturing the impacts of regulation on the shape of a frequency curve, especially when the data has large variations or scatter. Figure 5-2 shows the transform relationship between unregulated and regulated flows at Gavins Point. Note the wide variation in data and the smooth nature of the transform curve, which makes it difficult to capture variations in regulation.

Figure 6-23 through Figure 6-32 show the comparison plots for the unadjusted and adjusted, unregulated and regulated flow frequency curves created from the WAT simulation against the frequency curves created by Bulletin 17C and the transform methods. Table 6-17 and Table 6-18 summarize the final or adjusted unregulated and regulated flow frequency curves, respectively. With the WAT frequency curve for Gavins Point, there is a noticeable plateau in regulated flows at 164,000 cfs caused by the operational criteria previously described. When the transform method is used, a smooth regulated flow frequency curve is produced, which does not capture the operational nuance caused by Oahe's spillway operation. This plateau causes lower estimates of regulated flow frequency at Sioux City, Omaha, and Nebraska City when compared to the transform method, especially at the less frequent portions of the curve. The difference becomes less the farther downstream the gage is from Gavins Point. This is caused by less influence of regulation as more unregulated drainage area is incorporated. The WAT estimates higher flow frequency values downstream of Nebraska City as more highly unregulated events begin to influence the shape of the regulated flow frequency curve.

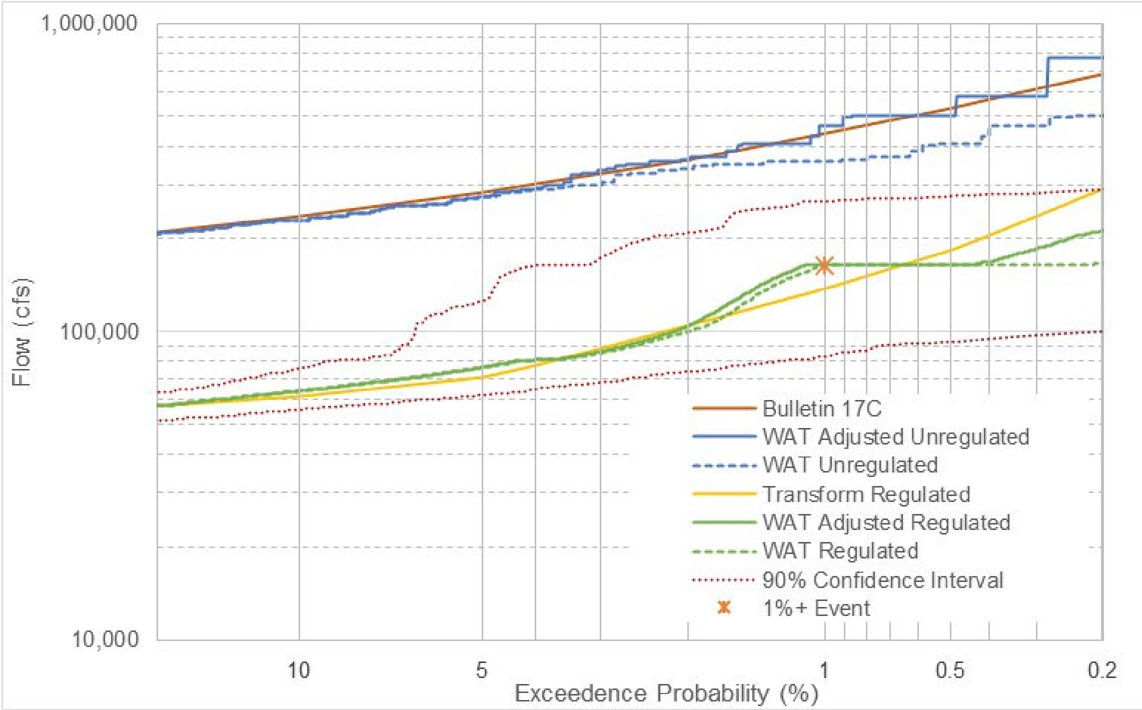


Figure 6-23. Comparison of Gavins Point Unregulated and Regulated Flow Frequency Curves

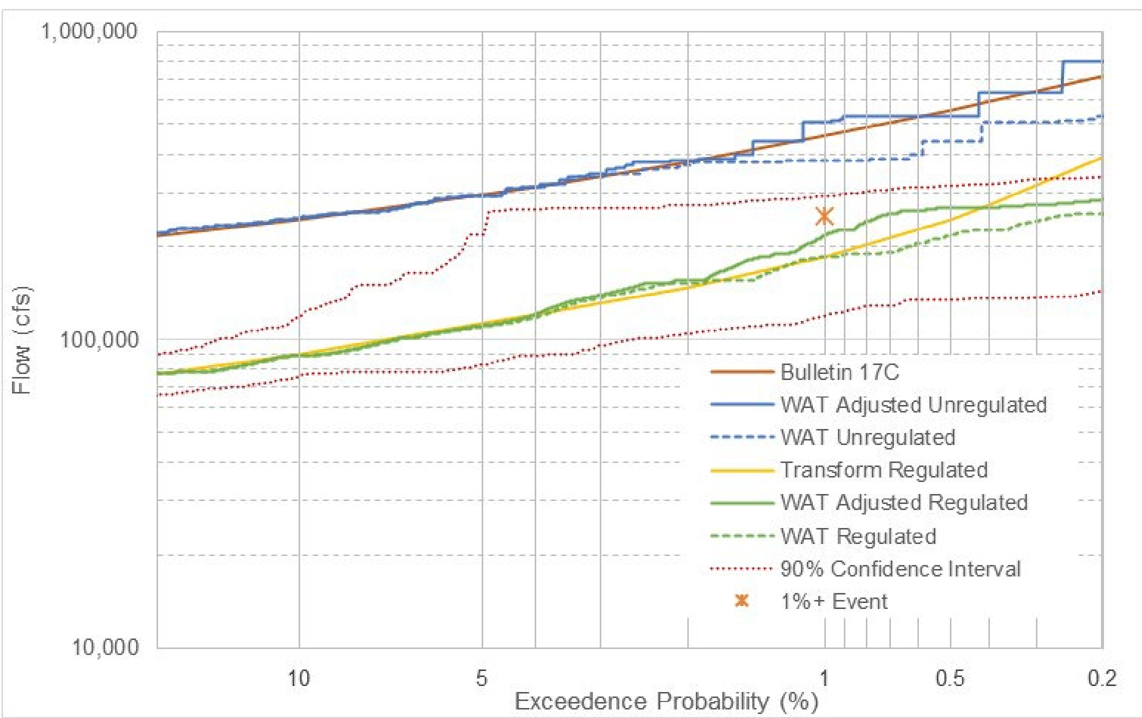


Figure 6-24. Comparison of Sioux City Unregulated and Regulated Flow Frequency Curves

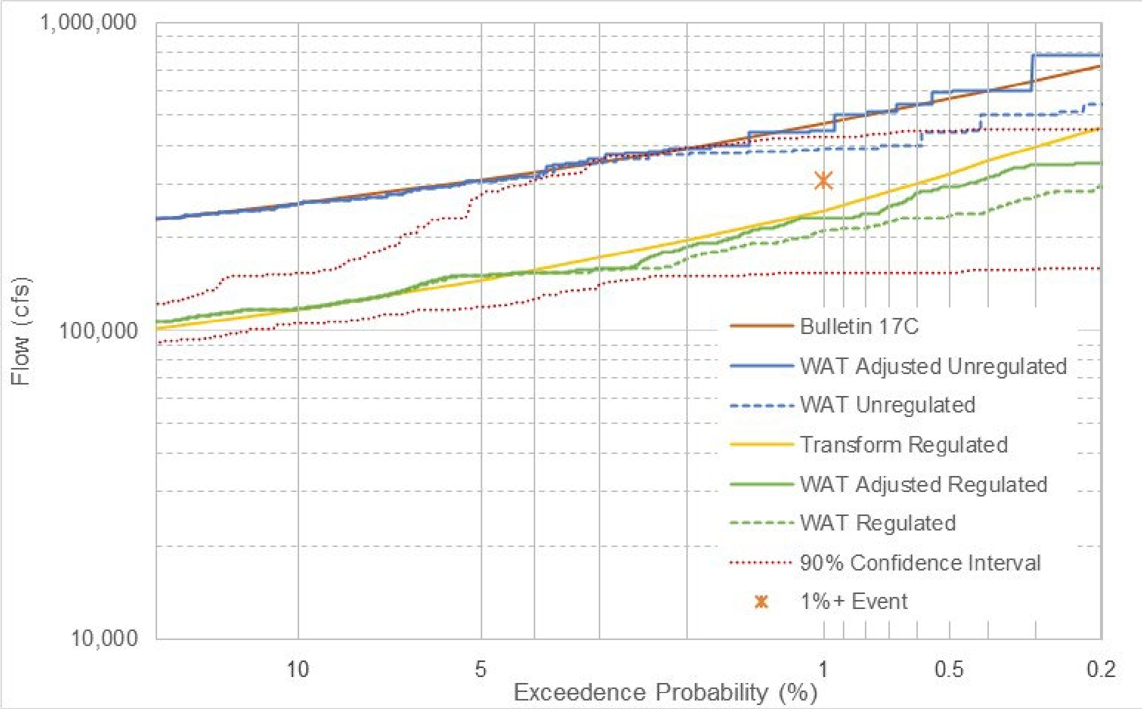


Figure 6-25. Comparison of Omaha Unregulated and Regulated Flow Frequency Curves

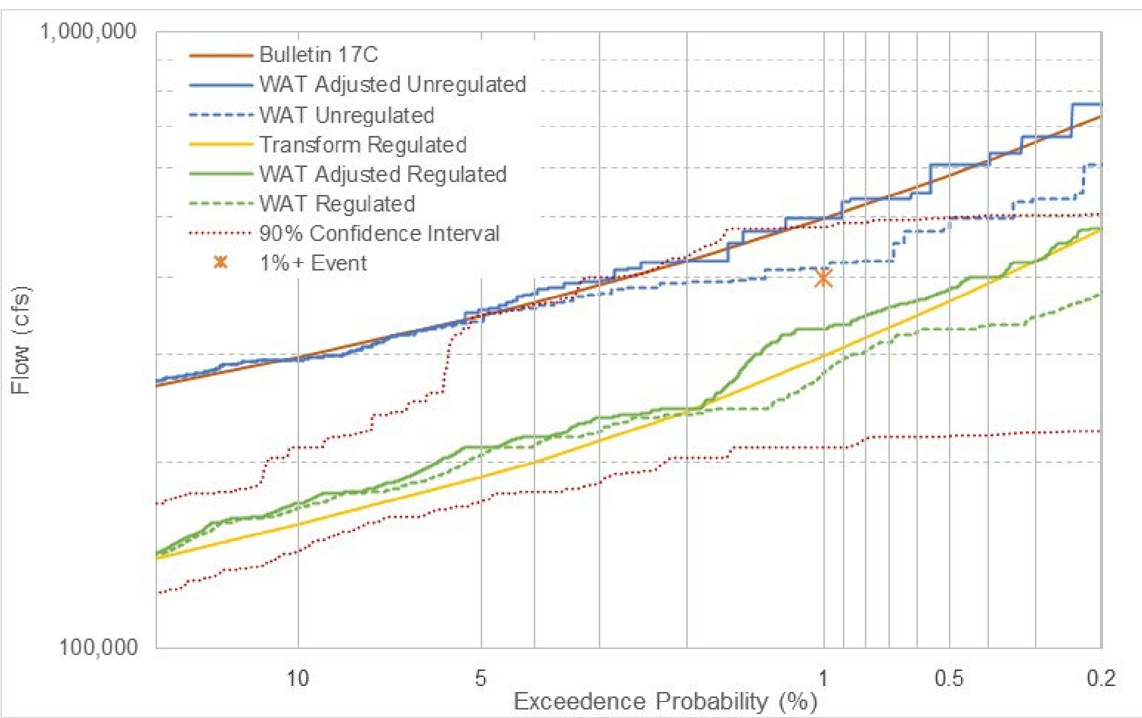


Figure 6-26. Comparison of Nebraska City Unregulated and Regulated Flow Frequency Curves

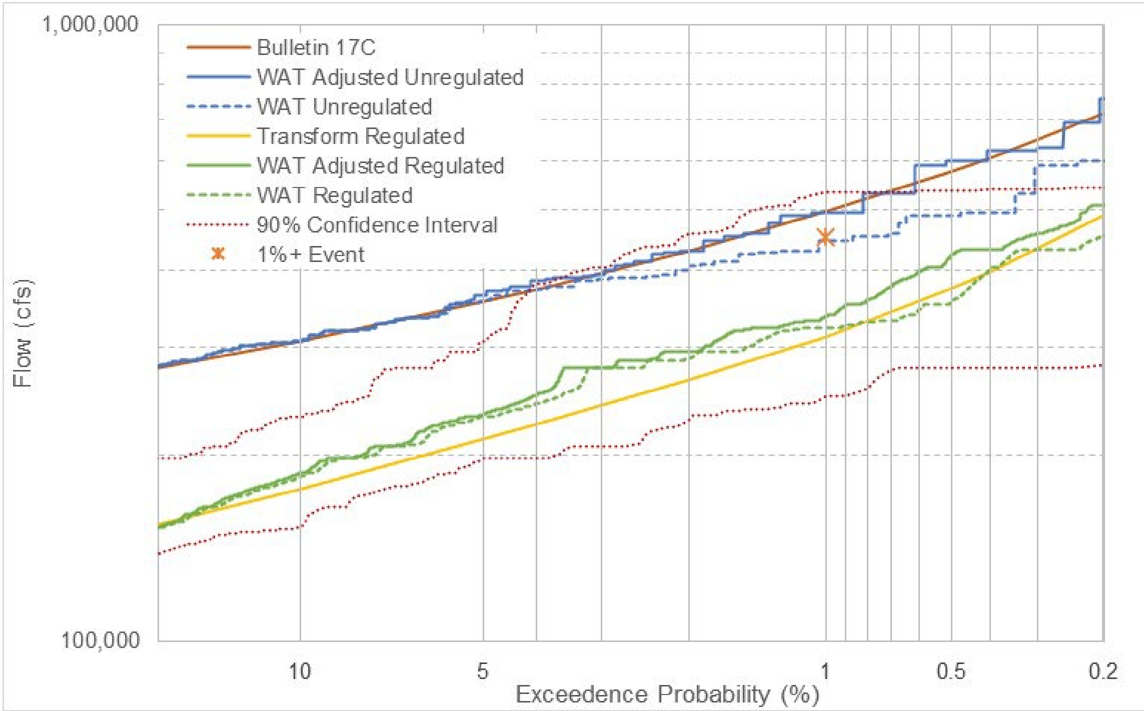


Figure 6-27. Comparison of Rulo Unregulated and Regulated Flow Frequency Curves

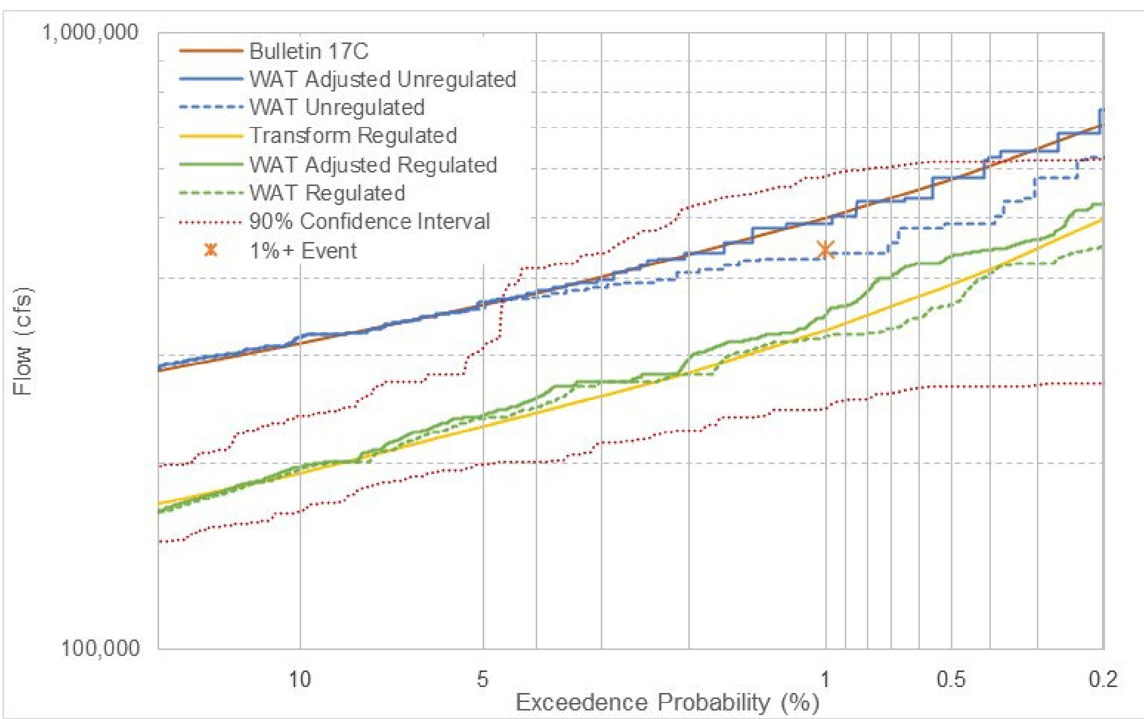


Figure 6-28. Comparison of St Joseph Unregulated and Regulated Flow Frequency Curves

