Missouri River Flow Frequency Study: HEC-WAT Monte Carlo Analyses

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Abstract

The purpose of the Missouri River Flow Frequency Study was to update both undeveloped and regulated flow frequency at ten locations along the Missouri River from Gavins Point Dam near Yankton, SD to Hermann, MO. Undeveloped flow frequency analyses were conducted according to the methodology advanced in Federal Guidelines for Determining Flood Flow Frequency - Bulletin 17C (U.S. Geological Survey, 2019). An estimate of regulated flow frequency was completed using a Monte Carlo approach that simulated 250,000 hydrologic events split among 5,000, 50-year continuous simulations. A 500-year synthetic flow record was developed by randomly combining flows from four different regions of the Missouri River Basin and three seasons. The 90-year historical record was also included, so a total of 590 years were used as the historical sample in the analysis. The 590-year historical sample was also supplemented with scaled floods to help define the regulated flow frequency curves for events less frequent than the 1% AEP event. To capture knowledge uncertainty in the frequency description, a 90-year sub-sample was randomly sampled from all available events and used as the sample of events to build 50-year continuous simulations within 1 realization or group of 2500 events. Finally, because event likelihoods were based on a single watershed location, a weighted adjustment of the Monte Carlo sample was completed at each gage. This adjustment allowed the resulting flow frequencies to match the frequency curves for undeveloped flows produced by the Bulletin 17C analyses at each gage. The weights were assigned to each event, not its plotting position, to ensure the resulting regulated flow was given the same weight as its corresponding undeveloped flow. Compared to the traditional transform method described in EM 1110-2-1415 (U.S. Army Corps of Engineers, 1993), the Monte Carlo approach produced better estimates of regulated flow frequency by capturing thousands of combinations of flow events, reservoir pool elevations, inflows, forecasts, and operations.

Background

The Missouri River Basin is one of the largest and hydrologically diverse basins in the country, which is why the Missouri River mainstem reservoir system (System) consisting of six large reservoirs beginning at Fort Peck, MT and ending at Yankton, SD was designed to handle widely varying runoff conditions. The System has 16.3 million acre-feet (MAF) of annual flood control and multiple-use storage and 38.5 MAF of carryover multiple-use storage. This carryover multiple-use storage allows the reservoirs to supply water during extended droughts in support of all authorized purposes. Unlike other large reservoir systems in the country that have less storage space than average annual runoff, the System storage is nearly three times the average runoff. This ratio means that drastically different operations can occur for the same runoff event depending on the amount of unoccupied System storage at the start of the event. Previous Missouri River planning studies such as the Missouri River Recovery Management Plan Environmental Impact Statement (MRRMP EIS) utilized a period-of-record (POR) simulation approach (U.S. Army Corps of Engineers, 2018). The Missouri River POR has a variety of floods and extended droughts that allow for a wide assessment of impacts to operations. However, large flood events tend to "reset" the System by refilling the reservoirs after droughts or other drawdowns due to operational changes. Because of this reset, alternatives with operational changes tended to show impacts only in a select number of modeled years, which limited assessment of impacts. External comments during the MRRMP EIS review noted that the limited number of times an operational change was able to run within several of the alternatives was not sufficient to adequately quantify changes in risk. The U.S. Army Corps of Engineers (USACE) acknowledged that while the POR approach was adequate for most situations, a different approach would be needed to quantify risk more completely on the Missouri River. Therefore, the USACE committed to develop a Monte Carlo approach for both ResSim and RAS modeling, so changes in risk on the Missouri River due to operational changes could be adequately quantified.

The Missouri River Monte Carlo approach used what had been done for the Columbia River Treaty (CRT) Flood Risk Assessment as a blueprint (U.S. Army Corps of Engineers, 2012). In this study, the Hydrologic Engineering Center's Watershed Analysis Tool (HEC-WAT) watershed was developed with the Flood Risk Analysis (FRA) compute option to assess proposed changes in the CRT provisions. The CRT analysis was done by sampling events from the historical POR and a group of scaled events, generating random snowmelt runoff forecasts, and then simulating operations for each event. Due to the hydrology of the Columbia River Basin and the fact that the reservoirs were not designed with a significant amount of carryover storage, each event was evaluated with approximately the same starting reservoir condition. Because of the Missouri River System's carryover multiple-use storage, this Monte Carlo approach of simulating each event with roughly the same starting reservoir conditions was modified. A 50-year continuous simulation was used instead, meaning that the reservoir conditions at the end of the first year provided the starting reservoir conditions of the second year. This approach allowed the Missouri River Monte Carlo approach to capture the influences that extended droughts combined with flood events have on operations.

Another modification from the CRT Monte Carlo approach was the use of a synthetic flow record. The CRT HEC-WAT watershed was setup to use the "Bootstrapping Historical/Synthetic Basin-wide Events" method, which samples entire years from a "bucket" of user-defined historical and optional scaled basin-wide events. The "bucket" used in the CRT HEC-WAT watershed consisted of a historical sample comprised of the historical POR (with years defined as equally likely) and several scaled events (defined with specific likelihoods). If the historical POR was short or not diverse enough (e.g., not enough large flood events), confidence in estimates of less frequent events would be lower than if a larger historical POR was used. The Missouri River Monte Carlo approach attempted to improve on this limitation by supplementing the historical sample with a synthetic flow record or Big Bucket. The Missouri River Basin was split into four regions and a year was split into three seasons. Utilizing years in the historical POR, flows from those regions and seasons were re-combined with correlated random sampling in such a way that events in the Big Bucket were still representative of the historical POR, but contained smaller and larger events, as well as events with different distribution of volume throughout the Missouri River Basin. The historical POR was also included in the historical sample, so the historical sample consisted of 500 years of synthetic events (Big Bucket) and 90 years of historical events. Scaled events were also added to the "bucket" with specified likelihoods. The Missouri River Monte Carlo analysis then sampled events from the "bucket" (historical sample and scaled events) to simulate reservoir operations for 1000s of events with various reservoir and river conditions.