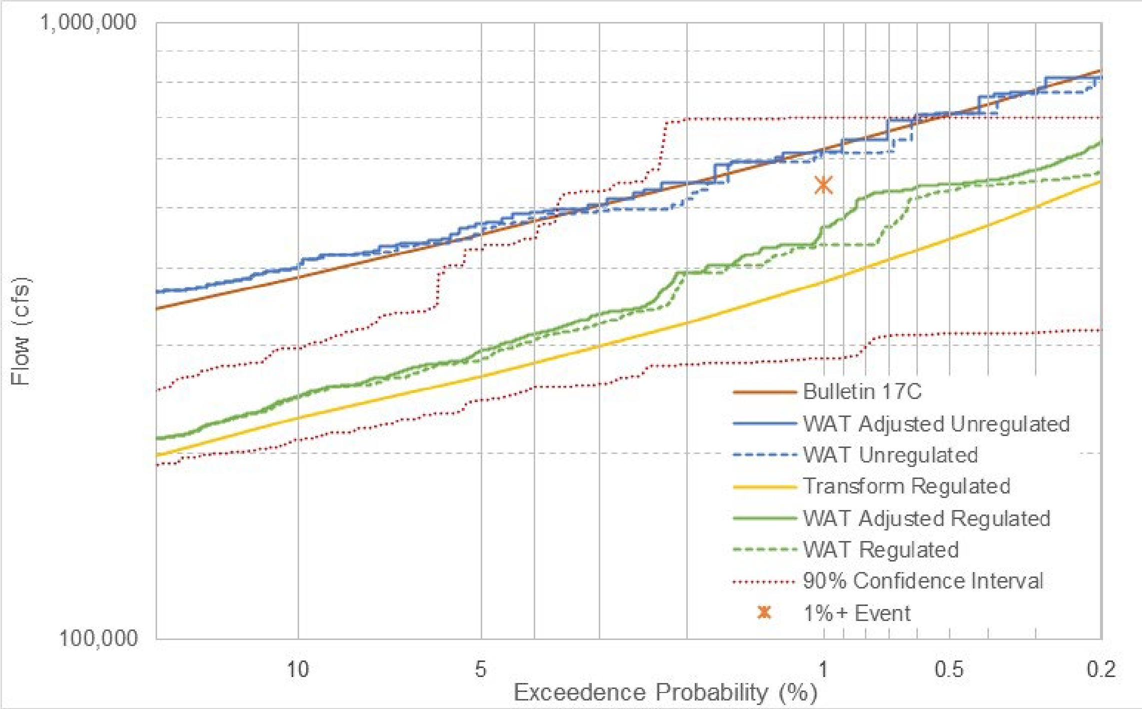


Figure 6-29. Comparison of Kansas City Unregulated and Regulated Flow Frequency Curves

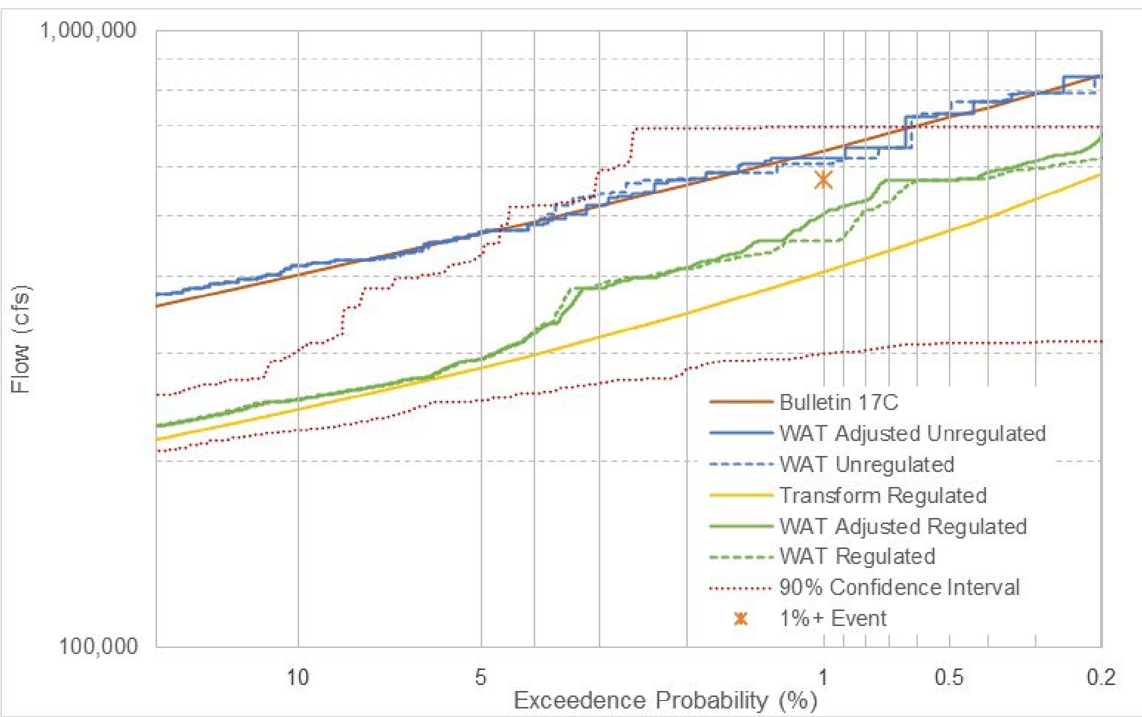


Figure 6-30. Comparison of Waverly Unregulated and Regulated Flow Frequency Curves

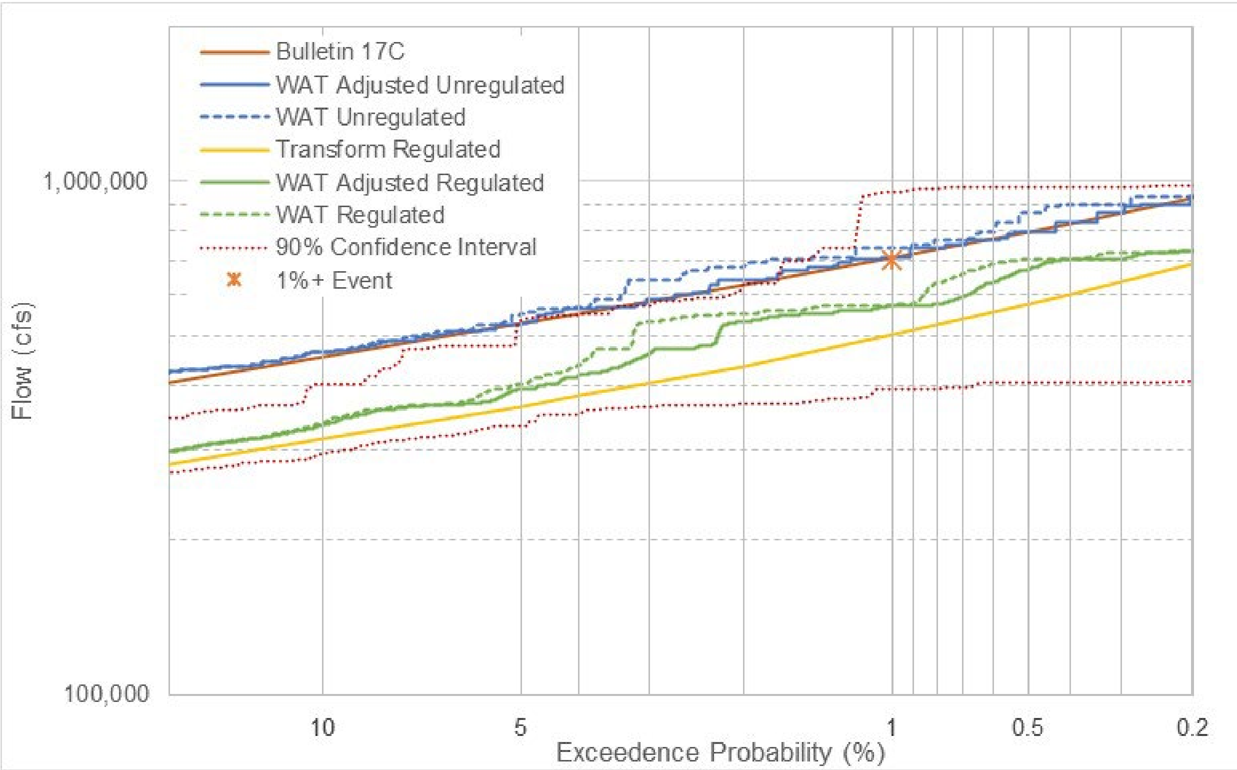


Figure 6-31. Comparison of Boonville Unregulated and Regulated Flow Frequency Curves

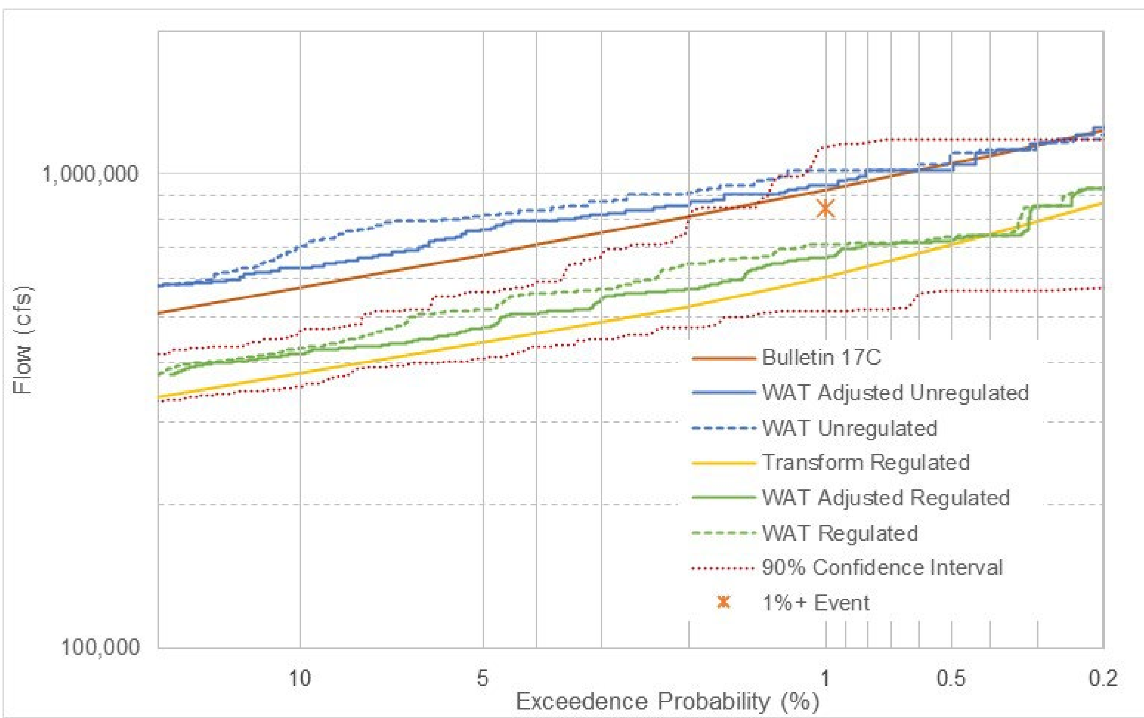


Figure 6-32. Comparison of Hermann Unregulated and Regulated Flow Frequency Curves

Table 6-17. Summary of Unregulated Flow Frequency Annual Exceedance % Probability (Flow in CFS) Produced by the Monte Carlo to reasonably match the Expected Probability Flows

AEP (%)	Yankton	Sioux City	Omaha	Nebraska City	Rulo	St Joseph	Kansas City	Waverly	Boonville	Hermann
0.2	772,000	800,000	780,000	762,000	757,000	748,000	814,000	840,000	932,000	1,248,000
0.4	582,000	636,000	598,000	607,000	623,000	630,000	759,000	766,000	833,000	1,109,000
0.5	500,000	532,000	592,000	607,000	600,000	582,000	711,000	733,000	794,000	1,014,000
1	465,000	511,000	445,000	497,000	494,000	489,000	619,000	623,000	711,000	944,000
2	362,000	383,000	390,000	424,000	429,000	438,000	550,000	571,000	641,000	857,000
4	292,000	313,000	318,000	375,000	383,000	379,000	492,000	485,000	563,000	797,000
5	273,000	292,000	305,000	353,000	364,000	366,000	471,000	472,000	528,000	761,000
10	230,000	248,000	258,000	294,000	307,000	320,000	405,000	415,000	465,000	632,000
20	193,000	209,000	214,000	258,000	267,000	277,000	349,000	348,000	406,000	543,000
50	143,000	150,000	159,000	187,000	195,000	202,000	241,000	247,000	291,000	385,000
80	104,000	108,000	116,000	142,000	147,000	151,000	177,000	181,000	210,000	260,000
90	90,000	93,000	101,000	121,000	123,000	129,000	149,000	152,000	173,000	210,000
95	81,000	82,000	90,000	112,000	114,000	120,000	135,000	136,000	153,000	185,000
99	74,000	73,000	78,000	96,000	98,000	104,000	113,000	114,000	121,000	142,000

Note: These flows were computed through the Monte Carlo analysis and are intended to reasonably match the expected probability results from Bulletin 17C. For official expected unregulated flow frequencies, please refer to Table 3-19.

Table 6-18. Summary of Regulated Flow Frequency Annual Exceedance % Probability (Flow in CFS) Produced by the Monte Carlo, EXPECTED Probability Flows

AEP (%)	Yankton	Sioux City	Omaha	Nebraska City	Rulo	St Joseph	Kansas City	Waverly	Boonville	Hermann
0.2	213,000	285,000	351,000	480,000	510,000	526,000	640,000	674,000	731,000	933,000
0.4	169,000	268,000	312,000	399,000	432,000	444,000	555,000	588,000	702,000	742,000
0.5	164,000	266,000	293,000	382,000	422,000	433,000	546,000	573,000	672,000	722,000
1	164,000	218,000	232,000	329,000	336,000	349,000	467,000	503,000	572,000	666,000
2	104,000	156,000	187,000	244,000	294,000	296,000	393,000	412,000	531,000	571,000
4	81,000	121,000	154,000	220,000	250,000	255,000	312,000	323,000	417,000	506,000
5	77,000	111,000	151,000	212,000	233,000	239,000	293,000	294,000	393,000	473,000
10	64,000	89,000	118,000	171,000	187,000	197,000	247,000	251,000	334,000	416,000
20	54,000	71,000	99,000	132,000	148,000	157,000	197,000	214,000	280,000	345,000
50	44,000	47,000	62,000	88,000	101,000	107,000	136,000	142,000	204,000	262,000
80	38,000	41,000	47,000	61,000	65,000	75,000	97,000	101,000	134,000	175,000
90	35,000	38,000	43,000	54,000	57,000	66,000	82,000	86,000	109,000	142,000
95	33,000	36,000	40,000	49,000	51,000	59,000	72,000	75,000	97,000	123,000
99	28,000	32,000	37,000	42,000	44,000	52,000	58,000	59,000	78,000	100,000

Note: See Table 6-11 for the regulated computed probabilities.

While this report uses expected probabilities throughout, certain uses of the data require the computed probability, which leverages the median from the statistics. These uses can include certain risk assessments that separately account for uncertainty, such as studies leveraging HEC-FDA, to avoid double counting this adjustment. This data was added to the report by adjusting the weighting at each gage to match the computed Bulletin 17C unregulated flow frequency results presented in Table 3-21. Table 6-19 presents the results for the computed regulated flow frequencies. Additional information on the differences between expected and computed probability are included in Section 3.9.

Table 6-19. Summary of Regulated Flow Frequency Annual Exceedance % Probability (Flow in CFS) Produced by the Monte Carlo, COMPUTED Probability Flows

AEP (%)	Yankton	Sioux City	Omaha	Nebraska City	Rulo	St Joseph	Kansas City	Waverly	Boonville	Hermann
0.2	212,000	275,000	347,000	457,000	497,000	462,000	603,000	632,000	724,000	855,000
0.4	164,000	266,000	293,000	384,000	430,000	428,000	546,000	575,000	681,000	723,000
0.5	164,000	258,000	271,000	362,000	401,000	420,000	543,000	573,000	634,000	715,000
1	164,000	200,000	232,000	323,000	329,000	331,000	435,000	485,000	562,000	662,000
2	102,000	156,000	187,000	244,000	294,000	282,000	381,000	406,000	529,000	568,000
4	81,000	121,000	154,000	220,000	246,000	253,000	313,000	318,000	415,000	506,000
5	76,000	111,000	151,000	212,000	232,000	238,000	294,000	292,000	392,000	472,000
10	64,000	89,000	118,000	171,000	186,000	197,000	247,000	251,000	334,000	416,000
20	54,000	71,000	99,000	132,000	147,000	157,000	197,000	213,000	280,000	345,000
50	44,000	47,000	62,000	88,000	101,000	107,000	136,000	142,000	204,000	262,000
80	38,000	41,000	47,000	61,000	65,000	75,000	97,000	101,000	134,000	175,000
90	35,000	38,000	43,000	54,000	57,000	66,000	82,000	86,000	109,000	142,000
95	33,000	36,000	40,000	49,000	51,000	59,000	72,000	75,000	97,000	123,000
99	28,000	32,000	37,000	42,000	44,000	52,000	58,000	59,000	78,000	100,000

Note: See Table 6-10 for the regulated expected probabilities.

7. Adopted Results

7.1 Introduction

This document discusses how the HEC-WAT (WAT) Monte Carlo and Transform methods were evaluated to determine which method to adopt as the regulated flood flow frequency values for the ten gages on Missouri River downstream of Gavins Point Dam. Figures of flow frequency plots at the ten Missouri River gages are presented in the final section of this document.

7.1.1 Summary

The team's recommendation is to endorse the WAT Monte Carlo methodology and adopt the results as the official USACE published numbers in the report. Table 7-1 summarizes the advantages and disadvantages of the two methods. The WAT Monte Carlo method has advantages over the Transform method because it is better able to account for regional variability in the basin and extrapolate the unregulated to regulated relationship in a probability context. Additional details on each criterion are provided in Section 7.2.

Table 7-1. Comparison of the WAT Monte Carlo and the Transform Methods of Computing Regulated Flow Frequencies against Selection Criteria

Criterion	WAT Monte Carlo	Transform
Agreement with Bulletin 17C, Unregulated Flow Frequency	• Good agreement after post-processing. Single probabilities must be assigned to scaled floods, which can be more significant in some reaches than others, to ensure they are sampled at a reasonable rate. **Neither method has advantage.**	• Full agreement, (17C curves are a direct input). **Neither method has advantage.**
Capturing Natural Variability	• **Advantage:** More regional variations and combinations of starting conditions from carryover reservoir storage are considered.	• **Disadvantage:** Limited to variability in POR in the same order as it occurred and scaled floods w/ reservoirs starting at the base of flood pools. Sensitivity to starting pool elevation could be tested but would increase already wide scatter in the transform and would not provide probabilities.
Capturing Knowledge Uncertainty	• Both methods used historic flood information to extend the historic period for Bulletin 17C unregulated flow frequencies; **neither method has advantage.** • **Advantage:** Able to reduce knowledge uncertainty by extending the record available for simulation through the reservoirs	• Both methods used historic flood information to extend the historic period for Bulletin 17C unregulated flow frequencies; **neither method has advantage.** • **Disadvantage:** Relies on the 90-year POR and scaled floods for simulation through the dams.