Synthetic Flow Record: Big Bucket

The first step in creating the Big Bucket was dividing the Missouri River Basin into regions and seasons. This task required determining which gages were correlated or had similar runoff characteristics, and when that runoff occurred during a typical year. Runoff in the Missouri River Basin can be broken up into three sources: mountain snow, plains snow, and rainfall. The mountain snowpack is confined to the reaches above Garrison Dam and tends to melt during May, June, and July. Plains snow typically melts during March and April and can be spread over most of the basin. However, it tends to be most concentrated in the upper basin above Sioux City, IA. This area does include part of the reaches that receive runoff from the mountain snowpack, but based on a correlation analysis, it was determined that the portion of the basin most influenced by plains snowpack is downstream of Garrison Dam and upstream of Sioux City, IA. Plains snowpack can still influence runoff downstream of Sioux City, IA, but it becomes negligible downstream of Rulo, NE. Therefore, the final two regions were split at Rulo, NE, which was confirmed with a correlation analysis showing high correlation of sites within the chosen regions and lower correlation between regions.

Since nearly eighty percent of the average annual runoff in the upper basin above Sioux City, IA occurs between March and July, the rest of the year, August through February, was lumped together into one final season. **Figure 1** shows a map of the four regions, summarized in **Table 1**, that were used to generate the Big Bucket. **Table 2** summarizes the three seasons. Each region and season were randomly sampled from the historical POR and stitched together to form new flow records for each input gage in the model. This random sampling maintained the spatial and temporal correlation between regions and seasons in the historical POR. The historical POR was also included in the historical sample so each historical year could potentially be sampled during an FRA compute. The final historical sample consisted of 500-year Big Bucket comprised of synthetic flow data and 90 years of the historical POR.

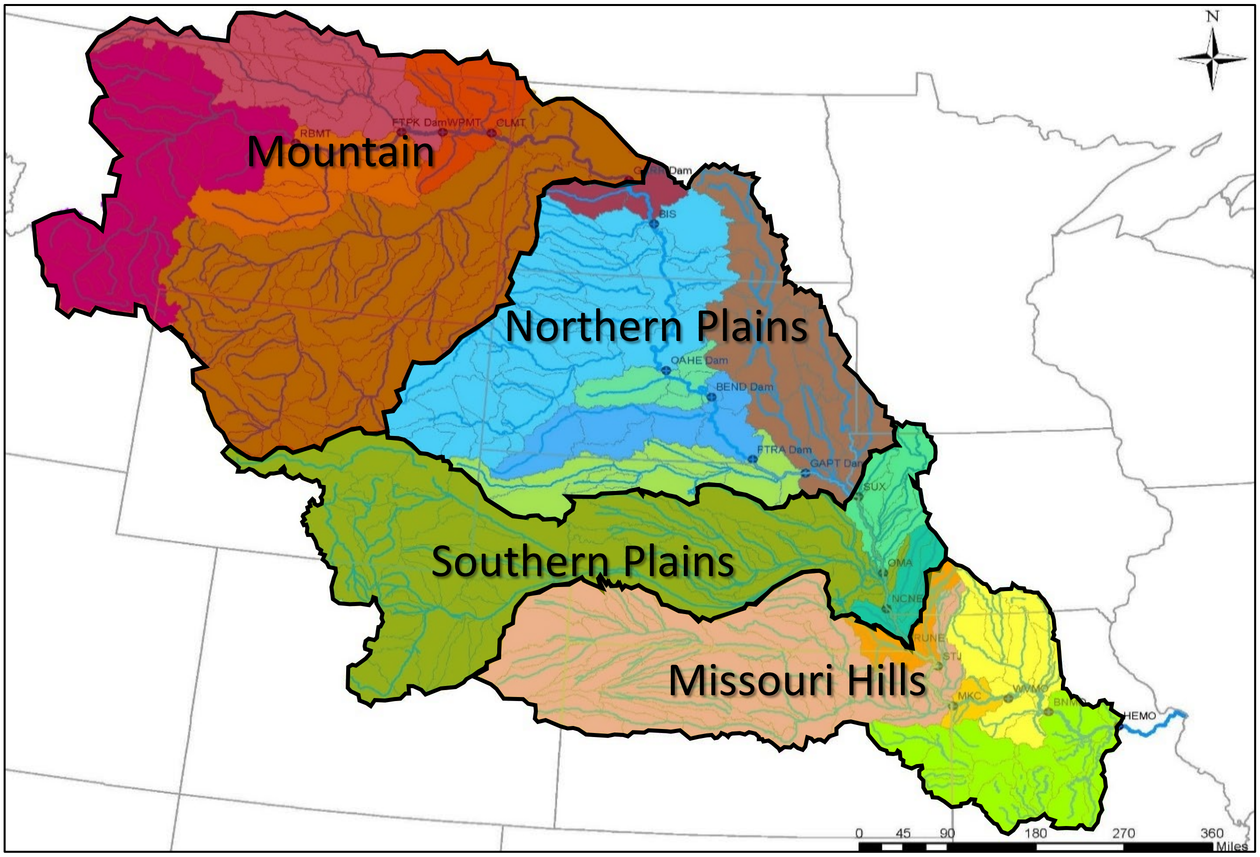

Figure 1. Regions represented in the Big Bucket.

Table 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 2. Seasons represented in the Big Bucket.

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

Correlation

In order to ensure the Big Bucket was representative of the historical POR, the spatial and serial correlations of the historical POR were analyzed and maintained in the sampling. The volume of flow at all locations within a region for the full season was calculated for each of the four regions and three seasons. Spatial and temporal correlations were then computed with these volumes. The method of random sampling used to create the 500-year Big Bucket used 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 POR. Bootstrap sampling will never produce a flow volume for a region 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 basin, can be more extreme (either larger or smaller) than the observed extremes, and is in fact a goal of this re-sampling procedure. This method that bootstraps the historical POR combines correlated sampling that maintains spatial correlation with a Periodic AR(1) Autoregressive Lag 1 model that maintains temporal (serial) correlation. The approach can be described as a series of steps as follows:

1. Generate spatially correlated Standard Normal random values,
2. Generate series of serially correlated Standard Normal random values that maintain the spatial correlation,
3. Transform Standard Normal N[0,1] values to Uniform[0,1] values and
4. Use those U[0,1] random values to re-sample the appropriate season from the historical record.

Table 3 shows the spatial correlations computed for each season from the sampled synthetic 500-year record on the left, and the specified values that formed the spatial correlation **Σ** matrices used for sampling on the right (in orange). Note, the matrices show only the non-diagonal elements (as the diagonals are always 1.0, reflecting the correlation of values to themselves). The correlation values differ by as much as 0.1 in the Remainder season, which was considered less important due to the lower runoff values but are within 0.05 in the other 2 seasons (Early Spring and Late Spring). **Table 4** similarly shows the serial correlations. Other random records generated were able to maintain these correlations more closely, but this random record was chosen for its success in extrapolating the regional seasonal frequency curve, shown in the next section.