Criterion	WAT Monte Carlo	Transform
	using the big bucket and synthetic (scaled) floods.	
Unregulated to Regulated Relationship	• **Advantage:** Relationship is not needed because regulated flow frequency is directly computed with scaled floods included. • Probabilities are assigned to scaled floods at a single representative location (see Bulletin 17C criteria); **neither method has advantage.**	• **Disadvantage:** Period of record and scaled floods produce wide scatter, requiring judgement to fit a relationship. • Probabilities are not assigned to scaled floods; **neither method has advantage.** • **Advantage:** If a relationship can be determined, simple math is needed to convert Bulletin 17C to regulated.
Regulated Flow Frequency Curve Shape	• **Advantage:** Shape of regulated flow frequency curves defined by combined probabilities of reservoir conditions and inflows. At Gavins Point, the shape captures operations expected to minimize spillway damage at Oahe, which is seen to diminish with distance downstream of the dams. Changes in shape below tributary dams correspond with transitions to surcharge operations.	• **Disadvantage:** Smooth curve caused by unregulated-regulated relationship fit through a cloud of data may result in an unrealistic shape on several gages, especially Gavins Point, but also Sioux City, and Omaha. • **Advantage:** At AEP's less frequent than 0.2%, the shape shows a transition that could begin to approach unregulated flow, which is expected as the ability to regulate flows is diminished.
Accepted Methodology	• **Advantage:** Modern methodology able to overcome limitations of the transform method.	• **Advantage:** Accepted methodology used for previous study of Missouri River flow frequency (disadvantage: with limitations described in the rows above).

7.2 Criteria for Evaluation of Flow Frequency Methodologies

The WAT Monte Carlo and Transform methods for estimating regulated flow frequencies were evaluated by several criteria: agreement with Bulletin 17C unregulated flow frequency, ability to capture natural variability, knowledge uncertainty, define the unregulated to regulated flow relationship, and the shape of the regulated flow frequency curves, and acceptance of the methodology.

7.2.1 Agreement with Unregulated Bulletin 17C Flow Frequency Curves

Bulletin 17C is the recommended methodology to estimate unregulated peak flow frequency. The undeveloped peak flow Bulletin 17C curves can be used to validate the WAT Monte Carlo output. If WAT Monte Carlo unregulated flow frequency curves track closely to the undeveloped Bulletin 17C flow frequency curves, we conclude that the WAT Monte Carlo method is producing hydrology that accurately represents the historical POR. It is known from previous studies and reviews of the underlying MR ResSim Model being used in the WAT that the MR ResSim model adequately simulates Missouri River Mainstem Dams operations and regulated flows. Simulations of the Kansas River and Osage River projects' operations were also reviewed to confirm their reasonableness. Therefore, if the WAT Monte Carlo undeveloped peak flows match the undeveloped Bulletin 17C flow frequency curves at the ten Missouri River flow frequency stations, the WAT is likely producing an acceptable estimate of regulated flow frequency.

The initial WAT Monte Carlo-generated undeveloped flows tracked closely with the Bulletin 17C curves, however, they slightly underestimated the 1% AEP and the 0.2% AEP at gages upstream of Kansas City. This was due to a limitation within the WAT: Each synthetic event is assigned one AEP based on one location. By default, the WAT Monte Carlo method assigns each year in the Big Bucket the same incremental probability. The default incremental probabilities can be overridden, and user-defined probabilities can be assigned to each year, which was done for two extreme floods on the Kansas and Osage Rivers, 1951 and 1986, that were skewing the results on the Missouri River. These user-defined probabilities are estimated from the unregulated Bulletin 17C frequency curves, but they are still based on one location. The AEP of years in the Big Bucket containing the 1951 and 1986 events could be accurately estimated based on one location because those events were mostly localized to a tributary watershed. This same issue exists for the scaled events that were added to the WAT to help shape the tail of the frequency curve. Each scaled event was assigned an AEP based on the Bulletin 17C frequency curve for the location where most of the inflow occurred. Selected events were scattered throughout the basin to provide a variety of upper and lower basin floods of various durations. Even with a variety of events, it is difficult to adequately capture the correct AEP of an event at every location along the Missouri River because a 1% AEP event at Sioux City may only be a 10% AEP event at Omaha.

To mitigate the limitation of assigning AEPs based on one location, HEC developed a probability weighting method that was applied to the data as a post-processing step. In general terms, the method changes how often an event is sampled during a WAT simulation. This method would be the equivalent of adjusting the incremental probabilities of each event and calibrating the WAT Monte Carlo simulation to reproduce the undeveloped Bulletin 17C flow frequency curves. However, the weighting method allows the undeveloped flow frequency curves to match the Bulletin 17C flow frequency curves at every location along the Missouri River. Probability weights were assigned to individual undeveloped events in order to match the undeveloped Bulletin 17C flow frequency curves at each gage. A weight greater than 1.0 signifies that event should have been sampled more during the WAT simulation and a weight less than 1.0 means the event should have been sampled less. Once the weights were assigned to each unregulated event, the resulting regulated event is given the same weight. The result is WAT Monte Carlo unregulated flow frequency curves that closely match the unregulated Bulletin 17C frequency curves and regulated flow frequency curves that were produced by the same sampling as the WAT Monte Carlo unregulated flow frequency curves. It is important to note that the weights are assigned to each individual event and not the plotting position. This keeps the sampling of the regulated events the same as the sampling of the unregulated flows. A drawback of this post-processing is that tests indicate it is possible to get different regulated flow frequency results by varying the weights while still getting good agreement with the Bulletin 17C curves as further discussed in Section 6.

The Transform method uses the unregulated Bulletin 17C curves directly, so that method does not need to reproduce them through sampling like the WAT Monte Carlo method.

7.2.2 Natural Variability

Natural variability is an inherent characteristic of the basin and cannot be reduced through further study. A good frequency analysis should capture natural variability as best as possible. Natural variability of regulated flow frequency can be captured by simulating many possible unregulated runoff volumes and timings and reservoir conditions through the reservoir model.

The WAT Monte Carlo method captures more natural variability than the Transform method by mixing and matching runoff from different regions and seasons to create the 590-year Big Bucket, along with scaled events coupled with a Monte Carlo simulation of various combinations of reservoir conditions and inflows.

The Transform method captures some natural variability by having a variety of scaled floods. However, only 90 systematic floods and a few dozen scaled floods overall provide less variability than the Big Bucket and Monte Carlo simulation approach. For the scaled floods, sensitivity to the starting pool elevation could be made, such as starting events below the base of the flood pool. However this would only serve to provide additional ranges of regulated flows for a given unregulated flow, providing additional scatter on the unregulated to regulated flow transform plots, and would not address the probability of a given starting pool elevation for the scaled floods.

7.2.3 Knowledge Uncertainty

Knowledge uncertainty is uncertainty associated with lack of data or small sample size. It can be reduced through further study. Currently, the WAT Monte Carlo has an advantage in knowledge uncertainty. The WAT Monte Carlo accounted for knowledge uncertainty using equivalent years of record. The WAT samples 90 years (length of the historical POR) from the Big Bucket and scaled events then uses only those 90 years of sampled data or a Small Bucket when sampling for a realization (2500 years). On the start of the next realization, the WAT would create another Small Bucket and use that in the next realization. The WAT uses the incremental probabilities of each of the Big Bucket years and scaled events when creating the Small Bucket. However, after the Small Bucket is created, each year is given an equal chance of being sampled during the realization.

With this approach, convergence needs to be verified to ensure an accurate estimate of flows are various AEPs. The general rule of thumb to achieve convergence is to ensure the number of events per realization is half or a full order of magnitude greater than the return interval you want to converge. For example, for the 1% AEP to converge, you will need 500 (1/2 order of magnitude) to 1,000 (full order of magnitude) events per realization. If you want the 0.2% AEP to converge, you will need 2,500 or 5,000 events per realization. This study is reporting up to the 0.2% AEP, so the Monte Carlo simulation used 2,500 events per realization and 100 realizations for a total of 250,000 events. Using 100 realizations also allows for the calculation of uncertainty bounds, which is an added benefit of the Monte Carlo analysis. Analyzing the output at each location in the lower river confirmed that both the undeveloped and regulated flows converged at the desired AEPs.

For unregulated Bulletin 17C curves used in the Transform method, knowledge uncertainty is reduced by including historical floods prior to the year 1930 and perception thresholds for intervening years. Historic floods and perception thresholds help reduce knowledge uncertainty for the unregulated flow frequency which indirectly improves the regulated flow frequency. However, since the WAT was post-processed to match Bulletin 17C, this applies to both methods. The only other means to reduce knowledge uncertainty in the transform method was the application of a wide array of scaled floods. However, similar synthetic floods were also incorporated into the WAT.

7.2.4 Unregulated-to-Regulated Relationship with Regard to Flow Frequency Curves

The probabilities of runoff volumes throughout the basin produce the unregulated (undeveloped) peak flow frequency, and in conjunction with the reservoir system they produce the regulated peak flow frequency. In general, a Monte Carlo analysis uses the probabilities of regional and seasonal basin runoff volumes by extrapolating them, sampling from them, and routing the sampled flows through the system, thereby extrapolating the regulated flow frequency while accounting for the probabilities of extreme floods. The Missouri River WAT Monte Carlo method currently does this by sampling from the Big Bucket that contains events larger than the simulated regulated POR and augmented with scaled floods with estimated AEPs, rather than sampling from continuous probability distributions. An unregulated-to-regulated relationship is not needed for the WAT Monte Carlo method because it directly computes regulated flow frequency. However, sensitivity analysis has indicated that two different combinations of weighting to post-process unregulated WAT results to match the Bulletin 17C curves can make minor to potentially significant differences in regulated flow frequencies especially as the frequencies approach 0.2% AEP. This introduces a degree of uncertainty with the method, though reduced from the method of developing an unregulated to regulated transform as described below. This uncertainty was mitigated by doing sensitivity analysis to the weighting at representative gages of

In contrast, the Transform method does not directly compute regulated flow frequency, so this method routes judiciously chosen scaled floods through the system and develops a relationship between unregulated and regulated flow from the systemic and scaled flood events. Developing this relationship requires filtering through results of the systemic and scaled floods which have very wide scatter in that the largest unregulated events may not be the largest regulated events depending on the volume and location of a flood event in relation to the federal dams. A process to "rank order" both the regulated and undeveloped data and plot those data sets is often used to help draw the relationship through the cloud of data, and judgement is applied in some cases if scaled events are not realistic. Once developed, this relationship is then applied to an undeveloped peak flow frequency curve to estimate a regulated flow frequency curve. No matter how carefully the scaled floods are chosen or how many are chosen, they will not capture the relative frequency of runoff throughout the basin at the extremes that determine the shape of the transform curve for extreme events. There is no monotonic function that can relate unregulated flow to regulated flow by magnitude in this large and complex of a system. However, there is a monotonic function that can relate unregulated and regulated peak flow in terms of their relative rate of occurrence. The transform must be thought of as a probability transform. In other words, how does the magnitude of flow at a given probability change between basin conditions, unregulated vs regulated?

7.2.5 Regulated Flow Frequency Curve Shape

Although both the Transform and WAT Monte Carlo methodologies utilize the same ResSim model, the WAT Monte Carlo method provides a wider range of reservoir and inflow combinations while accounting for probabilities of both reservoir conditions and inflows. Out of the 250,000 simulated events, there are only 618 unique flow events used in the WAT simulation. However, the reservoir conditions vary for the events, which means each unique flow event can produce many unique regulated flows. The WAT Monte Carlo method estimates the combined probabilities of reservoir conditions and inflow, which is how it can compute regulated flow frequency without an unregulated-to-regulated transform relationship.

Theoretically, the Transform method could simulate the same combinations of reservoir conditions and inflows as the WAT Monte Carlo methodology, which would provide a denser cloud of data to fit the transform relationship. However, even with the additional data, the Transform method would still miss a critical piece: probabilities of each combination. This is evident in the differences in the regulated flow frequency curves at Gavin's Point. The Transform method simulated many scaled events so the transform relationship could be extrapolated for events larger than observed in the historical POR. Because of the large variability of runoff across the Missouri River Basin, the Mainstem Reservoir System, with a total storage of 72.4 million acre-feet (MAF) was designed to draft into its carryover multiple use zone during extended droughts. A large event may occur with 16.3 MAF, 20.0 MAF, 25.0 MAF, etc. of available reservoir storage. The difference in releases from the most downstream project, Gavin's Point, can be significantly different depending on the available storage. There is also a threshold when releases from Gavin's Point will exceed 164,000 cfs. This is based on when Oahe's spillway will be utilized. Because it is an earthen spillway and there would be significant damage if utilized, Oahe's spillway would only be utilized under emergency situations or when the pool elevation exceeds the top of the gates in a closed position, 1620.0 feet (NGVD 1929). Until that point, the maximum release capability from Oahe is 164,000 cfs; the combined capacity of the flood tunnels and powerhouse. Since water released from Gavin's Point essentially comes from Oahe, the maximum release from Gavin's Point, dictated to a degree by Oahe's powerplant and flood tunnel capacity, is approximately 164,000 cfs until it is determined that Oahe's spillway needs to be utilized. This combination of reservoir conditions and inflows is captured in the WAT Monte Carlo method, evident with the flat portion of the regulated flow frequency curve. This flat portion is lost when a curve is fit through the cloud of data in the Transform method. Additional investigation of the transform was also conducted after receipt of ATR comments, and no improvement for how to draw the transform, given the information available, could be determined.

At downstream locations, as seen in Section 6.3.3, the shape of the WAT Monte Carlo has a more jagged appearance than for the transform curves at most gages. The WAT Monte Carlo results also show flat portions of the curves which could reflect reservoirs cutting releases during high stages coupled with the limits of the downstream tributaries to produce large floods. These plateaus can largely be seen for gages upstream of the Platte River for probabilities between approximately 0.3% and 0.2% AEP at Omaha, 0.7% to 0.2% AEP at Sioux City, and 1% to 0.2% AEP at Gavins Point, and with smaller plateaus between the Platte and Kansas Rivers. This indicates the regulated effects tend to decrease with drainage area downstream of the dams, as expected.

At Kansas City and Waverly, which are control points for Kansas River Basin operations, several inflection points in the shape of the WAT Monte Carlo curve were noted, including at approximately 390,000 cfs and about 450,000 cfs at both gages, 530,000 cfs at Kansas City and a similar inflection at 570,000 cfs at Waverly. Then, a flat portion of the curve exists between approximately 0.7% to 0.4% AEP especially at Waverly, then the WAT Monte Carlo curve shows reservoirs beginning to have less impact on the flow frequencies near the 0.2% AEP. A review of the reservoir operations makes it difficult to explain all of these inflection points as the Phase I, Phase II, and Phase III limits of 90,000 cfs, 130,000 cfs, and 180,000 cfs used at Waverly, which are more restrictive than at Kansas City, are lower than these inflection points. Three events in the 90 year POR resulted in several Kansas River Basin projects reaching surcharge pools as in 1993, 2019, and as simulated through the dams in 1951. In the 1993 example, which had an observed peak of 541,000 cfs at Kansas City, as flows through the uncontrolled spillways at Milford ant Perry became imminent, larger releases were made from the outlet works and held steady to help minimize spillway flows. Tuttle Creek had its only flow through its gated spillway also in 1993. This transition to surcharge operations likely coincides with the flat portion of the curve. Combined operations of the Mainstem and the Kansas River tributary dams could help explain other inflection points on the curves at Kansas City and Waverly.

At Boonville, which has other large tributaries, most significantly the Grand River entering downstream of Waverly, noticeable changes in slope occur at approximately 0.8% AEP where the slope steepens, up to approximately 0.4% AEP. For more extreme flows, the shape of the curve at Boonville is difficult to explain with reservoir operations as the flows tended to plateau. A potential factor may be the coincident flooding of the Grand and Chariton Rivers limiting the ability of the curve to continue upward as the shape indicates at Kansas City and Waverly.

Hermann, MO is the only location downstream of the Osage Basin Reservoir system. As summarized in Section 2.2, flows of the Osage Basin are curtailed on the rising limb of the floods once Hermann exceeds 260,000 cfs until the peak occurs, then releases up to 90% of the peak occur on the falling limb. This operation, coupled with flows of 260,000 cfs being exceeded frequently at Hermann, make the relatively straight shape at Hermann up until approximately 0.35% AEP reasonable. The nearly vertical shapes of the curve near 0.35% AEP and 0.27% AEP may be related to transitions into surcharge operations during large events to prevent overtopping of Osage Basin Dams. A 2022 semi-quantitative risk assessment for Harry S. Truman Dam indicates surcharge flows could begin around a 2.3% (1/43) AEP, approximately the frequency of the pool of record. The limited number of large events in the big bucket or synthetic floods could drive these two transition points near the assigned probability of those events. However, reporting values at only the 0.5% and 0.2% AEP helps smooth this type of data.

For all curves, especially those with plateaus near the 0.2% AEP, it is not advisable to extrapolate the WAT Monte Carlo results beyond the published 0.2% AEP flows, as larger floods are expected to eventually trend upwards to approach the unregulated flow frequency curves to some degree. In contrast, the transform relationships shape tends to show a bend towards the unregulated frequency flows for events less frequent than 0.2% AEP, which could reduce the risk of extrapolating results to some degree. Efforts to combine the two methods or extend the WAT Monte Carlo to estimate events less frequent than 0.2% AEP have not been completed at this time. Therefore, estimates in this study are only considered valid up to 0.2% AEP and smaller flood events at this time.

7.3 Accepted Methodology

The Upper Mississippi River System Flow Frequency Study completed in 2003 used the Transform Method to estimate regulated flow frequencies at the Missouri River gages consistent with EM 1110-2-1415. While a Monte Carlo approach is not new, for example it is referenced in Chapter 12 of EM 1110-2-1415, it hasn't been applied widely for regulated flow frequency at such a large scale primarily because of lack of computing power. Monte Carlo is being used more now with improved computing power and the development of the WAT. The WAT version of a Monte Carlo approach has been used in other studies such as the Columbia River Treaty (CRT). The approach completed for the Missouri River Study included the addition of the Big Bucket synthetic record and the post-processing method. The Big Bucket is seen as an improvement because of more variety in flows compared to the observed POR. The post-processing method was newly developed for this study but has been reviewed and allows the unregulated flow frequency curves produced by the WAT to match the Bulletin 17C frequency curves at each study location. Sensitivity analysis to the post-processing method was conducted ultimately making minor revisions to one gage to produce results near the median range produced by the post-processing and confirming the post processing at the other nine locations.

7.4 Conclusions

The WAT Monte Carlo method has multiple advantages over the Transform method for estimating regulated flow frequency on a complex regulated river system. The main advantage is the WAT Monte Carlo method simulates 1000s of reservoir operations to give a direct estimate of regulated flow frequency founded on coincident probabilities of flows and reservoir conditions. Another advantage of the WAT Monte Carol method is its ability to simulate reservoir regulation from the many realizations, thus providing a more meaningful, detailed, realistic unregulated to regulated transformation. Confidence in the results of this method is increased because the unregulated output matches Bulletin 17C unregulated peak flow frequency curves and the MR ResSim model was validated in previous studies. The WAT Monte Carlo methodology and results have undergone Agency Technical Review (ATR) and Technical Review Group (TRG) reviews and their comments addressed. Uncertainty introduced in the regulated frequencies when post-processing data has been explored and incorporated into the final report. Additionally, points of inflection in the final WAT regulated frequency curves have been explored and validated against reservoir operations and flow inputs to verify reasonableness. Therefore, the WAT Monte Carlo methodology and results have been adopted. The analysis is considered valid for events up to and smaller than the 0.2% AEP event and are reflective of the existing conditions of the Missouri River Basin.

7.5 Recommendations

Limitations and biases of the adopted methodology have been considered and recommendations made for potential future improvement. These include the following:

1. Utilize information from this report to conduct a stage frequency analysis for the Missouri River, updating the remainder of the 2003 UMRSFFS Study. Coordinate with the Mississippi River Studies to ensure Missouri River inputs are provided for their studies, and proper boundary conditions are provided for the confluence of the Missouri and Mississippi Rivers. Though difficult to accurately predict, sensitivity analysis should also be conducted for potential future levee raises, flood fighting, and levee breaches.
2. Determine flow changes along the Missouri River between the 10 study gages. Test alternative means for calculating or incorporating ungaged flows in future studies.
3. The Monte Carlo approach should be periodically maintained and improved, adding new data as it becomes available as it will provide useful data for numerous studies throughout the Missouri River basin. For example, a refined version of the WAT Monte Carlo with additional regions is being adapted for water control manual updates in the Kansas and Osage River Basins to aid alternative analysis. This would simplify future updates in the event of another major flood such as 1993 or 2019.
4. Complete the in-depth climate change assessment and consult experts to determine the best methods for incorporating future flows into the analysis for the systematic record and for historic peak flow information.
5. Consider ways to incorporate additional synthetic, or scaled flood events, and to increase the computations to estimate regulated flow frequencies for probabilities less frequent than the 0.2% AEP event. This should include a transition of the shape towards the unregulated flow frequencies at some point beyond the published range of flows at most of the study stream gages.
6. Expand research into the impacts of land use change in the Missouri River Basin on peak streamflows. Though available information was summarized in Section 2.7, uncertainty remains for the extent of land-use change impacts on peak streamflows of the Missouri River and its tributaries, and its relative contribution compared to climate related factors.

7.6 Summary of Results

Figures 7-1 through 7-10 present the final frequency curves from the unregulated Bulletin 17C, expected probability, adjusted WAT mean regulated flows as adopted for this study, and transform regulated curves. Bulletin 17C is the accepted method for computing unregulated flow frequencies. As shown in the figures, unregulated flow frequency from HEC-WAT as sampled from the “big bucket” and synthetic events and routed through the HEC-ResSIM model was plotted to indicate how close they match the Bulletin 17C curves. While some differences are present between the WAT unregulated flows and the Bulletin 17C curves, especially for lower flows at Hermann, the analysis matched closely at larger flows, especially at the 1% AEP flows at all ten study gages. For the regulated flow frequencies, the transform and WAT method both produce similar results for the reach between the Platte and Kansas Rivers. Upstream of the Platte River, the transform produced higher 0.2% AEP flows than the WAT, and specifically at Yankton or Gavins Point Dam, the WAT shows outflows of 164,000 cfs more frequently than the transform. Downstream of the Kansas River, and to a lesser degree at St. Joseph and Rulo, the WAT produces higher flows than the transform. Differences between methods are attributed to the incorporation of several additional scaled floods as in Appendix E to develop the transform, which may skew the results downward. As seen in Figure 7-7, the transform relationship used for the Kansas City Levees Feasibility Study, which was based on the 2003 UMRSFFS transform as extended and validated using additional hypothetical flood routings, if applied to the updated flow frequency matches very closely to the WAT results. Additionally, the WAT results match closer to the plotting positions of regulated data at Kansas City, Waverly, Boonville, and Hermann than does the Transform method.