Table 3. Spatial correlations of randomly sampled 500-year record, compared to specified values.

Season		**Computed from Sampled Record**			**Specified from Historic Record**		
	Region	**Mountain**	**N. Plains**	**S. Plains**	**Mountain**	**N. Plains**	**S. Plains**
Early Spring	**N. Plains**	0.54			**0.57**		
	S. Plains	0.26	0.54		**0.27**	**0.56**	
	Mo. Hills	0.24	0.32	0.68	**0.20**	**0.39**	**0.71**
Late Spring	**N. Plains**	0.59			**0.60**		
	S. Plains	0.32	0.76		**0.29**	**0.77**	
	Mo. Hills	0.34	0.54	0.66	**0.25**	**0.51**	**0.67**
Remainder	**N. Plains**	0.52			**0.41**		
	S. Plains	0.41	0.75		**0.45**	**0.80**	
	Mo. Hills	0.35	0.45	0.60	**0.37**	**0.49**	**0.66**

Table 4. Serial correlations of randomly sampled 500-year record, compared to specified values.

Season	**Computed from Sampled Record**				**Specified from Historic Record**			
	Mountain	**N. Plains**	**S. Plains**	**Mo. Hills**	**Mountain**	**N. Plains**	**S. Plains**	**Mo. Hills**
Early Spring	0.40	0.49	0.53	0.43	**0.42**	**0.44**	**0.54**	**0.44**
Late Spring	0.52	0.61	0.69	0.39	**0.47**	**0.54**	**0.71**	**0.42**
Remainder	0.69	0.76	0.76	0.43	**0.65**	**0.73**	**0.81**	**0.46**

Frequency

A factor considered more important than precisely maintained spatial and serial correlations was the extrapolation of the seasonal frequency curves of total flow volume in the basin, as summed from the four regions. **Figure 2** through **Figure 4** show frequency curves for total seasonal flow volume for each region, with plots for each season with a linear axis. The sum of all regional volumes in the basin is shown in each plot in green. The plots in **Figure 2** through **Figure 4** have the 90-year historical POR as solid markers, and the 500-year, sampled synthetic flow record (a potential Big Bucket) as hollow markers. It was desirable to have the total basin volume, shown in green, produce a reasonable upward and downward extrapolation of the frequency curve from the 90-year historical POR in the Early and Late Spring seasons.

One should note that the shapes of the sampled frequency curves (hollow markers) for each region follow the shape and irregularities of the historical 90-year frequency curves closely, as the only values available to be sampled come directly from that curve. The sum of all regions in green, however, may contain values not seen before, as it combines values from the four regions that did not actually occur together and so were not one of the historical sums. Therefore, the hollow green markers for the sum are less constrained to the irregularities of the historical POR and seem to produce smoother frequency curves between 0.99 and 0.01.

The chosen 500-year Big Bucket produces a good match of the basin sum curves in green, and a reasonable upward extrapolation of those curves for both early and late spring seasons. The lower end of Early Spring is well matched and well extrapolated by this synthetic record. The lower end of Late Spring season is much more difficult to match with sampling, as the driest years in the historical POR were more extreme than would be expected in a record of this length, so the frequency plot dips down, not following the trend of the rest of the data. Due to the limited historical sample size, these dry years plot farther to the right (toward the median) than perhaps they should. The result is that it is more difficult to match and extrapolate the lower end of Late Spring, and most of the random 500-year Big Buckets considered did a poor job. This chosen record has at least one year drier than the driest, and many years drier than the second driest year Late Spring volume.

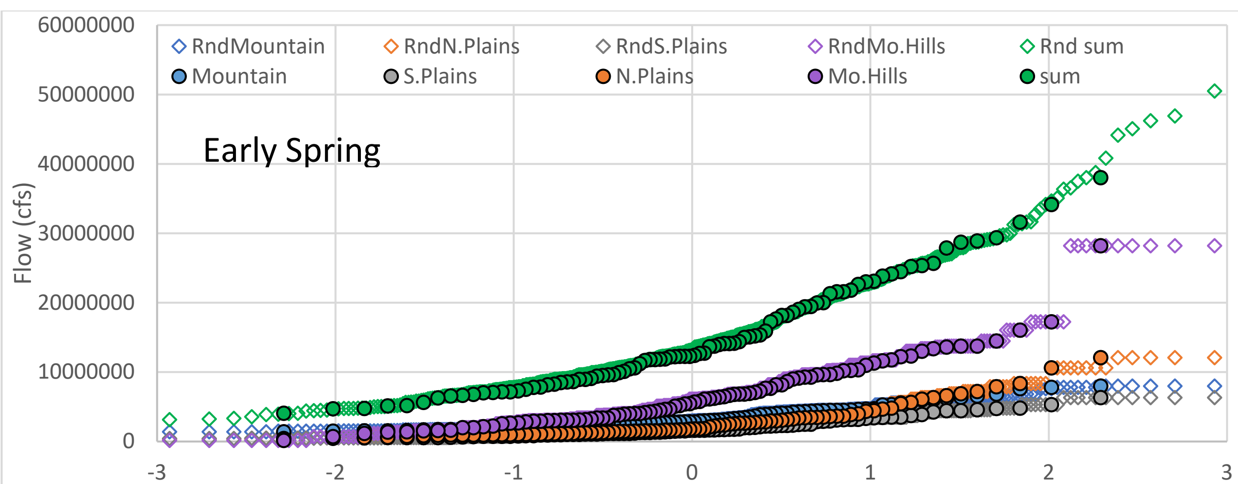

Figure 2. Seasonal volume frequency curves for the Early Spring season and each region, including sum of volumes across all regions.