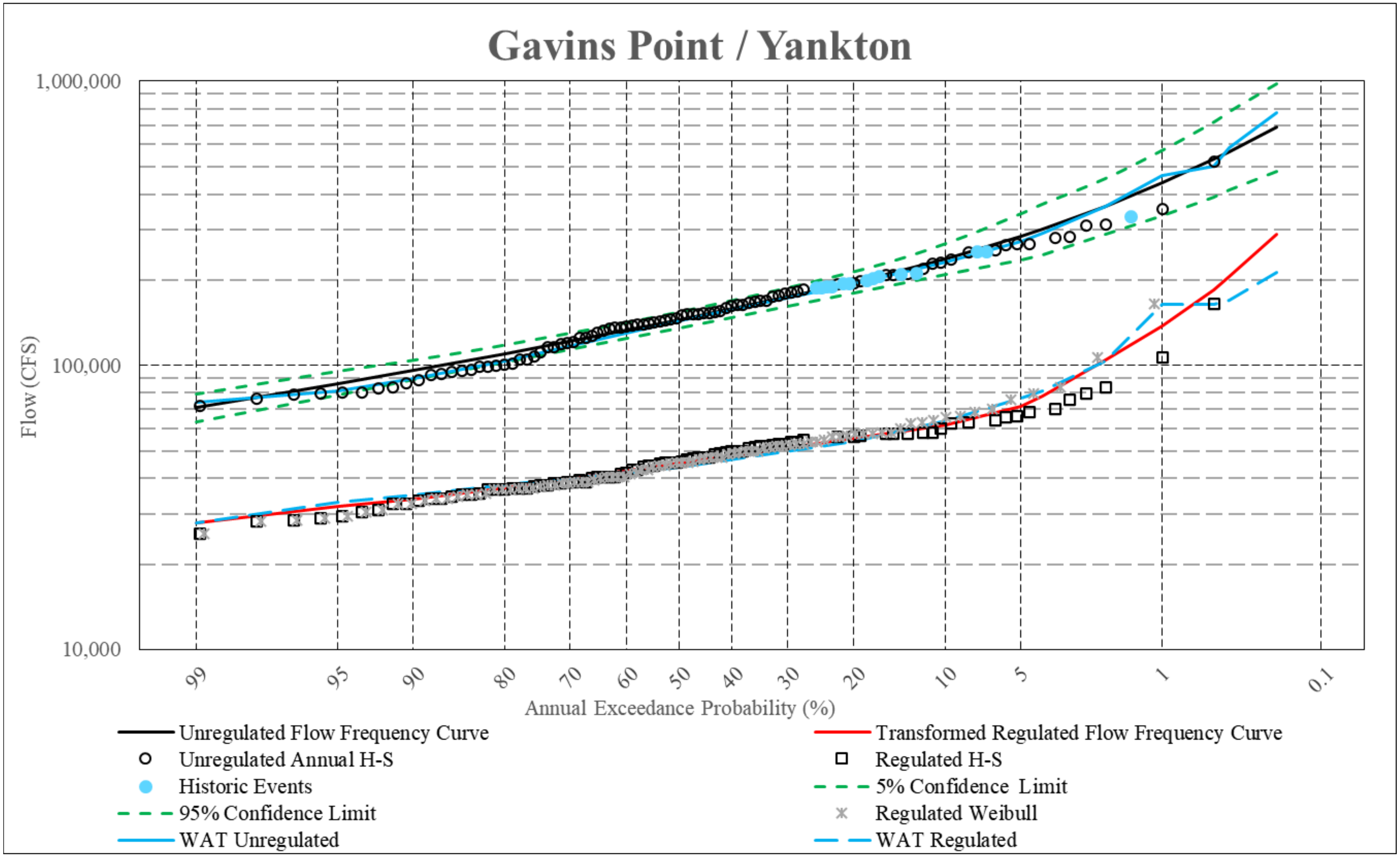


Figure 7-1. Gavins Point WAT and Transform Method Comparison

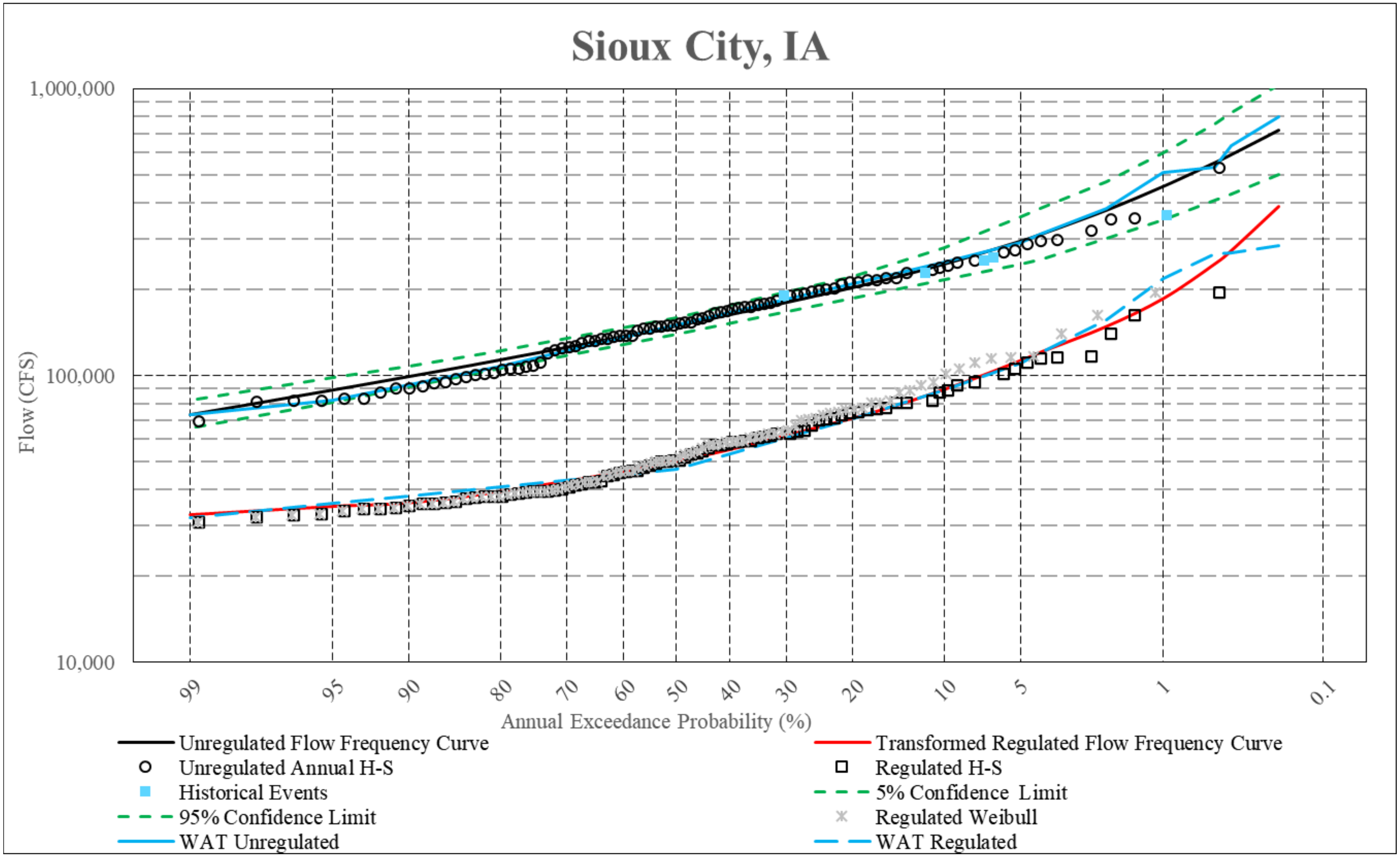


Figure 7-2. Sioux City WAT and Transform Method Comparison

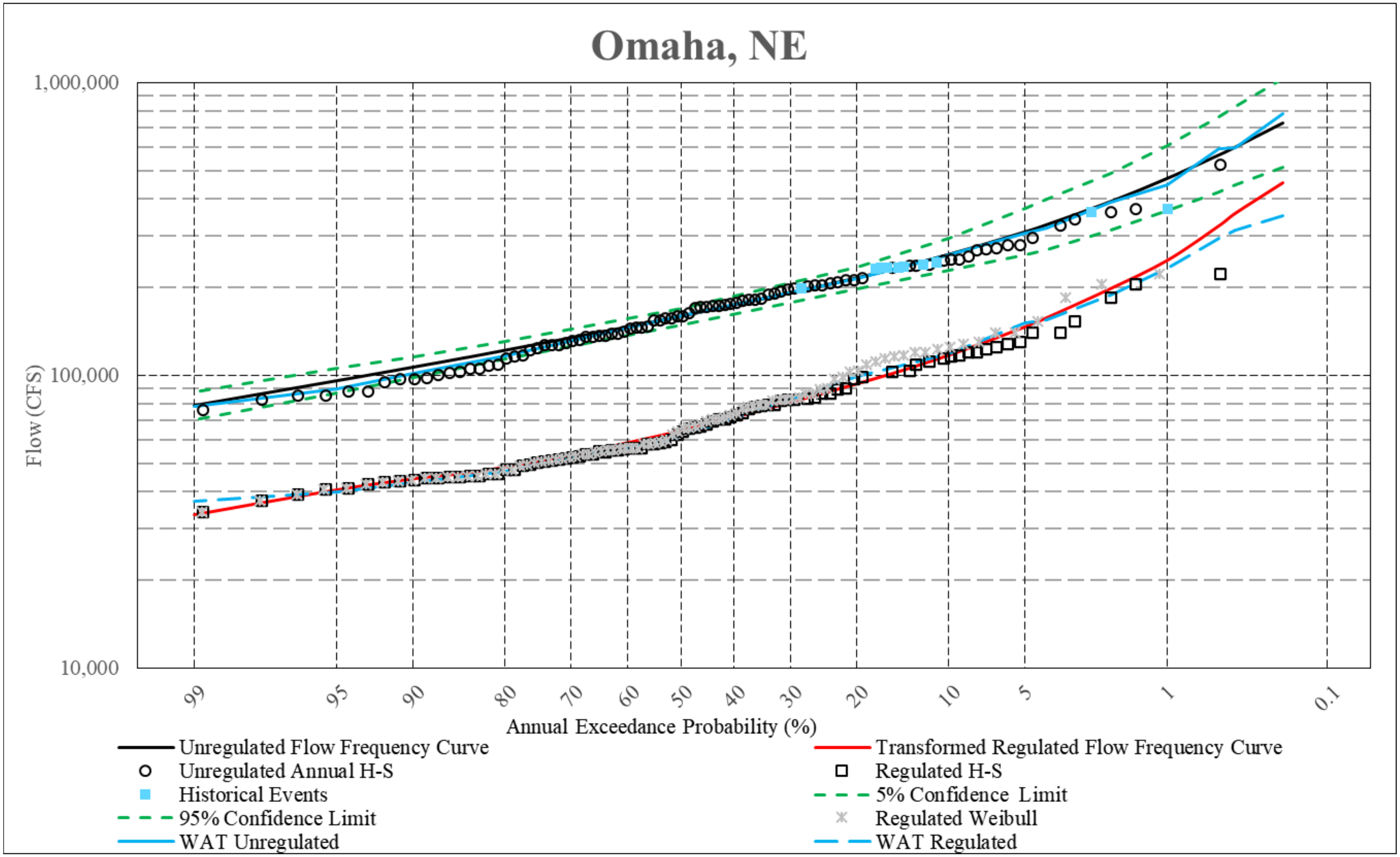


Figure 7-3. Omaha WAT and Transform Method Comparison

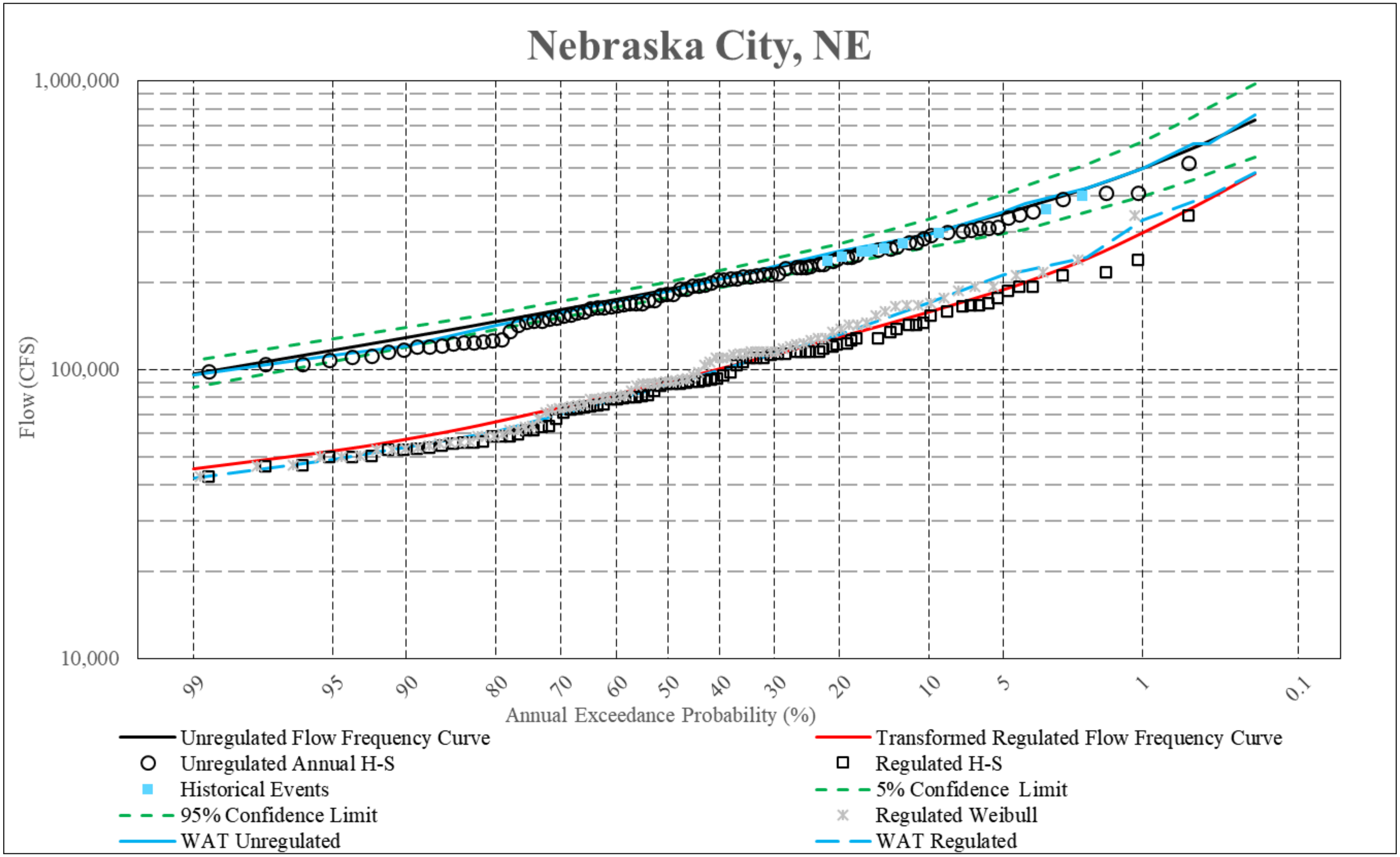


Figure 7-4. Nebraska City WAT and Transform Method Comparison

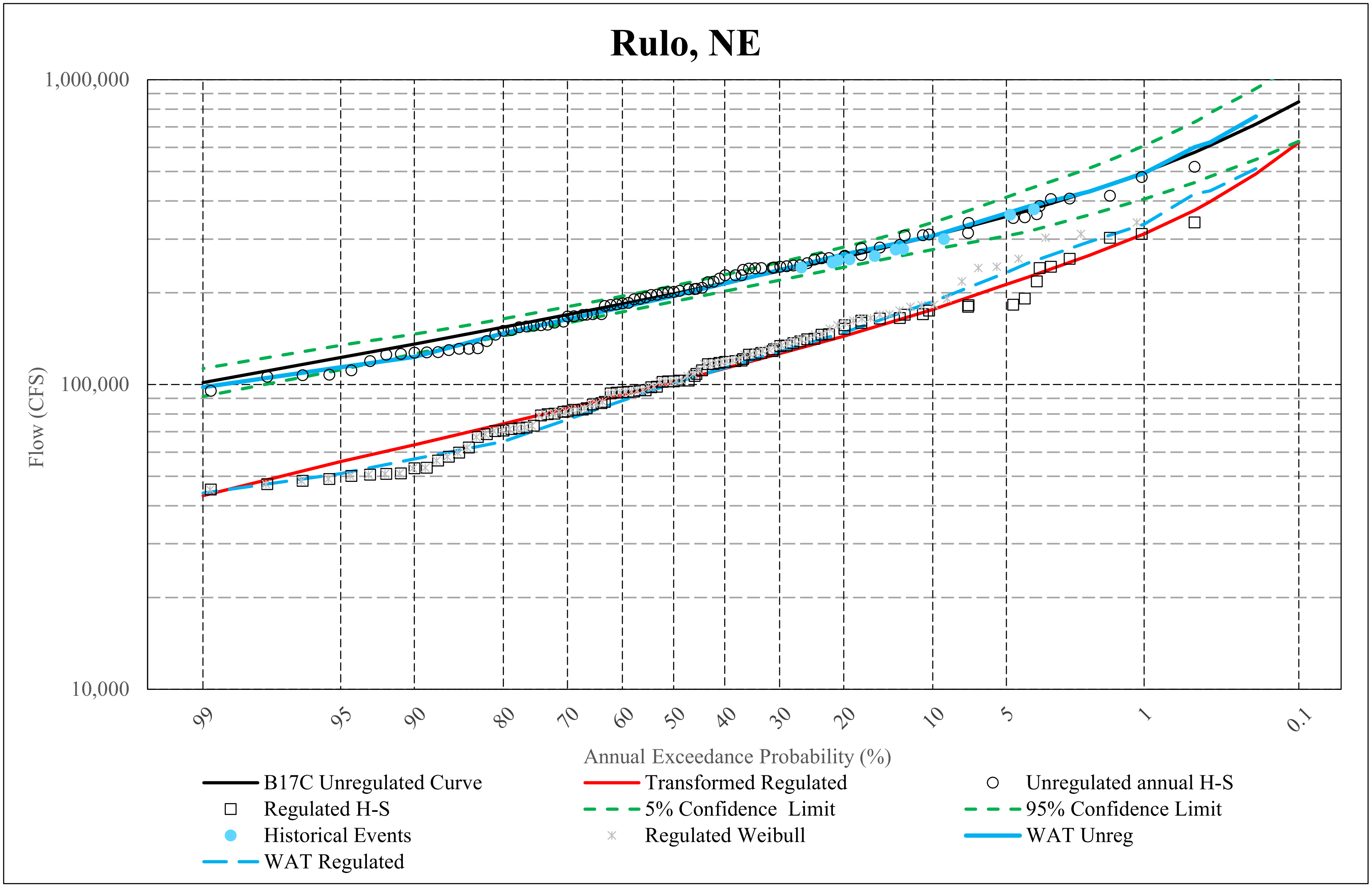


Figure 7-5. Rulo WAT and Transform Method Comparison

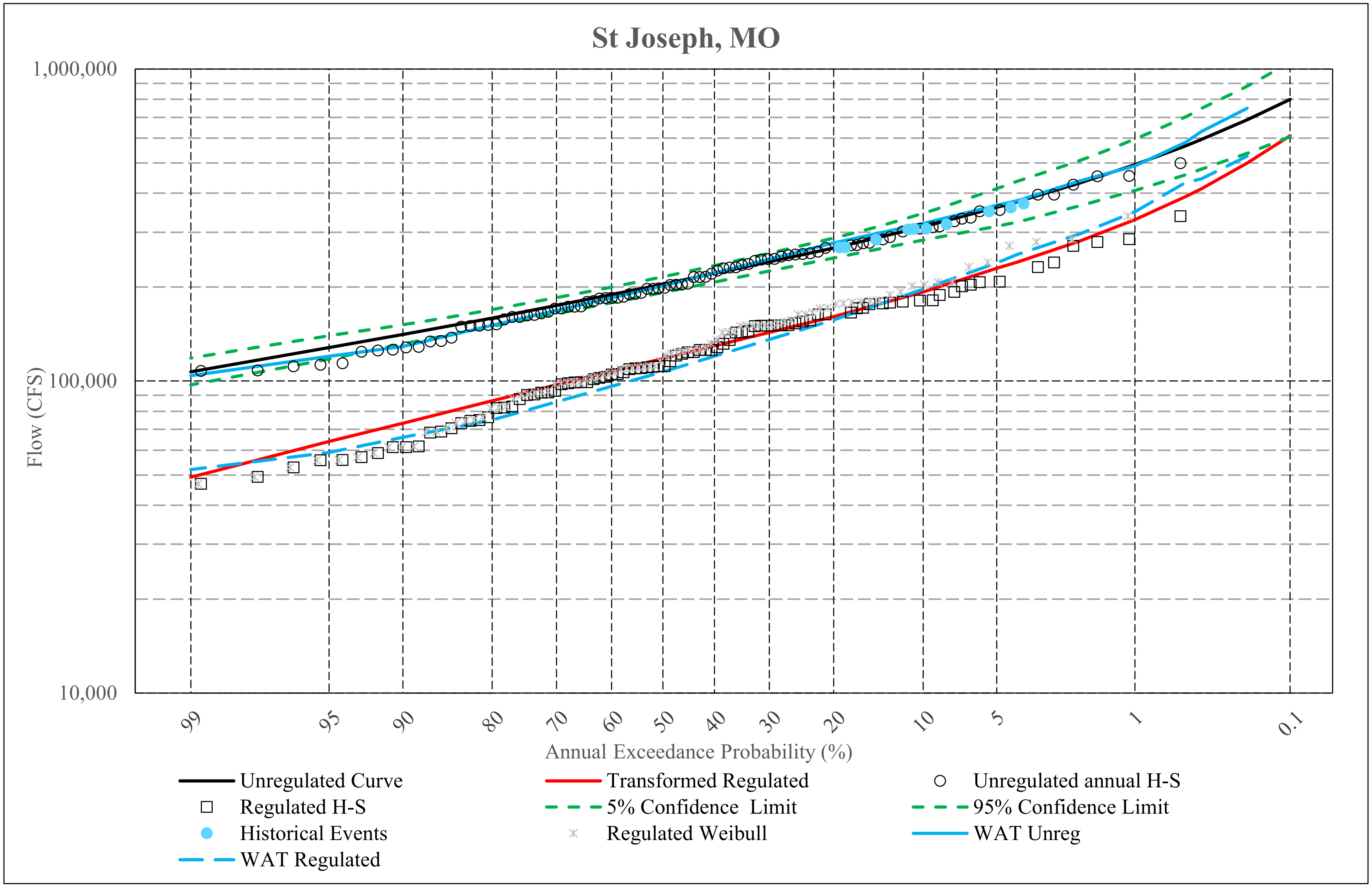


Figure 7-6. St. Joseph WAT and Transform Method Comparison

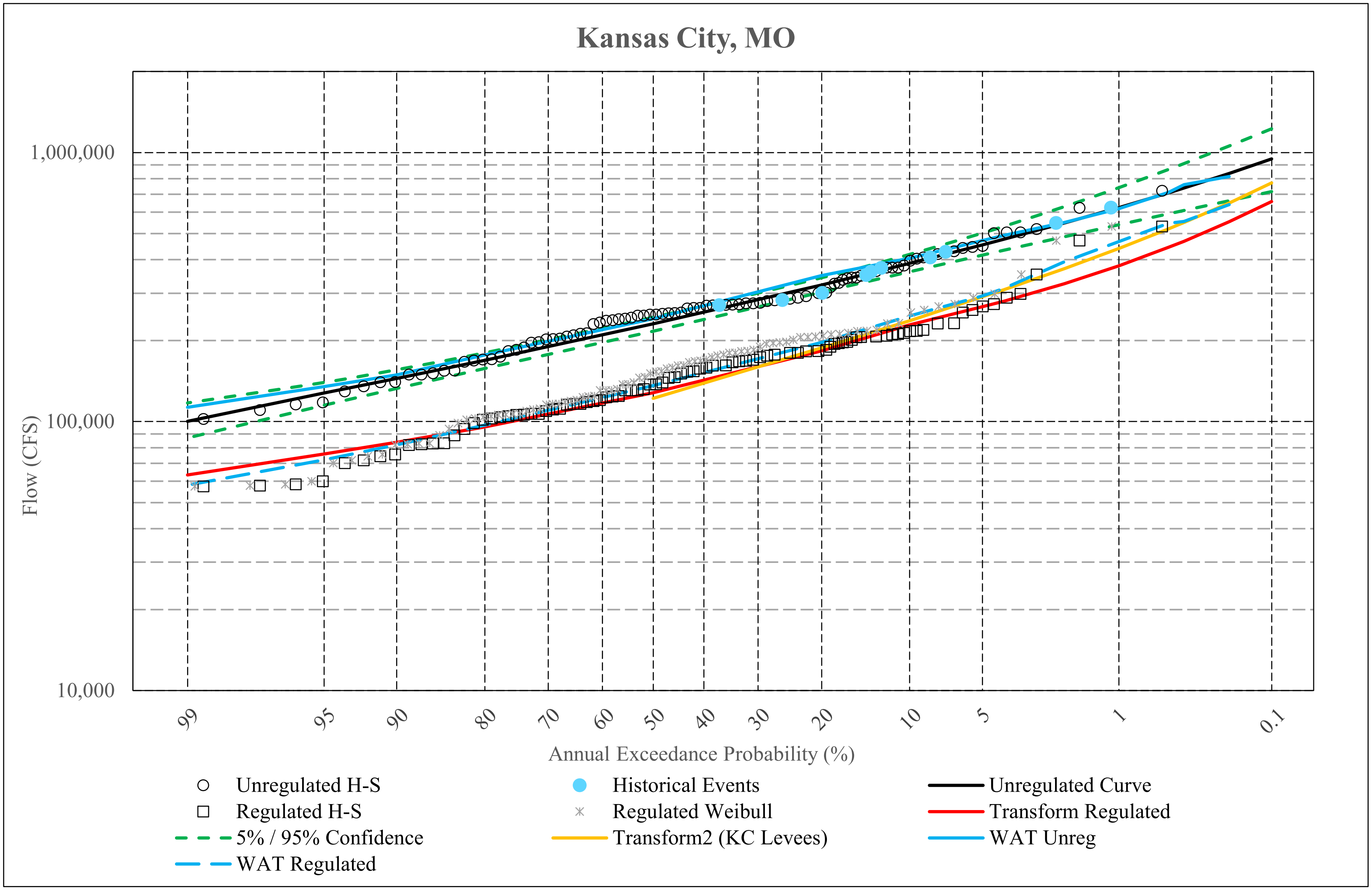


Figure 7-7. Kansas City WAT and Transform Method Comparison

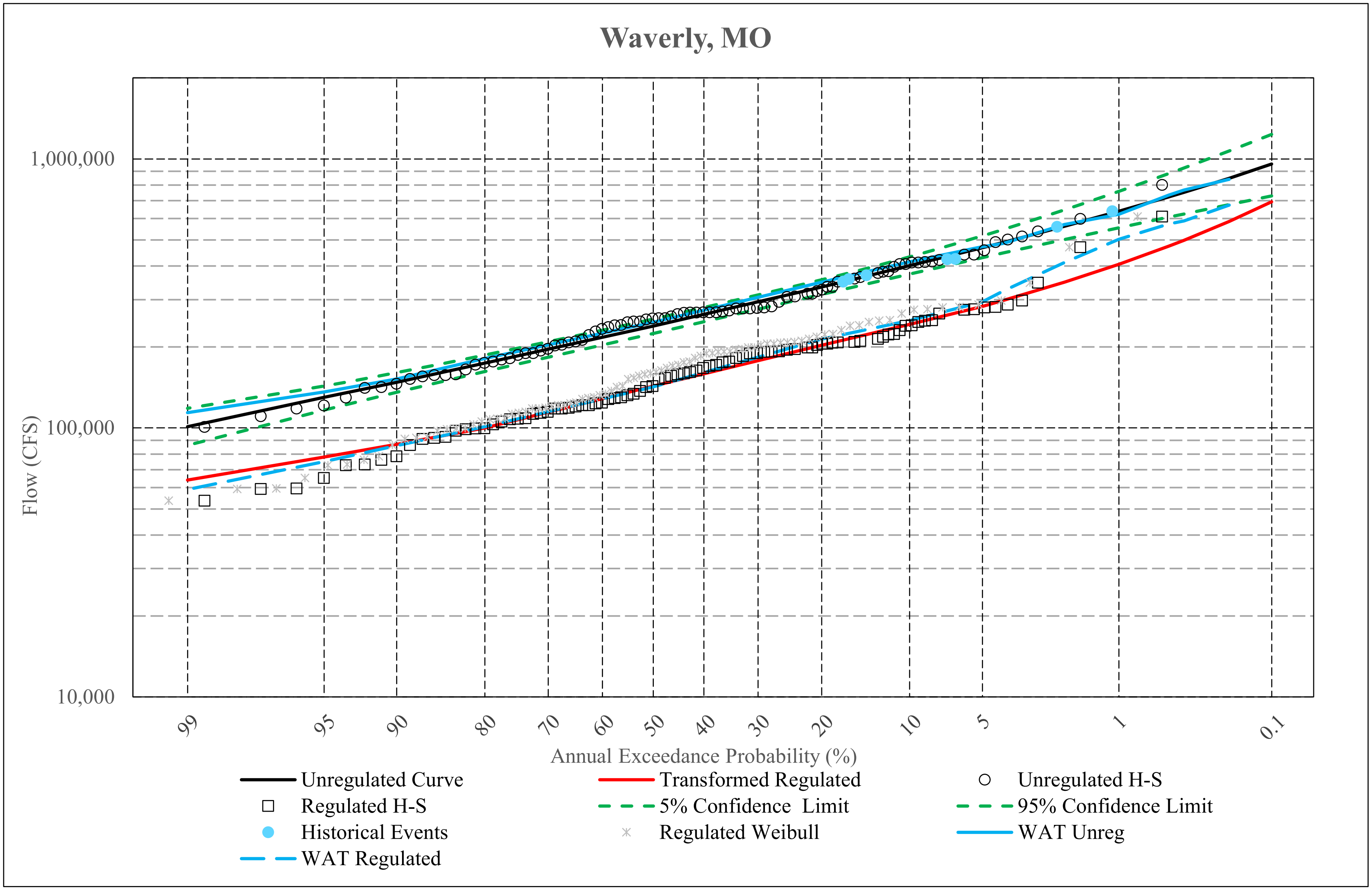


Figure 7-8. Waverly WAT and Transform Method Comparison

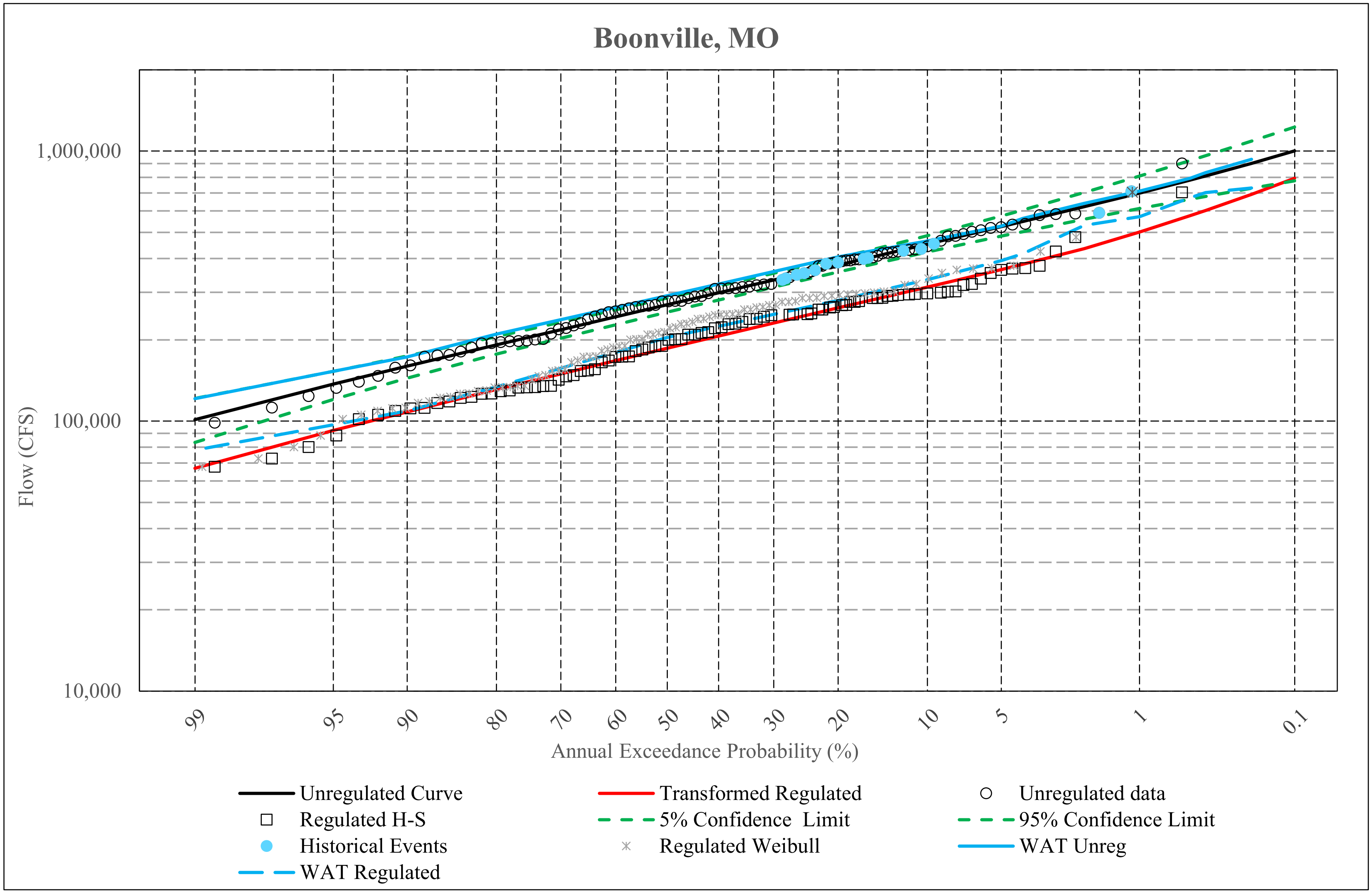


Figure 7-9. Boonville WAT and Transform Method Comparison

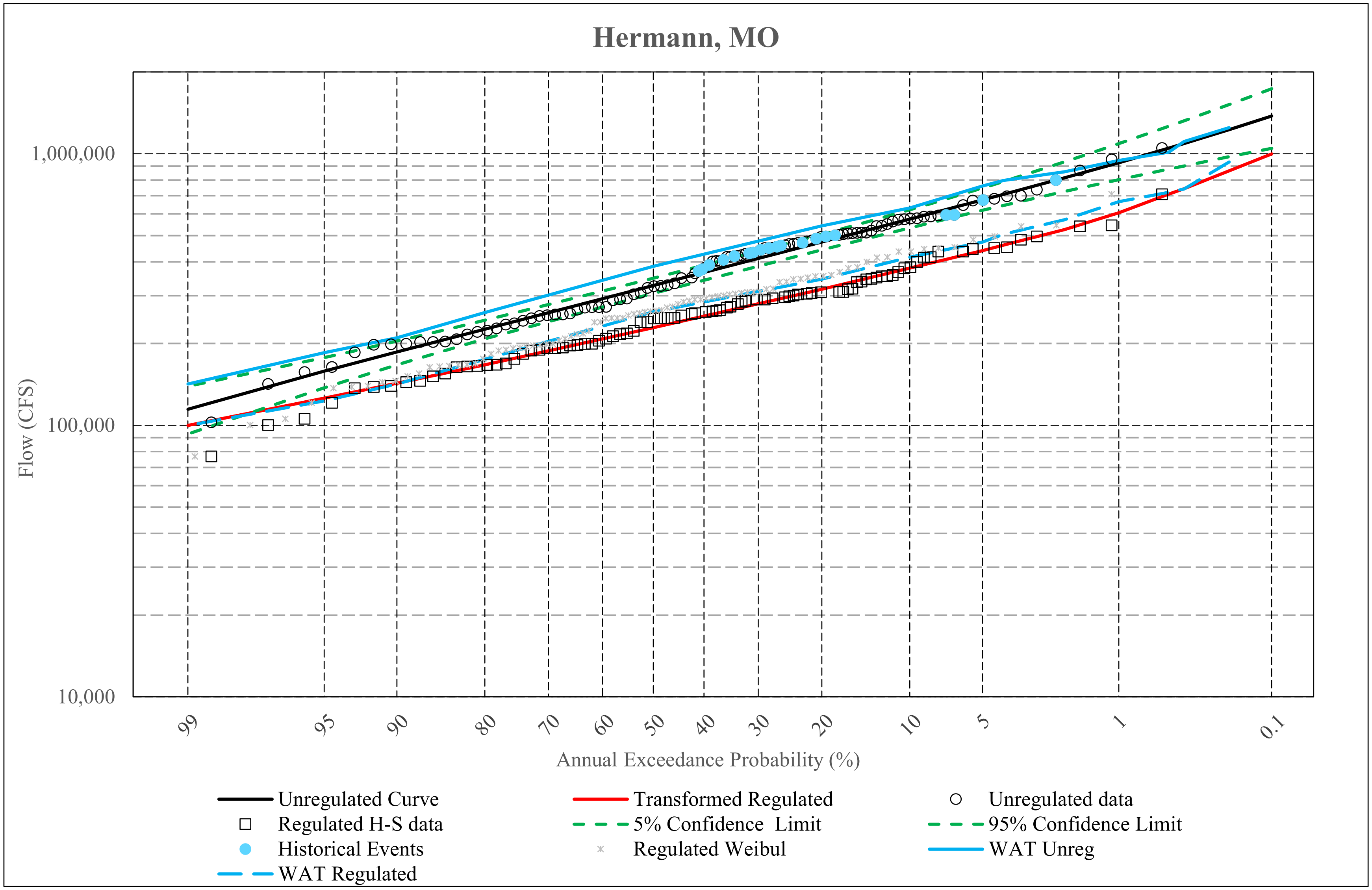


Figure 7-10. Hermann WAT and Transform Method Comparison

Figure 7-11 through Figure 7-13 present comparisons of the results for the unregulated flow frequencies compared to the 2003 UMRSFFS for the 10%, 1%, and 0.2% AEP flows at all study gages. Unregulated flows at the 10% AEP match the 2003 UMRSFFS very closely. At the 1% AEP, differences in unregulated flow increases generally taper from upstream to downstream, averaging 18%, 15%, 9%, 3%, and 7% higher than the 2003 UMRFFS from Gavins Point to the Platte River, Platte to Kansas River, Kansas to Grand River, at Boonville, and at Hermann, respectively. For the unregulated 0.2% AEP, increases average 36%, 27%, 17%, 7%, and 11% higher than the 2003 UMRFFS from Gavins Point to the Platte River, Platte to Kansas River, Kansas to Grand River, at Boonville, and at Hermann, respectively.

Approximately 1-2% of the increase in unregulated flows at the 1% AEP, and about 3% at the 0.2% AEP, is attributed to adopting the expected probability adjustment as summarized in Section 3.9. Computed flow results are also tabulated in this report, noting certain risk assessments may require use of computed flow frequencies to avoid double counting flood risks, such as analysis in HEC-FDA. Most of the difference in unregulated flows is attributed to the treatment of the 1898 to 1929 period data used as systematic data in the 2003 study, versus treatment as a historic period in this study, and regional smoothing of skew applied in the 2003 UMRFSS below the Kansas River. Ultimately this difference resulted in unregulated flows between those of the 2003 study and as calculated using only systematic records after 1930. Further extending the historic period back before the adopted 176- to 177-year historic period back to 1843/1844 slightly decreased flows, whereas reducing the systematic period to remove non-stationarities, such as the most common date of 1941 instead of 1930, either increased or decreased flows. Overall shorter periods using the most recent flow records show slightly to significantly higher unregulated flows than those of longer historic periods. Remaining differences are attributed to the new flow records, which include the floods of 2011 and 2019. Given all sensitivities, careful consideration of historical flood information, and limitations in the previous section, the unregulated flow frequencies in this report reflect the best existing conditions estimate available at this time. The adopted historic period of either 176 or 177 years back to 1843/1844 was selected as it could be reasonably estimated at all ten study gages when considering regional information.

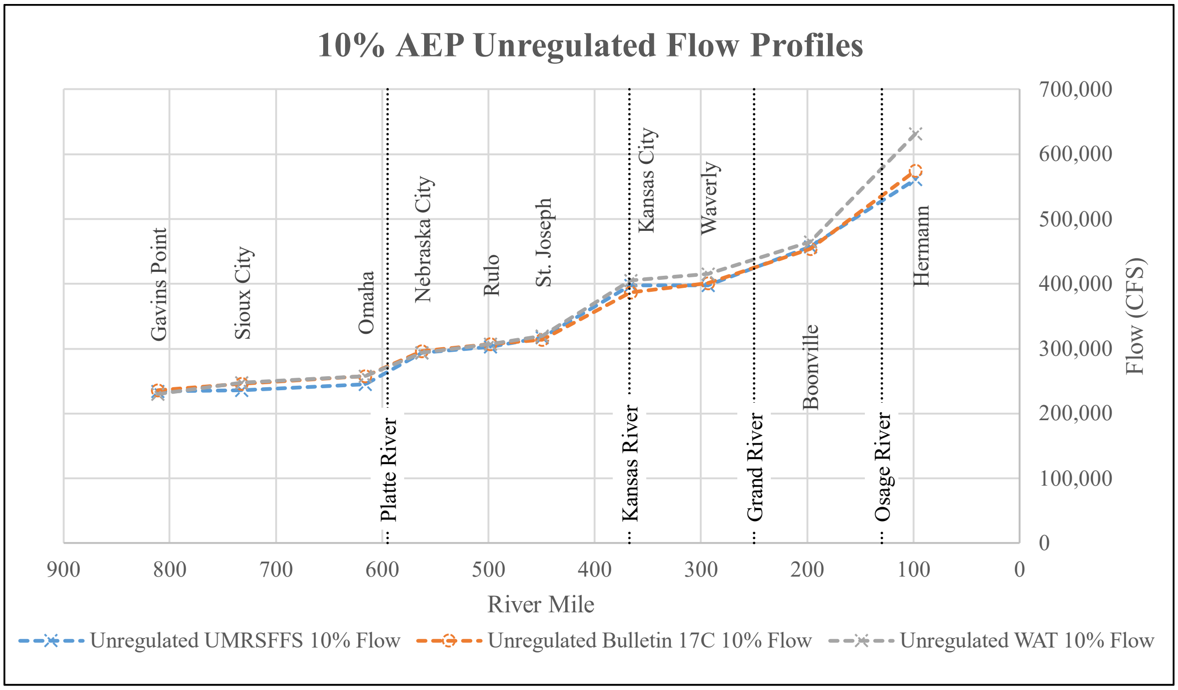


Figure 7-11. Unregulated 10% AEP Flow vs River Mile, 2003 UMRSFFS, and Current Study from Bulletin 17C and as Output from WAT

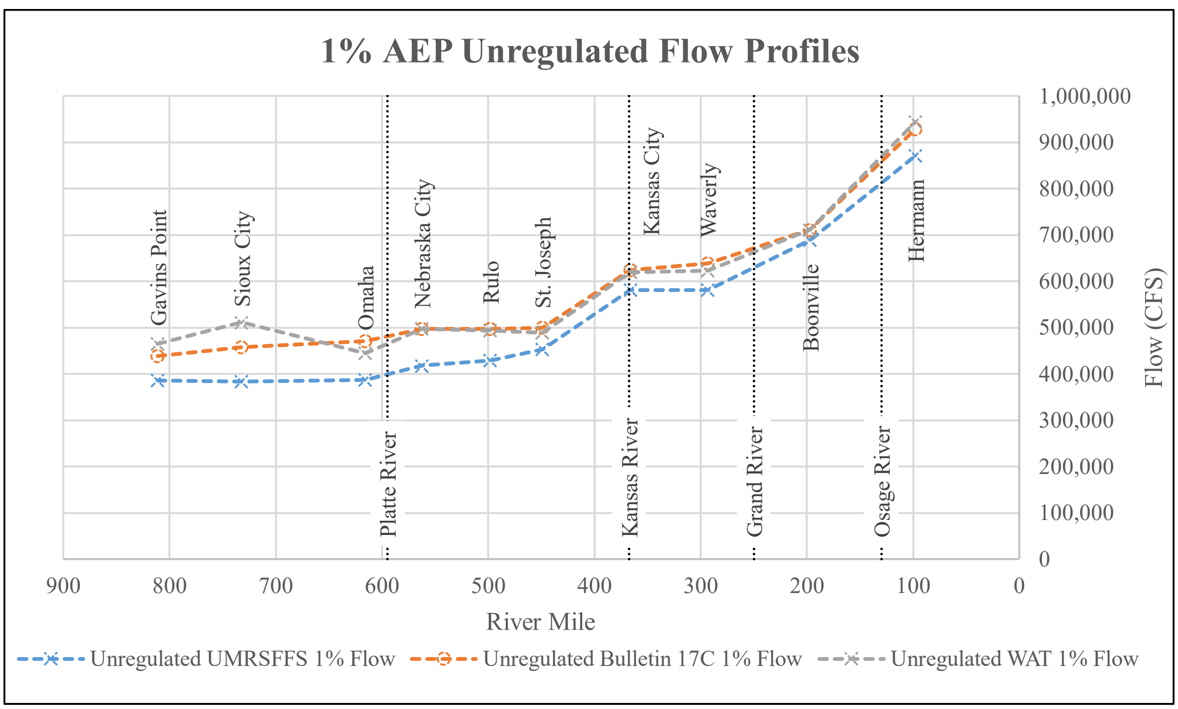


Figure 7-12. Unregulated 1% AEP Flow vs River Mile, 2003 UMRSFFS, and Current Study from Bulletin 17C and as Output from WAT

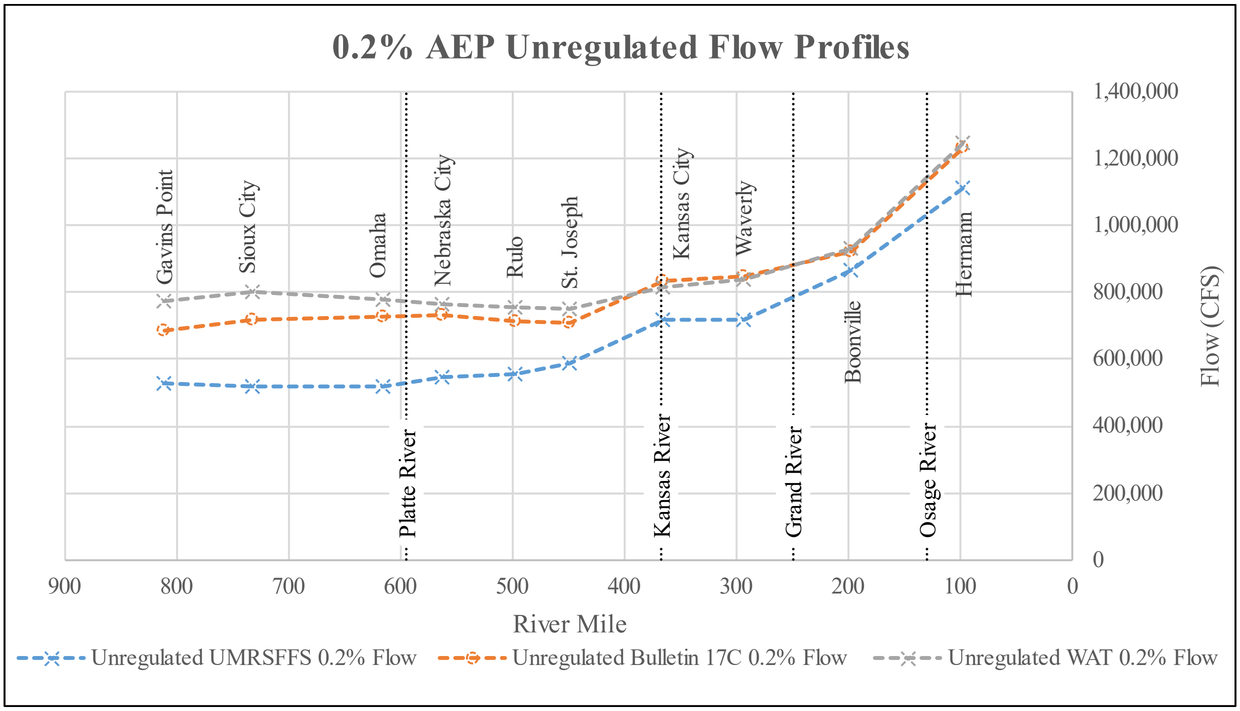


Figure 7-13. Unregulated 0.2% AEP Flow vs River Mile, 2003 UMRSFFS, and Current Study from Bulletin 17C and as Output from WAT

Figure 7-14 to 7-16 present comparisons of the results for the regulated flow frequencies from both the transformed Bulletin 17C and WAT Monte-Carlo methods compared to the 2003 UMRSFFS for the 10%, 1%, and 0.2% AEP flows at all study gages. Regulated flow frequency from the WAT Monte-Carlo analysis have been adopted in this study as in Table 6-18. At the 10% AEP, regulated flows are little changed from the 2003 UMRFFS study. For the 1% AEP, regulated flows on average increased 63% upstream of the Platte River, 35% between the Platte and Kansas Rivers, 18% between the Kansas and Grand Rivers, and are essentially unchanged below the Grand River compared to the 2003 UMRSFFS. At the 0.2% AEP, regulated flow increases average 56%, 46%, 20%, -3%, and 12% higher than the 2003 UMRFFS from Gavins Point Dam to the Platte River, Platte to Kansas River, Kansas to Grand River, at Boonville, and at Hermann, respectively. For the 1% and 0.2% AEP regulated flow frequencies, the largest increase was at Gavins Point Dam at approximately 93% and 73%, respectively, with Sioux City having the second highest increase of 53% at the 1% AEP and third highest at the 0.2% AEP. At the 0.2% AEP, St. Joseph had the second highest increase in regulated flow frequency compared to the 2003 UMRSFFS of 62%, compared to an average of about 39% for Omaha, Nebraska City, and Rulo, and 20% for Kansas City and Waverly. However, as seen in Figure 7-16, the 0.2% AEP 2003 UMRSFFS regulated flow at St. Joseph plots noticeably lower than the upstream gages at Rulo (2003 Appendix F) and Nebraska City.