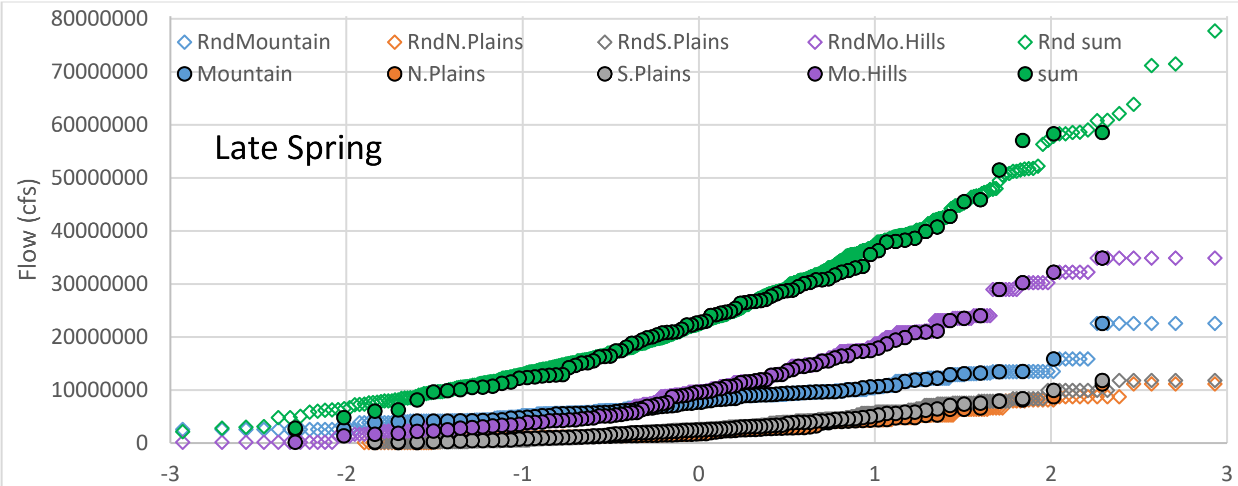

Figure 3. Seasonal volume frequency curves for the Late Spring season and each region, including sum of volumes across all regions.

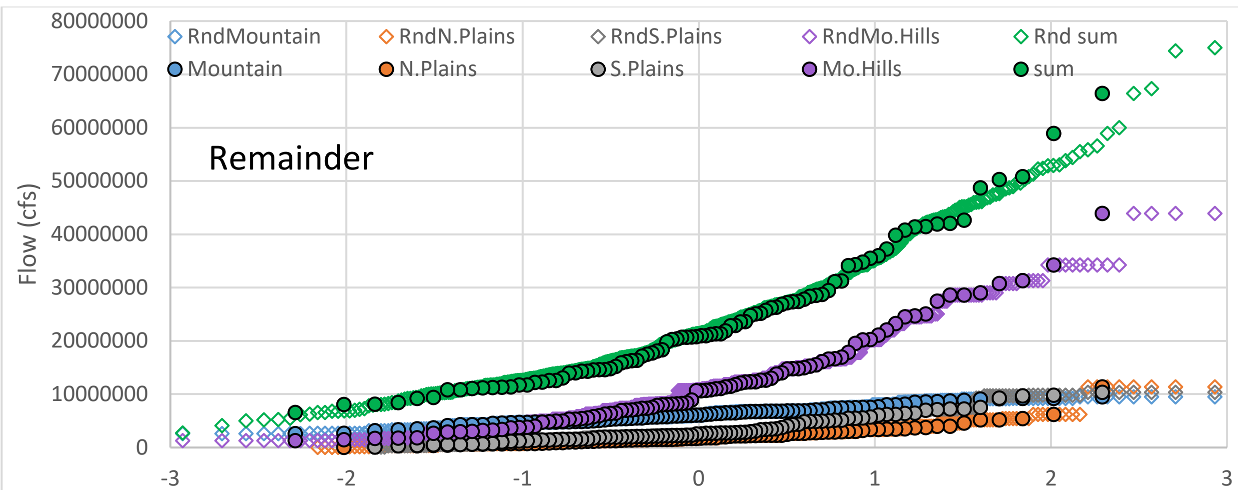

Figure 4. Seasonal volume frequency curves for the Remainder season and each region, including sum of volumes across all regions.

HEC-WAT Watershed

Missouri River ResSim Model

The Missouri River HEC-WAT watershed was setup with the Missouri River Mainstem ResSim (MR ResSim) model, which was originally created to assess alternatives developed for the MRRMP EIS (U.S. Army Corps of Engineers, 2018). The MR ResSim model originally simulated operations of the six Missouri River mainstem reservoirs for a 1930 through 2012 historical POR. All tributary reservoir operations were captured in the historical POR or through incorporation of the U.S. Bureau of Reclamation (USBR) depletions. The MR ResSim model was calibrated, tested, and thoroughly reviewed for the MRRMP EIS (U.S. Army Corps of Engineers, 2018), but only for events seen in the 1930-2012 historical 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 completed to allow accurate simulation of larger events. Along with improvements to the model's operations during large events, the MR ResSim model was expanded using two other ResSim models: Lower Kansas and Osage River. Both watersheds contain several reservoirs that can have a noticeable 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.

Hydrologic Sampler

The HEC-WAT software has the capability to use plug-ins during simulations. The Hydrologic Sampler is one of those plug-ins built to generate the random hydrologic time series necessary for an FRA compute (a Monte Carlo simulation). It uses pseudo random number generation to create flow or precipitation input time series from user inputs. For this study, only ResSim is within the Missouri River HEC-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 Missouri River HEC-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 compute. These sampled hydrologic time series are generated as separate realizations which each contain enough events to fully characterize the natural variability for a given instance of knowledge uncertainty. For this study, each realization contained 50 analysis periods or lifecycles. This study required a continuous simulation to capture the effects of varied reservoir levels, so each lifecycle was a 50-year continuous simulation where annual maximums and minimums of various parameters for each event were extracted for frequency curves.

Hydrographs: Development of the Big Bucket was done externally to the HEC-WAT, but the random sampling of the historical sample and scaled events as full years was done within the HEC-WAT. HEC-WAT sampling of the historical sample still needs to be related to the historical POR, meaning the Hydrologic Sampler should not over-sample dry years to create unrealistically long-term droughts or have too many flood events. This need is captured with serially-correlated random sampling, based on an annual serial correlation parameter for the Missouri River Basin. Even though the Missouri River Basin is large, the HEC-WAT can currently only use one location to define the probability of the total volume of each event's flows, so the most downstream computation point in the MR ResSim model was selected, Hermann, MO. The HEC-WAT calculates the total volume of each event during a specified season, which was defined as March 1 to September 30, to rank each event for sampling. Typically, the March through September season is when the bulk of the Basin runoff occurs. The annual serial correlation was set to 0.4, which was based on serial correlation in the historical POR.