To determine what drives the differences related to the 2003 UMRSFFS, the magnitude of the percent change for the regulated flow frequencies was compared to the change in the unregulated flow frequencies. Assuming the regulated flows would change at the same percent rate as the unregulated flow frequencies, 1% AEP regulated flows average increase is 67% higher than expected from Gavins Point to Sioux City, 30% higher from Omaha to St. Joseph, and 16% higher from Kansas City to Waverly. Below the Grand River, the magnitude of change of 1% AEP flows closely matched expectations. Similarly, the 0.2% AEP regulated flows average increase is 47% higher than expected from Gavins Point to Sioux City, 35% from Omaha to St. Joseph, 17% from Kansas City to Waverly, 3% lower at Boonville, and 11% higher than expected at Hermann. The change in flow in cfs of both the unregulated and regulated flows were also compared. For the reach from Gavins Point to the Platte River, 1% AEP unregulated flows increased an average of 88,200 cfs, whereas regulated flows increased an average of 73,500 cfs. Between the Platte and Kansas Rivers, the increase in 1% AEP unregulated and regulated flows averaged 60,100 cfs and 88,000 cfs, respectively. Between the Kansas and Grand Rivers, the increase in 1% AEP unregulated and regulated flows averaged 40,000 cfs and 72,500 cfs, respectively.

Increases in regulated flow frequency upstream of the Kansas River are driven more by the large volume and duration events of 2011 and 2019, and a more rigorous assessment of flows entering downstream of the reservoirs using the Monte Carlo. While the percent change in regulated flow is larger than the percent change in unregulated flow especially upstream of the Kansas River, the difference in flow compared at the 1% AEP indicates the flow increases between Gavins Point and the Platte River is similar between the unregulated and regulated flows. For the reach between the Platte and Kansas Rivers, and between the Kansas and Platte Rivers, the average increase in regulated flows was higher than the average increase in unregulated flows by approximately 30,000 cfs. Between the Kansas and Grand Rivers, the differences are attributed to a mix of unregulated flow frequency and these recent long duration floods. Downstream of the Grand River, overall little difference was found between studies, except for the 0.2% AEP at Hermann. In 2019, Truman Dam reached its record pool, and as discussed in Section 3.2.1 and Appendix D, more detailed analysis of reservoir routings resulted in a larger unregulated estimate of the 1986 flood than in the 2003 UMRSFFS. Therefore, some change in regulated flow frequency at the 0.2% AEP flow should be expected.

As detailed in Section 2.4, floods of 2011 and 2019 had extraordinary volume and duration compared to the rest of the period of record, exceeding 1881 which was used to size the Mainstem Reservoir System flood storage, and 1997, the record at the time of the 2003 UMRSFFS report. While it is difficult to assess 1881 for the full basin using reservoir routings with and without dams, the current study considered this event through the unregulated flow frequency analysis. In contrast, the 2003 study did not include the three largest volume events upstream of Sioux City in the record of 1881, 2011, and 2019 due to its adopted record of 1898 to 1997. Both methods, the transform and the WAT Monte-Carlo, show significant regulated flow increases upstream of the Kansas River at the 1% and 0.2% AEP. As previously discussed, difficulty in drawing a transform relationship through a wide scatter of data was noted throughout Section 5 and Section 7.2.4. While the transform shows lower flows for Kansas City than the WAT Monte Carlo, had the transform relationship from Kansas City Levees Feasibility Study been applied (see Section 5.3.3.1), flows would match within approximately 6% and 1% at the 1% and 0.2% AEP, respectively. Systematic data points including 1951 and 1993 as seen in Figure 7-7 would also plot closer to the transform relationship. Similar uncertainty is present in transform relationships at other gages. Therefore, as previously discussed, the WAT Monte Carlo results are viewed as the best estimate of regulated flow frequencies at this time.

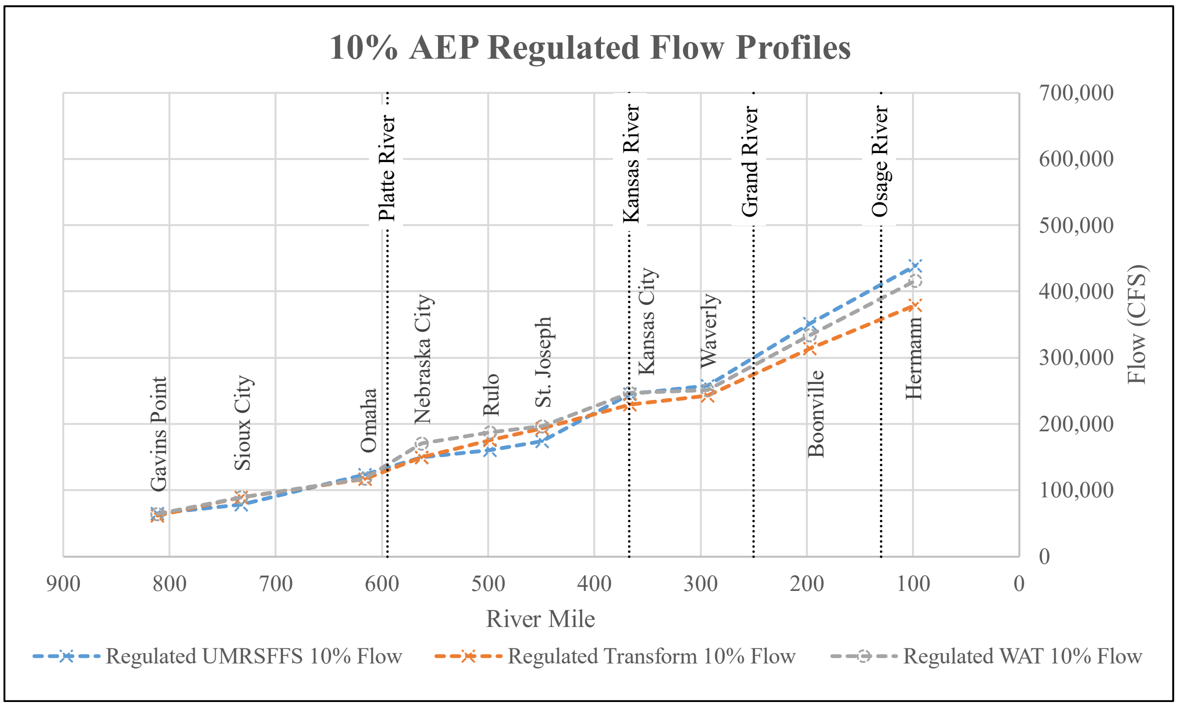


Figure 7-14. Regulated 10% AEP Flow vs River Mile, 2003 UMRSFFS, and Current Study from Transform and from WAT Monte Carlo (Adopted)

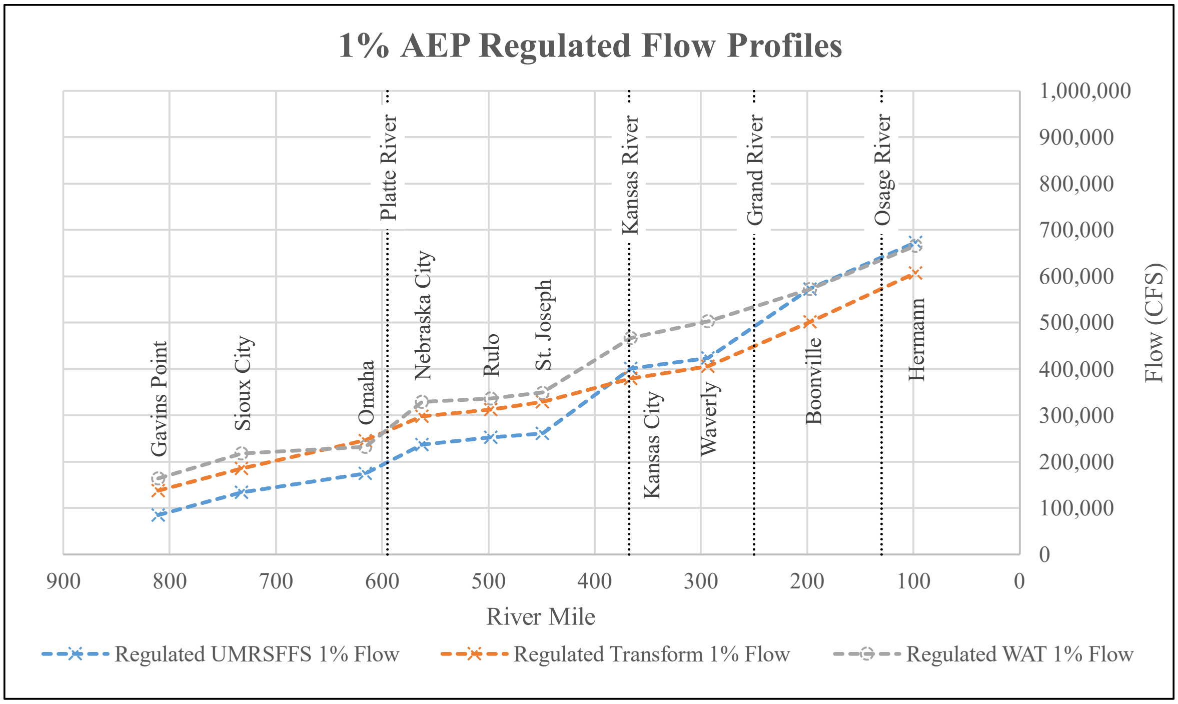


Figure 7-15. Regulated 1% AEP Flow vs River Mile, 2003 UMRSFFS, and Current Study from Transform and from WAT Monte Carlo (Adopted)

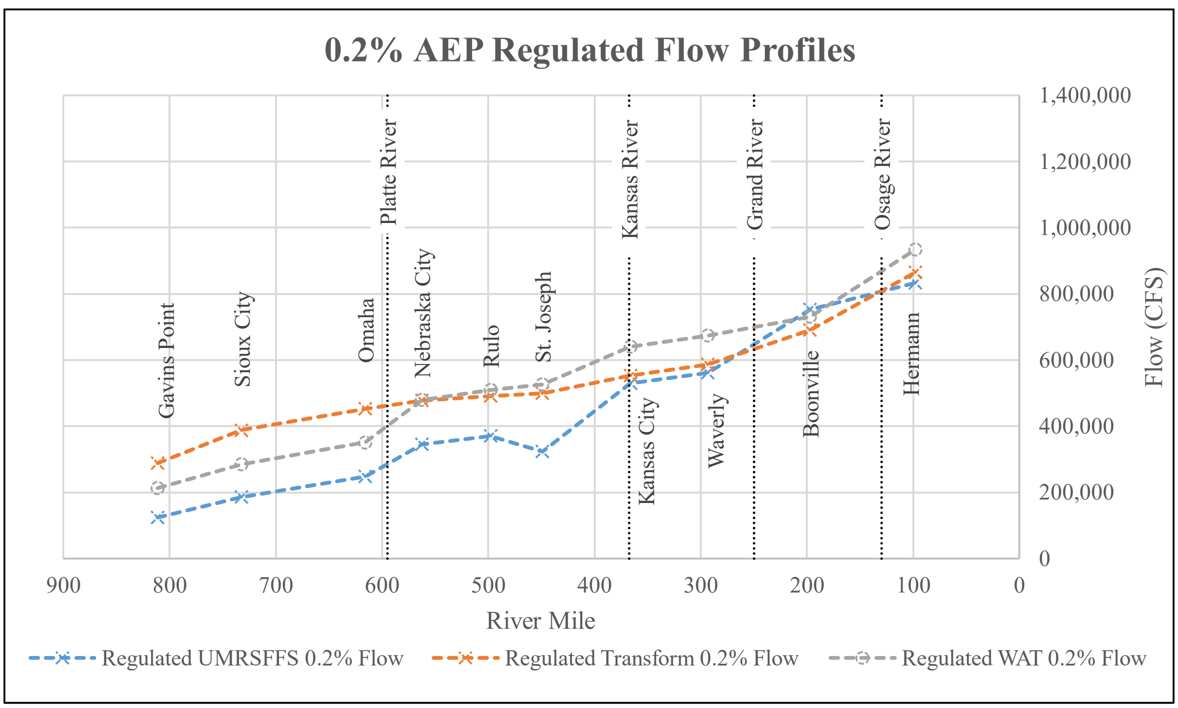


Figure 7-16. Regulated 0.2% AEP Flow vs River Mile, 2003 UMRSFFS, and Current Study from Transform and from WAT Monte Carlo (Adopted)

Flow frequencies published in this report reflect the fifth comprehensive update to flows on the lower Missouri River by USACE. Original "without reservoir" flow frequency information published in 1932 utilized Hazen plotting positions for stage records of six gages having 48 to 59 years of record and Fort Benton having 36 complete years of record (USACE, 1935). One percent chance flows were estimated by applying the best rating curve available to the 1% chance stage. According to the 1932 report, "In a river having a constant, or nearly constant stage-discharge relation, the error would be small; but for an alluvial river such as the Missouri where the stage-discharge relation is constantly changing, the error might be rather large. The results, as obtained by applying the one-percent chance gage heights to the best rating curve available, are very approximate." In the 1932 report, benefits of Fort Peck Dam and other potential reservoirs were considered, however, a comprehensive analysis of all mainstem dams, and todays tributary projects, was not foreseen at that time.

Flow frequencies in the 1946 to 1947 Levee Definite Project Report were computed at St. Joseph, Kansas City, Waverly, Boonville, Hermann for the natural conditions using a period of record of up to 72 years from 1873 to 1944 as at Kansas City and Hermann (USACE, 1947). Estimates of frequencies in the present conditions at the time with Fort Peck in operations, and ultimate build out of reservoirs and levees were made at the 1946 study gages Sioux City to the mouth. Frequency estimates were made by converting pre-USGS stage records to flow using historic rating curves, combining those with USGS flow records, and fitting a curve to the data. Reservoirs assumed were the Garrison, Oahe, and Fort Randall mainstem dams in addition to Fort Peck, all major existing Kansas River Basin Dams except Milford, Perry, and Clinton, dams in the Osage Basin slightly upstream of the Truman Dam site, and reservoirs never constructed in the Grand and Gasconade River basins. The 1946-1947 Agricultural Levee DPR proposed that levees in the Kansas City to the mouth reach be designed for the 1% AEP flood discharge with reservoirs in operations. Upstream of Kansas City, design discharges were determined by a combination of a frequency analysis and study of transposition of large historic floods and reservoir releases.

In the 1962 Levee Re-study Report, flow frequencies were updated using a 62-year period of record of 1898 to 1960, with updated information on reservoirs and additional consideration of levee confinement to include a 3,000 feet floodway below Kansas City, instead of 5,000 feet as in the 1947 Study (USACE, 1962). Condition VI flows were used for early regulatory flood mapping and studies on the Missouri River, as there were only minor differences in reservoirs assumed operational and those constructed. As previously discussed, the 2003 UMRFFS utilized a 100-year period of record of 1898 to 1997, whereas the current study utilized a systematic record of 1930 to 2019, and historic period back to 1843/1844, representing up to a 177-year period. Table 7-2 presents a summary of 1% AEP flows of these five studies and the 1947 agricultural levee design flows. Tables 7-3 to 7-5 present a summary of flow frequencies from the 1962, 2003, and 2023 studies.

Table 7-2. Summary of Published Lower Missouri River 1% AEP Flow Frequencies from USACE 1932, 1947, 1962, 2003, and 2023 Reports, and the 1947 Agricultural Levee Design Flows (cfs)

Location	Unregulated 1% AEP Flows				1947 Levee Design Flows	Regulated 1% AEP Flows			
	1932 "308 Report"	1946/47* App. A "Natural"	2003 UMRSFFS	2023 MRFFS		1947 "Ultimate build"	1962 Levee Re-Design	2003 UMRSFFS	2023 MRFFS
Yankton			385,600	438,000				84,900	164,000
Sioux City	325,000		383,800	458,000	150,000	110,000	90,000	133,800	218,000
Omaha			387,000	471,000	250,000	125,000	190,000	174,700	232,000
Nebraska City			417,600	497,000	295,000	215,000	220,000	236,700	329,000
Rulo			429,300	497,000	310,000		241,000	252,200	336,000
St. Joseph	400,000	255,000	452,800	500,000	325,000	293,000	270,000	261,000	349,000
Kansas City	512,000	510,000	581,000	624,000	431,000	431,000	425,000	401,000	467,000
Waverly			581,000	639,000	437,000	437,000	445,000	424,000	503,000
Boonville	603,000	550,000	689,000	711,000	475,000	475,000	550,000	573,000	572,000
Hermann	634,000	660,000	871,000	928,000	529,000	529,000	620,000	673,000	666,000

*Included a shortened 51 year period of record of 1893 to 1944 at St. Joseph, which excluded the 1881 flood; compared to 72 years at Kansas City and Hermann, and 71 years at Boonville in the 1946 Appendix A of the 1947 Levee DPR. Waverly was also computed but had missing records and was assumed similar to Kansas City. Upstream stations were only reported in the 1946/47 documents with Fort Peck in operations and therefore were not included in this table.