Knowledge uncertainty was included in the analysis by specifying "Equivalent Years of Record," or EYR. The Hydrologic Sampler parameter generates an EYR-length sub-sample from the historical sample and scaled events for each realization, in effect replicating the sampling error an actual record might experience. It then samples events from the sub-sample to populate each lifecycle within a realization. For example, for this study, the Missouri River has a 90-year historical POR. When the HEC-WAT begins a realization, a 90-year sub-sample is randomly selected from the historical sample and scaled events based on the incremental probabilities assigned to each year. Fifty-year lifecycles are then sampled from the 90-year sub-sample, with each year having the same likelihood of being sampled (as it replicates a plausible historical record).

WAT Forecasts: 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 artificial/generated years in the Big Bucket or scaled events. The HEC-WAT random forecast feature was used instead of developing forecasts. This option has the added benefit of allowing the model 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. If the same year is sampled from the historical sample and scaled events multiple times, a different runoff forecast will be created based on the error statistics, which results in different regulated flows.

Scaled Events & Incremental Probabilities: Even though the historical sample provides larger and smaller events than observed during the historical POR, this does not guarantee the probabilities of less frequent events such as the 0.002 annual exceedance probability (AEP) event are accurately represented. To ensure estimates of regulated AEPs converged and gave accurate results for the tails of the frequency curves, scaled events, or events from the historical POR that were scaled to match volumes for defined AEPs, were also used in the simulations.

Twenty-eight events were chosen to help define the frequency curves of undeveloped flows generated by the HEC-WAT sampling, so they would closely match the Bulletin 17C flow frequency curves. Undeveloped flows represent a basin condition with no regulation and no surface water withdrawals. One limitation with the HEC-WAT is that only one AEP can be assigned for each event. Since the Missouri River Basin is large and the runoff varies widely throughout the basin, each scaled 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 5** summarizes the AEP for each scaled event.

Table 5. Scaled events on the Missouri River.

Year	Location for AEP	σ	Duration	AEP	WAT Assigned AEP
1971	DESO	2.5	1-Day	0.0292	0.02
1985	DESO	1.5	1-Day	0.0167	0.02
1981	STTM	1.5	1-Day	0.018	0.02
1941	STTM	2	1-Day	0.0156	0.02
1992	DESO	2	1-Day	0.0131	0.01
1971	DESO	3	1-Day	0.0086	0.009
1974	STTM	2	1-Day	0.0075	0.008
2007	DESO	1	1-Day	0.0068	0.007
2019	NCNE	1	3-Day	0.0048	0.005
1947	SUX	2	1-Day	0.0046	0.005
1985	DESO	2	1-Day	0.0045	0.005
1995	HEMO	0.5	3-Day	0.0044	0.004
1967	MKC	1	7-Day	0.0042	0.004
1978	SUX	1.5	31-Day	0.0041	0.004
1992	DESO	2.5	1-Day	0.0035	0.004
1952	OAHE	1	1-Day	0.0033	0.003
1943	HEMO	1	3-Day	0.0032	0.003
1972	SUX	2	15-Day	0.0031	0.003
1997	SUX	1	181-Day	0.0022	0.002
2010	NCNE	1.5	91-Day	0.0021	0.002
2007	DESO	1.5	1-Day	0.0015	0.002
1960	HEMO	1.5	15-Day	0.0014	0.001
1944	HEMO	1.5	3-Day	0.0012	0.001
1984	STTM	2.5	1-Day	0.0016	0.001
1993	MKC	0.5	3-Day	0.0009	0.0008
2011	SUX	1	181-Day	0.0005	0.0005
1982	STTM	3	1-Day	0.0005	0.0005
1951	DESO	0.5	3-Day	0.0002	0.0002

FRA Simulation

With the Hydrologic Sampler setup complete, there is one last parameter that needs to be set for the FRA compute: the number of events per realization. There is variation 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. A general rule 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 there is interest in the 0.01 AEP or 100-yr return interval, the simulation needs 500 (1/2 order of magnitude) to 1000 (full order of magnitude) events per realization. If there is interest in the 0.002 AEP or 500-yr return interval, the simulation needs 2500 or 5000 events per realization. For this study, the 0.002 AEP or 500-yr return interval was of interest, so the FRA simulation used 2500 events per realization and 100 realizations for a total of 250,000 events. Using 100 realizations also allows for the calculation of uncertainty bounds around the output frequency curves, which is an added benefit of the Monte Carlo analysis.

A check was performed at multiple gages along the lower river to verify convergence was achieved at the 0.01 and 0.002 AEPs. **Figure 5** shows an example convergence plot for Gavins Point for the 0.01 AEP. Since variation in both regulated and undeveloped values is close to zero by the time 250,000 events are considered, it can be inferred that the regulated and undeveloped flows have converged during the FRA compute and adding more events will not significantly change the results.

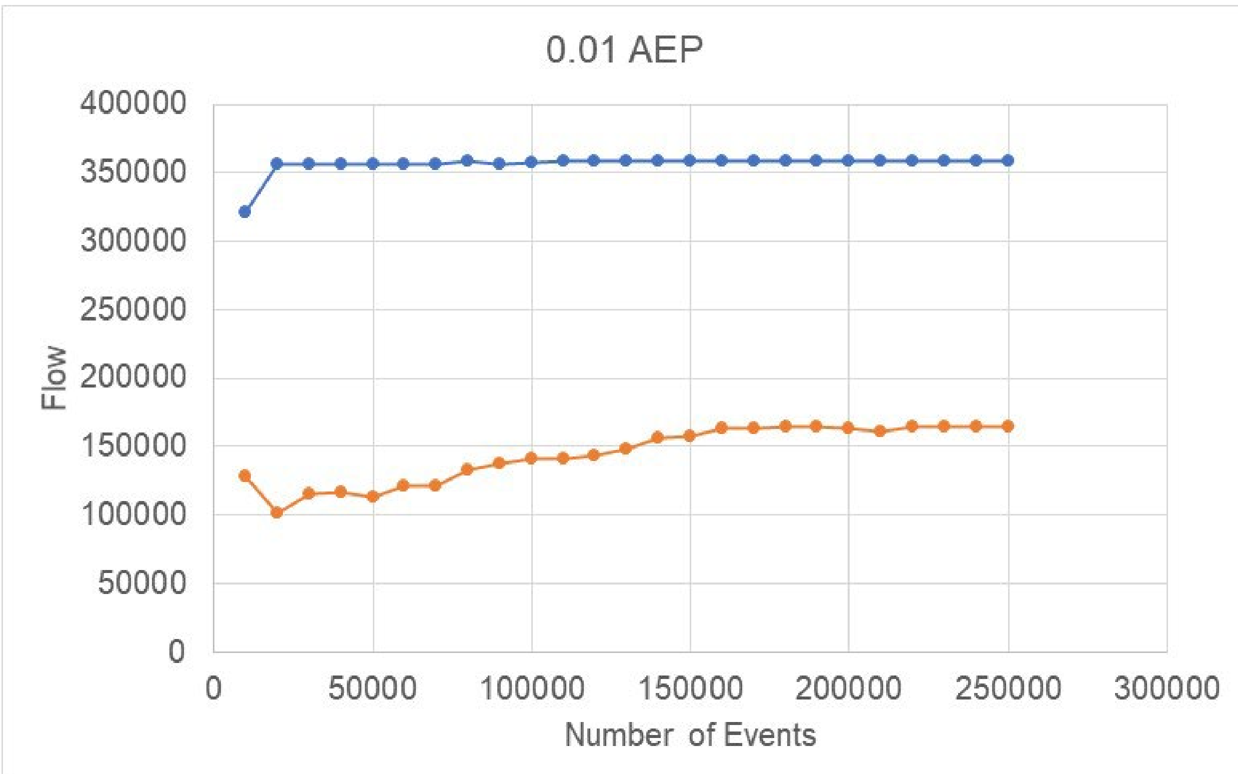

Figure 5: Gavins Point undeveloped and regulated convergence plots for the 0.01 AEP.

If the simulation did not contain any scaled events, the Hydrologic Sampler would assign each year in the historical sample with the same incremental probability of occurring: 1/590, which means the total probability equals 1.0. When a scaled event is added to the Hydrologic Sampler, it removes the incremental probability of the scaled event from events in the historical sample, so the total probability is still 1.0. Incremental probabilities defined automatically in the Hydrologic Sampler can be overwritten, if necessary, which was done for two types of events. The 1951 event on the Kansas River and the 1986 event on the Osage River were extreme events and were not reflective of 1/90 AEP (based on the historical POR) used when creating the Big Bucket. Seven years within the historical sample contained the 1951 event on the Kansas River and six years contained the 1986 event on the Kansas River. This means the probabilities of the 1951 and 1986 events are 0.012 (7/590) and 0.01 (6/590), respectively, but based on the Bulletin 17C curves, their probabilities should have been closer to 0.0011 and 0.0038. Therefore, each event containing these specific events had their incremental probabilities reduced to reflect their estimated AEP and to prevent these events from skewing the results. **Table 6** summarizes the incremental probabilities for each historical and scaled event.

Table 6: Summary of incremental probabilities for each year in the simulation.

Year or Scaled Event	Year Type	Incremental Probability	Cumulative Probability
1951 Years (7)	Historical	0.000157	0.001099
1986 Years (6)	Historical	0.000633	0.004897
All other Years (577)	Historical	0.001660	0.962717
SynDeso1971_25SD	Scaled - 33	0.012465	0.975182
SynDeso1985_15SD	Scaled - 50	0.004160	0.979342
SynSttm1941_20SD	Scaled - 50	0.004160	0.983502
SynSttm1981_15SD	Scaled - 50	0.004160	0.987662
SynDeso1992_20SD	Scaled - 100	0.001254	0.988916
SynDeso1971_30SD	Scaled - 111	0.001254	0.990170
SynSttm1974_20SD	Scaled - 125	0.001254	0.991424
SynDeso2007_10SD	Scaled - 142	0.002499	0.993923
SynDeso1985_20SD	Scaled - 200	0.000423	0.994346
SynNcne2019_10SD	Scaled - 200	0.000423	0.994769
SynSux1947_20SD	Scaled - 200	0.000423	0.995192
SynDeso1992_25SD	Scaled - 250	0.000319	0.995511
SynHemo1995_05SD	Scaled - 250	0.000319	0.995830
SynMkc1967_10SD	Scaled - 250	0.000319	0.996149
SynSux1978_15SD	Scaled - 250	0.000319	0.996468
SynHemo1943_10SD	Scaled - 333	0.000423	0.996891
SynOahe1952_10SD	Scaled - 333	0.000423	0.997314
SynSux1972_20SD	Scaled - 333	0.000423	0.997737
SynDeso2007_15SD	Scaled - 500	0.000423	0.998160
SynNcne2010_15SD	Scaled - 500	0.000423	0.998583
SynSux1997_10SD	Scaled - 500	0.000423	0.999006
SynHemo1944_15SD	Scaled - 1000	0.000091	0.999097
SynHemo1960_15SD	Scaled - 1000	0.000091	0.999188
SynSttm1984_25SD	Scaled - 1000	0.000091	0.999279
SynMkc1993_05SD	Scaled - 1250	0.000382	0.999661
SynSttm1982_30SD	Scaled - 2000	0.000195	0.999856
SynSux2011_10SD	Scaled - 2000	0.000195	1.000051*
SynDeso1951_05SD	Scaled – 5000	0.000257	1.000308*

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

Results

Post-Process Weighting

With 250,000 events simulated and convergence verified, the last step was to verify that the Hydrologic Sampler was sampling and producing hydrology that closely matched the historical POR. This step required comparing the resulting 1-day volume frequency curves to the curves created from the historical POR. The Bulletin 17C frequency curves reported in the Missouri

River Flow Frequency Study at gages between Gavins Point Dam/Yankton, SD and St Joseph, MO used a mixed-population analysis to account for the snowmelt events and their influence on the frequency curves, as well as the rain events. The HEC-WAT data only processed annual maximums, but with the large sample size of the HEC-WAT output, the output should closely match the mixed-population curves. **Figure 6** shows the initial comparison between the HEC-WAT undeveloped flow frequency curves and the Bulletin 17C flow frequency curves at Gavins Point. The HEC-WAT output underestimates the 1% AEP and the 0.2% AEP events at this location, a problem caused in part by assigning only one AEP to each event for all locations.