Table 7-3. Summary of Published Lower Missouri River Regulated Flow Frequency Results of the current 2023 study, 2003 UMRSFFS, and 1962 Levee Re-study Report, Gavins Point, Sioux City, Omaha, and Nebraska City (cfs)

	Gavins Point		**Sioux City**			**Omaha**			**Nebraska City**		
AEP	2003	2023	1962	2003	2023	1962	2003	2023	1962	2003	2023
%	[2]UMRSFFS	[3]MRFFS	[1]Restudy	[2]UMRSFFS	[3]MRFFS	[1]Restudy	[2]UMRSFFS	[3]MRFFS	[1]Restudy	[2]UMRSFFS	[3]MRFFS
0.2	123,500	213,000		185,400	285,000		247,900	351,000		345,400	480,000
0.4		169,000			268,000			312,000			399,000
0.5	98,000	164,000		155,000	266,000		204,500	293,000		275,900	382,000
1	84,900	164,000	90,000	133,800	218,000	190,000	174,700	232,000	220,000	236,700	329,000
2	74,700	104,000	82,000	113,800	156,000	170,000	147,900	187,000	200,000	206,400	244,000
4		81,000			121,000			154,000			220,000
5	69,100	77,000		93,900	111,000		132,700	151,000		189,900	212,000
10	65,000	64,000	65,000	78,300	89,000	125,000	123,600	118,000	160,000	149,800	171,000
20	63,000	54,000		66,800	71,000		85,300	99,000		118,700	132,000
50	45,300	44,000	44,000	49,500	47,000	74,000	64,200	62,000	108,000	88,000	88,000
80	38,300	38,000		39,100	41,000		49,900	47,000		70,500	61,000
90	34,800	35,000		36,100	38,000		44,800	43,000		60,500	54,000
95	32,100	33,000		34,000	36,000		40,700	40,000		53,500	49,000
99	27,000	28,000		31,200	32,000		34,600	37,000		40,600	42,000

[1]U.S. Army Corps of Engineers, 1962. 'Missouri River Agricultural Levee Restudy Program -- Hydrology Report,' Missouri River Division, Omaha District, Kansas City District. Reproduced from Table F-3 of UMRSFFS. NOTE: flows for Gavins Point Dam / Yankton were not published in the 1962 Report.

[2]Data from Table F-49 of the 2003 Upper Mississippi River System Flow Frequency Study (UMRSFFS) Appendix F.

[3]Current Missouri River Flow Frequency Study Adopted Results from the WAT Monte Carlo Analysis

Table 7-4. Summary of Published Lower Missouri River Regulated Flow Frequency Results of the current 2023 study, 2003 UMRSFFS, and 1962 Levee Re-study Report, Rulo, St. Joseph, and Kansas City (cfs)

	Rulo			St. Joseph			Kansas City		
AEP	1962	2003	2023	1962	2003	2023	1962	2003	2023
%	[1]Restudy	[2]UMRSFFS	[3]MRFFS	[1]Restudy	[2]UMRSFFS	[3]MRFFS	[1]Restudy	[2]UMRSFFS	[3]MRFFS
0.2		370,700	510,000	330,000	324,000	526,000	540,000	530,000	640,000
0.4			432,000			444,000			555,000
0.5		296,900	422,000		287,000	433,000		454,000	546,000
1	241,000	252,200	336,000	270,000	261,000	349,000	425,000	401,000	467,000
2	220,000	217,300	294,000	246,000	233,000	296,000	380,000	351,000	393,000
4			250,000			255,000			312,000
5		188,600	233,000		199,000	239,000		289,000	293,000
10	170,000	160,900	187,000	185,000	174,000	197,000	270,000	245,000	247,000
20		132,300	148,000		147,000	157,000		210,000	197,000
50	117,000	94,700	101,000	120,000	109,000	107,000	150,000	142,000	136,000
80		72,600	65,000			75,000			97,000
90		62,800	57,000			66,000			82,000
95		55,800	51,000			59,000			72,000
99		44,900	44,000			52,000			58,000

[1]U.S. Army Corps of Engineers, 1962. 'Missouri River Agricultural Levee Restudy Program -- Hydrology Report,' Missouri River Division, Omaha District, Kansas City District. Reproduced from the Executive Summary of Appendix E and 50% AEP from Table F-3 of UMRSFFS.

[2] Data from Table E-15 of the 2003 Upper Mississippi River System Flow Frequency Study (UMRSFFS) Appendix E, except Rulo which is from Appendix F. NOTE: Appendix E, also publishes flows for Rulo, being 320,000 cfs at the 0.2% AEP, 281,000 cfs at the 0.5% AEP, and 250,000 cfs at the 1% AEP.

[3]Current Missouri River Flow Frequency Study Adopted Results from the WAT Monte Carlo Analysis

Table 7-5. Summary of Published Lower Missouri River Regulated Flow Frequency Results of the current 2023 study, 2003 UMRSFFS, and 1962 Levee Re-study Report, Waverly, Boonville, and Hermann (cfs)

	Waverly			Boonville			Hermann		
AEP %	1962 [1]Restudy	2003 [2]UMRSFFS	2023 [3]MRFFS	1962 [1]Restudy	2003 [2]UMRSFFS	2023 [3]MRFFS	1962 [1]Restudy	2003 [2]UMRSFFS	2023 [3]MRFFS
0.2		561,000	674,000	700,000	753,000	731,000	820,000	833,000	933,000
0.4			588,000			702,000			742,000
0.5		480,000	573,000		648,000	672,000		742,000	722,000
1	445,000	424,000	503,000	550,000	573,000	572,000	620,000	673,000	666,000
2	395,000	371,000	412,000	485,000	503,000	531,000	555,000	604,000	571,000
4			323,000			417,000			506,000
5		305,000	294,000		415,000	393,000		511,000	473,000
10	285,000	258,000	251,000	365,000	352,000	334,000	405,000	439,000	416,000
20		212,000	214,000		289,000	280,000		363,000	345,000
50	158,000	150,000	142,000	195,000	203,000	204,000	220,000	248,000	262,000
80			101,000			134,000			175,000
90			86,000			109,000			142,000
95			75,000			97,000			123,000
99			59,000			78,000			100,000

[1]U.S. Army Corps of Engineers, 1962. 'Missouri River Agricultural Levee Restudy Program -- Hydrology Report,' Missouri River Division, Omaha District, Kansas City District. Reproduced from the Executive Summary of Appendix E and 50% AEP from Table F-3 of UMRSFFS.

[2]Data from Table E-15 of the 2003 Upper Mississippi River System Flow Frequency Study (UMRSFFS) Appendix E.

[3]Current Missouri River Flow Frequency Study Adopted Results from the WAT Monte Carlo Analysis

8. Review Process

8.1 Purpose and Requirements

8.1.1 Purpose.

This Review Plan defines the scope and level of peer review for the Missouri River Flow Frequency Study. This project updates the flood flow frequency estimates on the Missouri River from Gavin's Point Dam to St. Louis, Missouri along the lower Missouri River. The prior estimates were provided in the 2003 Upper Mississippi River System Flow Frequency Study (UMRSFFS).

This study will be conducted under the Flood Plain Management Services (FPMS) Authority provided in Section 206 of the 1960 Flood Control Act (PL 86-645) as amended

8.1.2 References

1. Engineering Regulation (ER) 1165-2-217, Civil Works Review Policy, 01 May 2021
2. EC 1105-2-412, Model Certification, 31 May 2005
3. Engineering Regulation (ER) 1110-1-12, Quality Management, 30 Sep 2006
4. ER 1105-2-100, Planning Guidance Notebook, Appendix H, Policy Compliance Review and Approval of Decision Documents, Amendment #1, 20 Nov 2007

8.2 Purpose and Requirements

The Missouri River Flow Frequency Study was conducted under the FPMS authority and as such covered by the Programmatic Review Plan for General Investigations National Programs Managed within Northwestern Divisions (NWD) MSC Approval Date 22 Oct 2012. The following factors were identified in supporting an extended review process.

- This is a large-scale hydrologic analysis covering a very large watershed
- The results of this study are likely to impact many flood risk management decisions on the lower Missouri River and as such likely to encounter resistance from concerned public stakeholders.
- Methods used in this analysis are unique compared with typical hydrologic analysis due to the size of analysis and accounting for regulation.

8.3 Review Management Organization (RMO) Coordination

The RMO is responsible for managing the overall peer review effort described in this review plan. The RMO for this project is the home District. The home District will coordinate and approve the review plan and manage the Agency Technical Review (ATR) as well as the Independent External Peer Review (IEPR).

8.4 Project Information

8.4.1 Final Document.

The Missouri River Flow Frequency report will be the culmination of the study.

8.4.2 Study/Project Description

The Missouri River is the longest river in North America. Rising in the Rocky Mountains of the Eastern Centennial Mountains of Southwestern Montana, the Missouri flows east and south for 2,341 miles (3,767 km) before entering the Mississippi River north of St. Louis, Missouri. The river drains a sparsely populated, semi-arid watershed of more than 500,000 square miles. Six Mainstem reservoirs and dozens of tributary reservoirs in the basin are operated for various purposes including flood risk management, irrigation, hydropower, navigation, water supply, water quality, fish and wildlife, and recreation by multiple Federal, State, and Local agencies.

This project's objective is to provide regulated flow frequency estimates for the Lower Missouri River from Gavin's Point Dam to the most downstream river gage at Hermann, MO. Regulated flow frequency values for locations between the gage locations will be included in the future Stage Frequency study.

8.4.3 In-Kind Contributions

No in-kind contributions are a part of this project. If products and analyses provided by non-Federal sponsors as in-kind services are provided, they will be subject to District Quality Control (DQC) and ATR, similar to any products developed by USACE.

8.5 District Quality Control (DQC)

All decision documents (including supporting data, analyses, environmental compliance documents, etc.) shall undergo DQC prior to ATR. The home district shall manage DQC. DQC will be conducted through supervisor and technical expert review.

8.5.1 Required DQC Team Expertise.

DQC Team Members/Disciplines	**Expertise Required**
Hydrology	The hydrology reviewer will be an expert in the field, with experience in precipitation, extreme storms, snowmelt, frozen ground, and HMS.
Flow Frequency Bulletin 17C	The reviewer will be familiar with the process of using Bulletin 17B/C and HEC-SSP to complete flow frequency analysis on both regulated and unregulated watersheds.

8.5.2 Documentation of DQC.

DrChecks review software will be used to document DQC comments, responses and associated resolutions accomplished throughout the review process. Comments should be limited to those that are required to ensure adequacy of the product. If an DQC concern cannot be satisfactorily resolved between the DQC team and the PDT, it will be elevated to the vertical team for further resolution. The DQC DrChecks project will be shared with ATR reviewers for situational awareness. Additional review comments conducted using over the shoulder supervisory reviews and cross-district reviews are reflected in the progression of the document and final report.

8.6 Agency Technical Review (ATR)

One ATR was conducted on this study report (including supporting data, analyses, etc). ATR is managed within USACE by the designated RMO and is conducted by a qualified team from outside the home district that is not involved in the day-to-day production of the project/product. ATR teams will be comprised of senior USACE personnel. ATR for this effort is resourced to USACE Subject Matter Expert(s) (SME) as listed below.

8.6.1 Required ATR Team Expertise.

ATR Team Members/Disciplines	Expertise Required
Hydrology	The hydrology reviewer will be an expert in the field, with experience in precipitation, extreme storms, snowmelt, frozen ground, and HMS.
Flow Frequency Bulletin 17C	The reviewer will be familiar with the process of using Bulletin 17B/C and HEC-SSP to complete flow frequency analysis on both regulated and unregulated watersheds.
HEC-WAT Hydraulic Sampler	HEC developed hydrologic sampler is used to develop the 250,000 years of discrete flow conditions used in the analysis. The reviews have experience in sampler development and sensitivity of sampler outputs
ECB 18-14 Qualitative Climate Assessment	The reviewer will be experienced with previous ECB 18-14 assessments and have experience on climate assessments in highly regulated watersheds.

8.6.2 Documentation of ATR.

ProjNet-DrChecks review software was used to document all ATR comments, responses and associated resolutions accomplished throughout the review process. Comments should be limited to those that are required to ensure adequacy of the product. If an ATR concern cannot be satisfactorily resolved between the ATR team and the PDT, it will be elevated to the vertical team for further resolution in accordance with the policy issue resolution process described in either ER 1110-2-12 or ER 1105-2-100 as appropriate. Unresolved concerns can be closed in ProjNet-DrChecks with a notation that the concern has been elevated to the vertical team for resolution.

8.7 External Peer Review (EPR)

External peer review (EPR) is the most rigorous level of review and is applied in cases that meet certain criteria where the risk and magnitude of the proposed project are such that a critical examination by a qualified team outside of USACE is warranted. External review and input were coordinated through a Technical Review Group (TRG) of academic and agency professionals that has been established to provide input on the study methods and interpretation of results. This team was tasked with four meetings to review and provide feedback on study processes. This team was comprised of Subject Matter Experts in Statistical Hydrology and Climate Assessments. The SME's represent multiple Federal agencies and academia. Research Triangle Institute (RTI), was contracted to both coordinate the above TRG group as well as provide External Peer Review of the study. A detailed summary of the TRG and RTI meetings and Feedback is included in Appendix K, and the summary of the ATR comments is provided in Appendix L.

8.8 Policy and Legal Compliance Review

The Missouri River Flow Frequency report will become a building block for many efforts along the Missouri River which will undergo policy and legal compliance review. Guidance for policy and legal compliance reviews is addressed in Appendix H or ER 1105-2-100. These reviews culminate in determinations that the recommendations in the reports and the supporting analyses and coordination comply with law and policy, and warrant approval or further recommendation to higher authority by the home MSC Commander. DQC and ATR augment and complement the policy review processes by addressing compliance with pertinent published Army policies, particularly policies on analytical methods and the presentation of findings in decision documents.

8.9 Model Certification and Approval

ATR will be used to ensure that models and analyses are compliant with Corps policy, theoretically sound, computationally accurate, transparent, described to address any limitations of the model or its use, and documented in study reports.

8.9.1 EC 1105-2-412.

As part of the USACE Scientific and Engineering Technology (SET) Initiative, many engineering models have been identified as preferred or acceptable for use on Corps studies and these models should be used whenever appropriate. The selection and application of the model and the input and output data is still the responsibility of the users and is subject to DQC, ATR, and IEPR (if required).

8.9.2 Planning and Engineering Models.

The following models were used in the development of this report, where HH&C refers to the USACE Hydrology, Hydraulics, and Coastal Community of Practice:

Model Name and Version	Description of the Model and How It Will Be Applied in the Study	Status
HEC-ResSim	The Hydrologic Engineering Centers Reservoir Simulation (HEC-ResSim) software package is used by the Division Water Management Office to model reservoir operations in the Missouri River basin for a variety of operational goals and constraints.	HH&C CoP preferred software
HEC-SSP	The Hydrologic Engineering Center's Statistical Software Package program will provide the capability to manage and compile flow data for the Bulletin 17C Flow frequency Analysis.	HH&C CoP preferred software
HEC-WAT 1.1	The Hydrologic Engineering Center's Watershed Analysis Tool (HEC-WAT) will be used to perform a Monte Carlo analysis of the winter storm volumes by stochastically sampling hyetographs and computing storm precipitation volumes from a probabilistic distribution and running many HEC-HMS simulations with these inputs.	HH&C CoP preferred software

8.10 Public Participation

The Missouri River Flow Frequency Study is a technical product updating flow frequency data using methods from the 2003 study, which underwent a public participation process, and improving upon them to match current guidance and capabilities. Public participation was not a part of the study scope, however, public outreach is being conducted to communicate the study methodology and results, and to gather input to inform the scope of the Missouri River Stage Frequency Study. Associated efforts including the Missouri River Planning Assistance to States (PAS) study completed in 2022 and ongoing Lower Missouri River Flood Risk and Resiliency General Investigation Study (FRRS), which is partially funding work on the Stage Frequency Study, do include public participation and agency coordination. These resources are being utilized to provide awareness and communication about the Flow Frequency Analysis and to gather public input and concerns.

For example, a recorded public webinar and question-and-answer session on the Flow Frequency Study methods was conducted on April 20, 2023 and posted to the Lower Missouri River Flood Risk and Resiliency Study Website. This call largely included levee district representatives, with peak participation of about 100 callers, at a time when technical comment resolution from the Technical Review Group and Agency Technical Review was in progress. Questions pertinent to the flow frequency included why flows were not reported downstream of Hermann, MO, what was causing the increase in flows, whether flows are representative of existing or future conditions, and when the data would be available? This study focused on ten mainstem Missouri River gages, where the future Stage Frequency Study will need to consider more detailed tributary flow inputs between and downstream of the study gages, although historically peak flows at Hermann are nearly identical as at the mouth. Details on the causes for increases flow frequency are included in Section 7.6, Results Summary. As detailed in Section 2.6 this study reflects existing conditions hydrology without adjustment for climate change.

The remainder of the questions asked during the March 20, 2023 webinar were centered around items that are pertinent to the Stage Frequency Study, or subsequent further study and action by USACE or FEMA. Questions pertinent to stage frequency scoping included concerns for how scour, levee breaching, and flood fighting are accounted for, whether districts would be allowed to raise levees, and what type of hydraulic model would be used. Concerns to understand impacts to levee districts, such as potential levee accreditation and whose decision that is, or changes to overtopping frequency were also raised during the call. Though not currently scheduled, decisions to update any regulatory products or levee accreditation fall under the jurisdiction of FEMA.

The intent of updating flood risk products, such as 2-dimensional modeling by FEMA using the flow frequency information, or the USACE stage frequency scope, are intended to become available for use to aid decision making. For example, this could result in additional tools to help consider potential adverse stage impacts of proposed development along the river once the models are complete, or for developing alternative plans to reduce flood risk, or informing elevations of temporary risk reduction measures during a flood. Lastly, USACE intends to use the results of the Flow Frequency Study as part of the Lower Missouri River Flood Risk and Resiliency Study and associated spinoff feasibility studies to help reduce flood risk. Additional input and coordination with levee districts and other interested entities is planned to continue through routine public webinars as part of the Missouri River Flood Risk and Resilience Study, with the ability to input questions via email at **lomoriverstudy@usace.army.mil**.

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