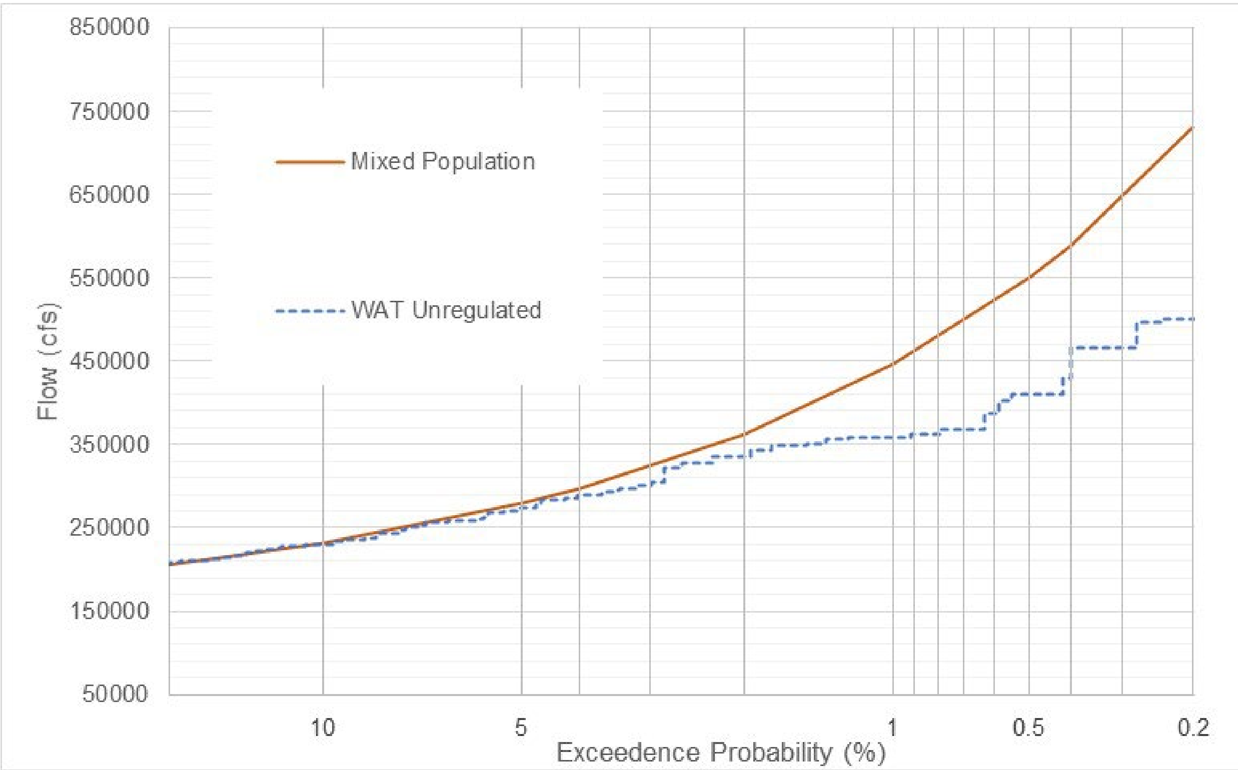

Figure 6: Gavins Point undeveloped flow frequency curves.

To mitigate the limitation of assigning AEPs based on one location, a probability weighting method was applied to the data as a post-processing step. In general terms, the method recognizes how often an event *should* have been sampled for that location during an FRA compute and changes the resulting event frequencies to reflect it. This method would be the equivalent to adjusting the incremental probabilities of each event (and thus calibrating the HEC-WAT output) to match a Bulletin 17C flow frequency curve. However, since the HEC-WAT only uses one incremental probability per event, it would be possible to match one location's Bulletin 17C flow frequency curve, and the other locations would likely not match their respective frequency curves. The weighting method, performed separately for each location, allows the HEC-WAT frequency curves of undeveloped flows to match the Bulletin 17C flow frequency curves at every location along the Missouri River. Once the weights are determined for the undeveloped flows, they are applied to the resulting regulated flows. This means the weights do not correspond to the plotting position but rather the events themselves, which is important because the largest undeveloped event does not necessarily produce the largest regulated event. When the weights correspond to the event, the adjustment made to the undeveloped frequency curves is equivalent to the adjustment made to the regulated frequency curves.

Confidence Limits

Post-processing frequency curves based on all 250,000 events alters the uncertainty around the mean frequency curve. 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. Confidence limits were calculated by creating a probability distribution for each quantile using data from each realization. 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 7**. 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.

Figure 7: Mean and confidence limits for both raw and weighted, regulated frequency curves.

Final Results

Figure 8 through **Figure 9** show the comparison plots for the unadjusted and adjusted, undeveloped and regulated flow frequency curves created from the HEC-WAT simulation against the frequency curves created by Bulletin 17C and the transform methods described in Engineering Manual 1110-2-1415 (U.S. Army Corps of Engineers, 1993). With the HEC-WAT frequency curve for Gavins Point, there is a noticeable plateau in regulated flows at 164,000 cfs caused by the operational criteria for the System. Oahe Dam and Reservoir is the most downstream project in the System with a significant amount of storage, and essentially provides water for releases from Gavins Point. Oahe's spillway is earthen lined and 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 maximum capacity of Oahe's flood tunnels and powerhouse is approximately 164,000 cfs. Because Oahe essentially provides the volume for Gavins Point releases, Gavins Point releases are only increased above 164,000 cfs during extreme flood events or emergency situations. 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, IA; Omaha, NE; and Nebraska City, NE 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 because there is less influence of regulation as more unregulated drainage area is incorporated. The HEC-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.

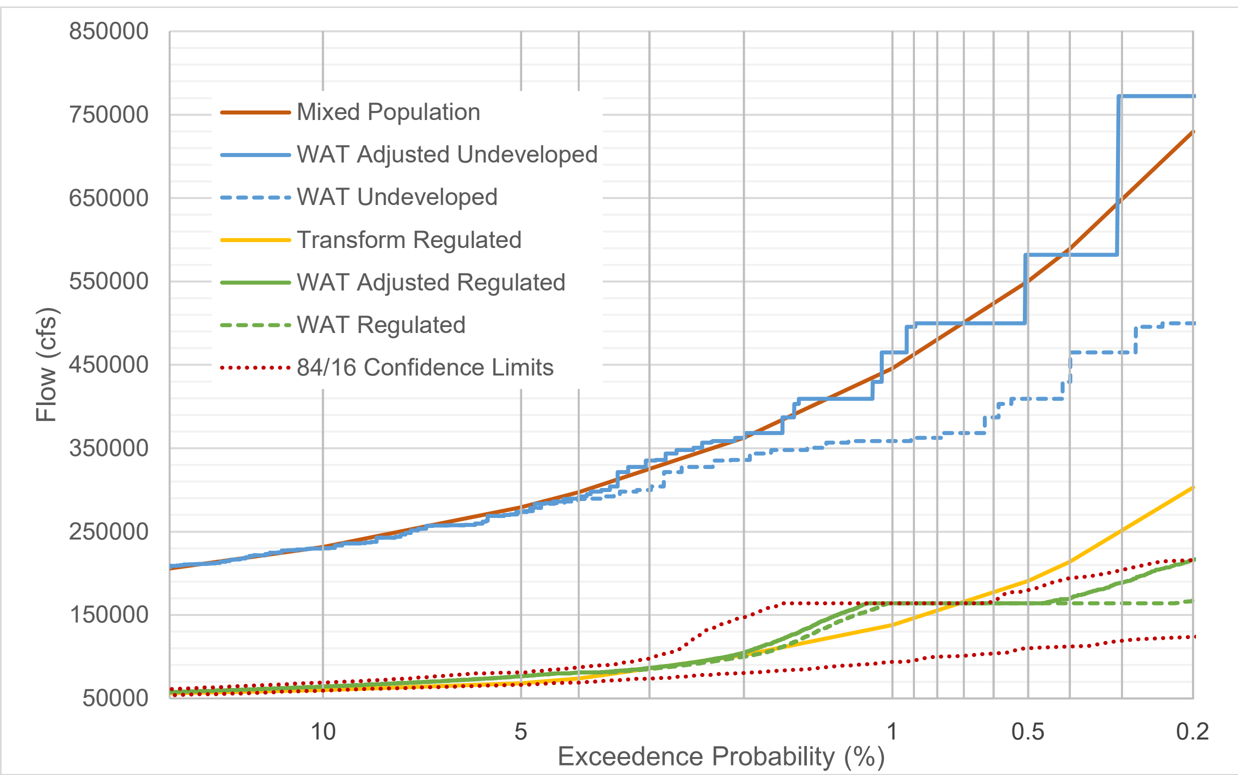

Figure 8: Comparison of Gavins Point undeveloped and regulated flow frequency curves.

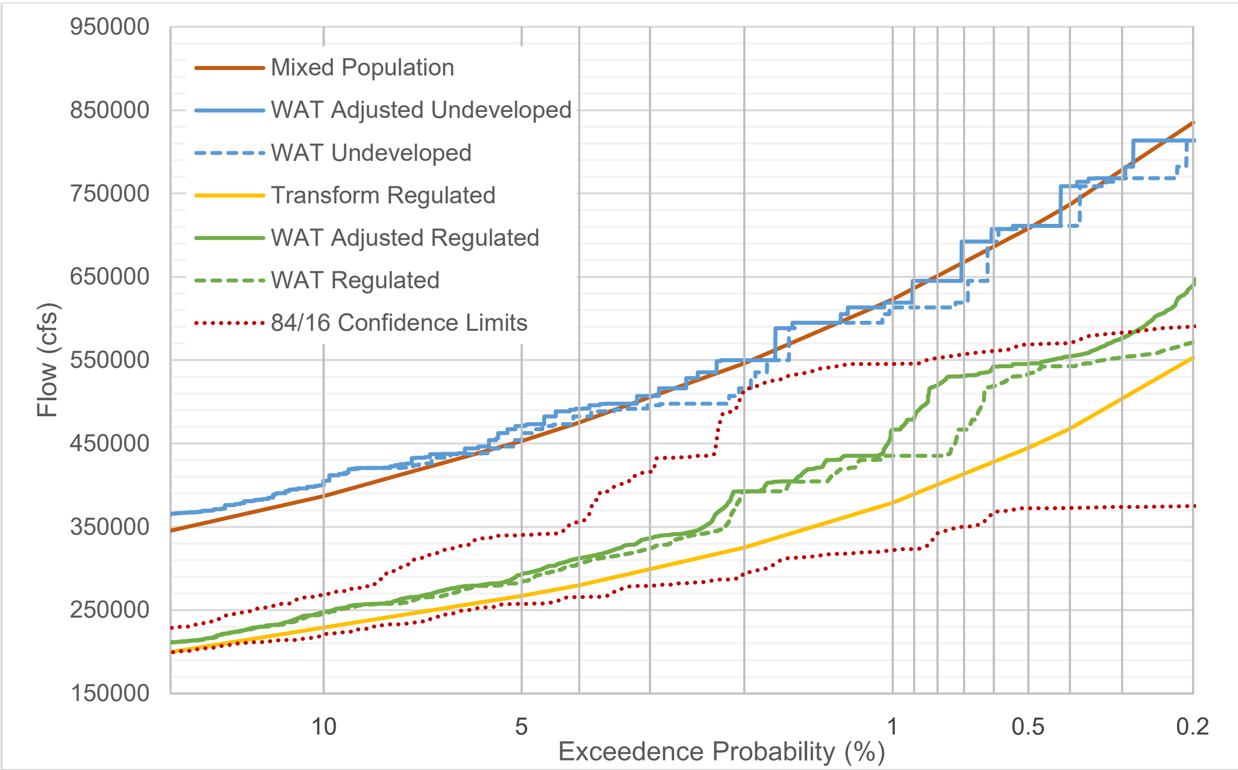

Figure 9: Comparison of Kansas City undeveloped and regulated flow frequency curves.

Summary

In summary, the HEC-WAT was used to simulate 250,000 hydrologic events, sampled from a 590-year historical sample and scaled events. Events simulated as part of the 50-year continuous simulations were able to estimate the influence regulation has on flow frequency. A weighted adjustment of the Monte Carlo sample was completed at each gage allowing the resulting flow frequencies to match the frequency curves for undeveloped flows produced by the Bulletin 17C analyses. The weights were assigned to each event, not its plotting position, to ensure the resulting regulated flow was given the same weight as its corresponding undeveloped flow. Compared to the traditional transform method, the Monte Carlo approach produced better estimates of regulated flow frequency by capturing thousands of combinations of flow events, reservoir pool elevations, inflows, forecasts, and operations.

References

U.S. Army Corps of Engineers. 1993. "Engineering and Design Hydrologic Frequency Analysis (EM 1110-2-1415)."

U.S. Army Corps of Engineers. 2012. "Columbia River Treaty 2014/2024 Review Datasets and Models for Flood Risk Assessment Report Appendix A."

U.S. Army Corps of Engineers. 2018. "Missouri River Recovery Management Plan and Environmental Impact Statement (Vols 1-4)."

U.S. Geological Survey. 2019. "Guidelines for Determining Flood Flow Frequency Bulletin 17C"